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Assessment of the Hydrometric Network and Hydrodynamic Behaviour of Small Irish Catchments

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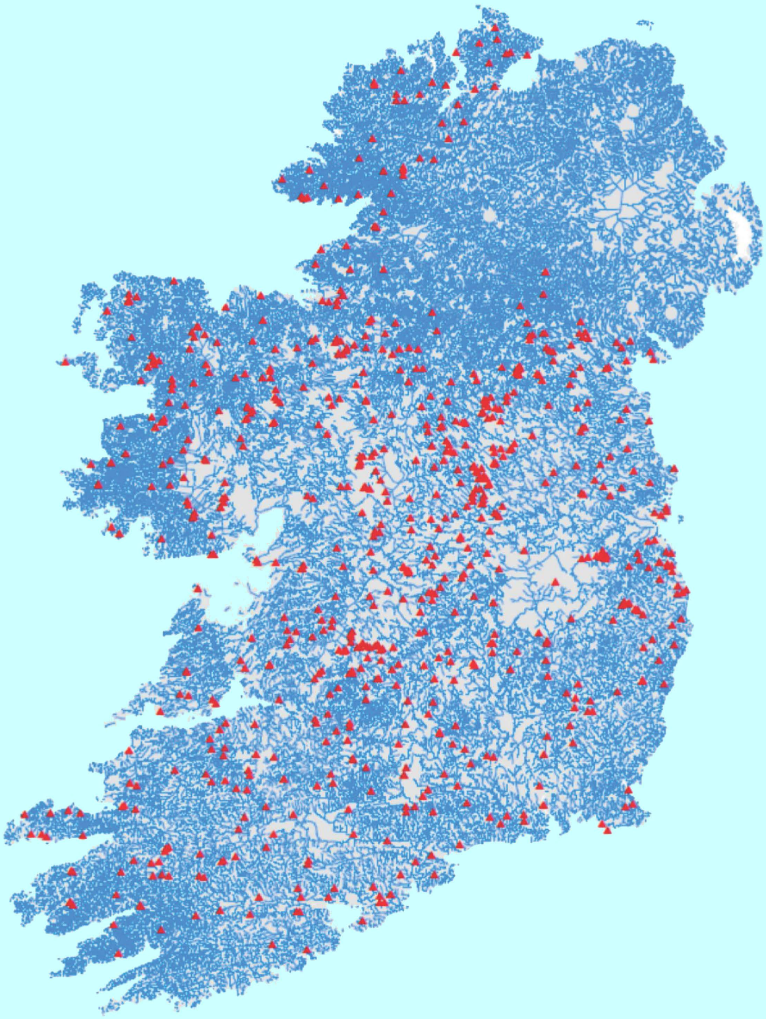

Roinn Cumarsáide, Gníomhaithe ar son na hAeráide & Comhshaoil
Department of Communications, Climate Action & Environment

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ENVIRONMENTAL PROTECTION AGENCY

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- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

Assessment of the Hydrometric Network and Hydrodynamic Behaviour of Small Irish Catchments

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Final Report

Prepared for the Environmental Protection Agency

by

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The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Improving our understanding of the hydrodynamics of small Irish river catchments is of paramount importance in addressing a range of water resource management challenges including municipal and commercial water abstraction, flood risk management and water quality. In 2015/2016, Ireland experienced the wettest winter on record, bringing the issues of flooding, flood prediction, and flood management into sharp focus. Widespread flooding, which occurred at small catchment scale, was associated with serious economic and human health implications. Moreover, hydrometric monitoring in Ireland and further afield is increasingly focusing on larger catchments and river basins, resulting in decreased data availability and modelling capabilities with respect to smaller (and often flashier) catchments. Accordingly, this study sought to develop recommendations relating to hydrometric monitoring requirements for small catchments in Ireland via an integrated mixed-methods approach. The study design encompassed (1) a statistical assessment of the current and historical small catchment network, (2) selection of study catchments, (3) quantification of the temporal and spatial hydrodynamics of selected small catchments via multiple existing approaches, and (4) examination of current hydrometric data usage, perceived network and data efficacy and limitations, and potential (prioritised) network improvements among users of the Irish hydrometric network.

Recent years have seen significant contraction of the small catchment monitoring network in Ireland. While many river gauging stations are no longer active for various reasons, data from these stations still exist, resulting in a low-density network that focuses on monitoring of larger catchments. Network density is extremely low in specific geographical regions and for particular catchment types. Concurrently, elicitation of expert opinion found that over half (50.5%) of network data users perceived the current network as inadequate within the context of their professional requirements, with hydrometric data quality, data representivity, the small catchment network and flooding found to be the primary issues raised in terms of required network improvements. More specifically, small catchment data users reported a need for increased levels of groundwater monitoring and improved rating curves. Network users and stakeholders alike are in agreement that focused network density increases are necessary, with small catchments and flood-prone regions selected as areas of particular significance with respect to (re)activation of recording stations.

Hydrological modelling of selected study catchments at both daily and hourly intervals found that existing models provide low to moderate accuracy ($R_{eff}=0.54-0.84$), with lowest model efficiencies associated with a small urban catchment for all modelling approaches ($R_{eff}=0.54-0.58$). While low (baseflow) and moderate flows were reasonably simulated, the magnitude of high flows and flood events were systematically underestimated. It is likely that the conceptual structure of many existing models may not be suitable for small catchments because of their development for and frequent use within larger catchments, with model efficiency shown to increase in concurrence with increasing catchment size, even at the small scale ($<30\,km^2$).

Overall, study results indicate that small catchment hydrometric data are at a premium in Ireland; currently, data requirements far outstrip data availability, while existing hydrometric models do not perform well as a result of both conceptual and data limitations. Accordingly, the authors recommend developing a small catchment classification system in the short term, followed by identifying representative “sentinel” catchments within each identified cluster. It is envisaged that clustering will aid in the development of cluster-specific small catchment hydrological models, thus improving current knowledge of small catchment hydrodynamics. Furthermore, this approach would effectively inform future catchment instrumentation and network amendments via development of decision-making tools based on identified clusters.

1 Introduction

1.1 Introduction

This study proposed to address three main issues related to the small catchments in Ireland: (1) developing a comprehensive understanding of the temporal and spatial dynamics of key water balance components (e.g. rainfall, evaporation, stream flow, groundwater recharge) in small catchments; (2) identifying small-scale benchmark catchments for the purpose of long-term monitoring to allow studying the impact of future climate change on these catchments, and to act as study catchments demonstrating the dynamics of typical small catchments; and (3) assessing the feasibility of upscaling the knowledge gained about detailed hydrological processes from small-scale catchments to large-scale catchments. These three issues are collectively considered essential to addressing a range of water resources management challenges, including municipal and commercial water abstraction, flood risk management and water quality. To achieve this goal, a systematic hydrological analysis and evaluation of small catchment hydrodynamics is required, thus necessitating the availability of relevant hydrological, meteorological and physical catchment data. Previous studies in Ireland (OPW, 2012) and further afield (Kapangaziwiri *et al*., 2009; Faulkner *et al*., 2012; Parajka *et al*., 2012; Tayfur *et al*., 2014; Jarihani *et al*., 2015) have identified the paucity of small stream monitoring as a fundamental obstacle to undertaking any rigorous investigation of the hydrodynamic behaviours of small catchments. Thus, a comprehensive review of the existing hydrometric network represents a critical step in assessing the current efficacy and necessary future network amendments to small catchment monitoring in Ireland. Moreover, the findings of this assessment will permit evidence-based selection of small catchments with high-quality hydrometric records for evaluation of the hydrodynamic behaviour of small catchments in Ireland. Such an evaluation may be used to inform ongoing and future research undertaken 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 ungauged catchments) by the Environmental Protection Agency (EPA) and the Electricity Supply Board (ESB). Accordingly, the current study aims to address the above-mentioned knowledge gaps through completion of the following four primary research objectives.

1. Review and assess the existing Irish hydrometric network of small catchments, thus aiding identification and selection of suitable small-scale study catchments.
2. Quantify, from existing measured data, the temporal and spatial hydrodynamics of selected small catchments.
3. Examine current hydrometric data usage, perceived network and data efficacy and limitations, and potential (prioritised) network improvements among users of the Irish hydrometric network.
4. Use the findings of these three objectives to develop recommendations relating to hydrometric monitoring requirements for small catchments in Ireland and to the upscaling of hydrological processes from small to large catchments.

1.2 Study Methodology

Prior to undertaking an analysis of the small catchment hydrometric network, it is essential to appropriately define the maximum spatial extent of a “small” catchment. Typically, small catchments are characterised by the presence of low-order streams, with catchment size dependent on the number of streams contained within the individual catchment. Jenkins *et al*. (1994) have suggested that small catchments should be large enough to encompass all interacting components of the hydrological cycle, e.g. the atmosphere, vegetation, soils, bedrock, and water bodies including the aquifer and the surrounding lands. Previous hydrological studies of small catchments carried out in Ireland and the UK have typically defined and examined catchments of $\leq 30\,km^2$. For example, an OPW study conducted by Gebre and Nicholson (2012) focused on flood estimation in small urbanised Irish catchments, and comprised 42 small (≤ 30 km^2) catchments with areas ranging from 2.8 km^2 to 28.63 km^2. Similarly, a study carried out in Northern Ireland examined the behaviour of seven small catchments with areas ranging from 12.77 km^2 to 30.67 km^2 (Gardner and Wilcock, 2000). Three small catchments, namely Clarianna (28 km^2), Bellsgrove (12.5 km^2) and Grange-Rahara (12 km^2), have been examined as part of a study to assess the impact of agricultural management practice on river water quality (KMMP, 2001) (Figure 1.1a), while the Clarianna catchment was also employed by Carton *et al*. (2008), in concurrence with the Dripsey catchment (15.24 km^2), as part of a large EPA-funded project (LS2.2) to examine eutrophication from agricultural sources (Figure 1.1b).

Another, more recent EPA-funded project sought to investigate the fate and transport of contaminants from the land surface to aquatic receptors (Archbold *et al*., 2010; Mockler *et al*., 2013); four small catchments were selected for this work, namely the Gorinlieve (5 km^2), Glen Burn (5 km^2), Mattock (11.6 km^2) and Nuenna (21.6 km^2) catchments (Figure 1.1c). Finally, six small catchments with areas < 30 km^2 were used in the Agricultural Catchment Programme (ACP) conducted by Teagasc (ACP, 2013). These were the Screenty/Corduff (578 ha; 5.78 km^2), Dunleer (948 ha; 9.48 km^2), Ballycanew (1191 ha; 11.91 km^2), Castledockerell (1117 ha; 11.17 km^2), Timoleague (758 ha; 7.58 km^2) and Cregduff (2998 ha; 29.98 km^2) catchments (Figure 1.1d).

Based on a review of these Irish small catchment studies, a benchmark of 30 km^2 (maximum spatial extent) was selected for definition, identification and delineation of small catchments in this study.

To appropriately realise the four primary study objectives (section 1.1), four explicit study components have been developed, namely (1) network assessment, (2) study catchment selection, (3) hydrodynamic analysis and (4) expert elicitation (Figure 1.2).

Completion of the first study objective was achieved via a descriptive and bivariate statistical assessment of all hydrometric stations associated with a catchment area ≤ 30 km^2 since network initiation. Analyses focused on (1) the historical and current scale of the Irish hydrometric network and associated spatio-temporal trends; (2) monitored water body type; (3) agencies responsible for monitoring/management; (4) operational status; (5) range of hydro-meteorological variables; (6) range of flows; (7) station type and data availability; (8) geographic distribution at multiple scales; and (9) catchment size.

Realisation of the second study objective was undertaken via selection of four small catchments from the current operational network, followed by an investigation of their hydrodynamic behaviours via application of a suite of hydrological techniques.

The third study objective was achieved through development and completion of an expert elicitation survey to gather the views of hydrometric network users and stakeholders in Ireland. Findings obtained from the previous work packages have been concurrently employed to develop evidence-based recommendations pertaining to the current efficacy and future requirements of small catchment monitoring in Ireland.

1.3 Data Used in the Study

The main focus of most previous small catchment dynamics studies in Ireland (e.g. Nasr and Bruen, 2006; Fealy *et al*., 2010) was on the evaluation of the impact of diffuse and point sources of pollution on surface water quality. The knowledge generated on catchment dynamics in these cases is limited to what was required for investigating the patterns of pollutant transfer from soils to streams and for describing the processes responsible for such losses (Jordan *et al*., 2005). In other studies on small catchment hydrology, the primary objective was to estimate peak flood flows for the purpose of designing water infrastructure, as in Gebre and Nicholson (2012) where the information on catchment behaviour was related only to the flood response of the catchment during the high-flow season. Therefore, a full understanding of catchment behaviour under various weather and hydrological stresses can only be obtained by employing a more holistic approach in which all elements of small catchment dynamics are thoroughly studied. This requires the use of extensive sets of hydrometric data, meteorological data and catchment physical data to study the complex dynamics of a catchment.

Data requirements for hydrodynamic analysis of small study catchments were determined based on previous Irish hydrological studies (e.g. Bree *et al*., 2010; Mills *et al*., 2014); these indicate that the

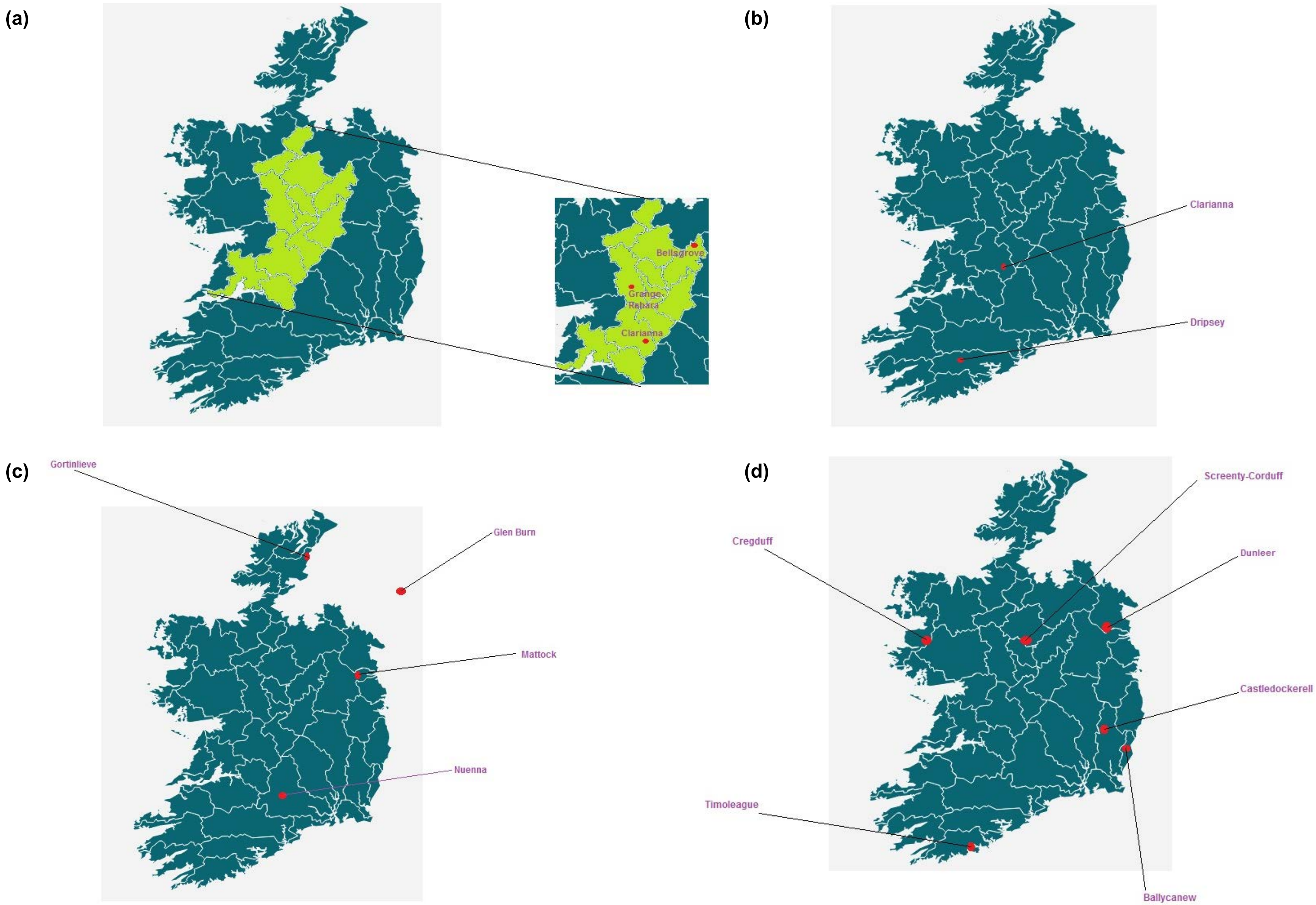

Figure 1.1. Small catchments (≤ 30 km²) used in previous Irish studies. (a) Three small catchments used in Lough Derg/Lough Ree study; (b) two small catchments used in LS2.2 Project; (c) four small catchments used in PATHWAYS Project; and (d) six small catchments used in Teagasc ACP Study.

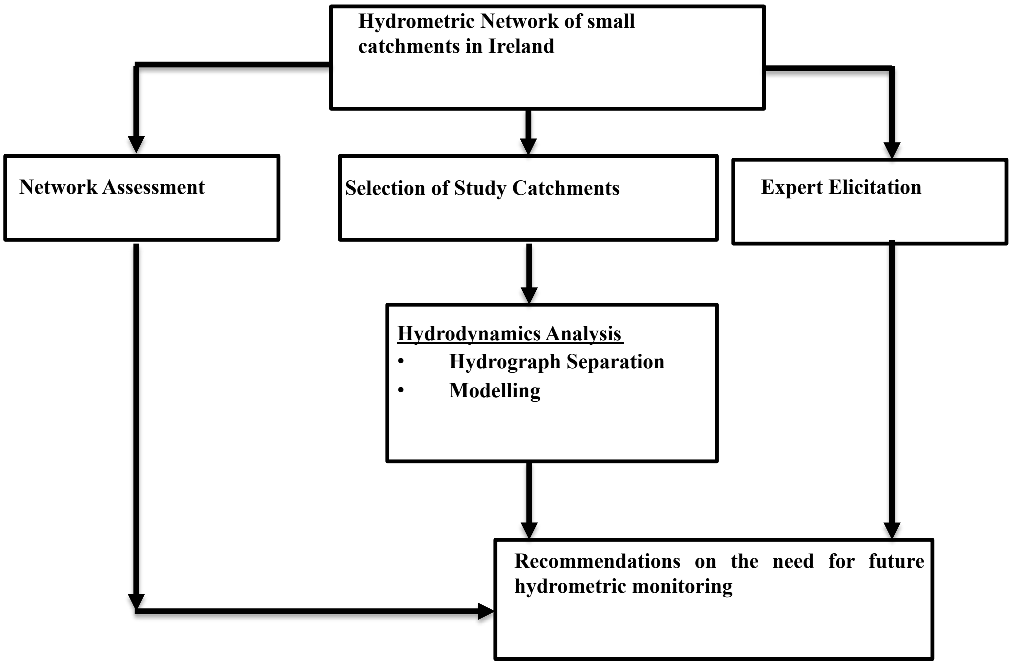

Figure 1.2. Overview of study components and workplan.

hydrodynamic behaviour of a catchment may be studied using physical catchment characteristics and hydro-meteorological data. Physical catchment characteristics include (1) topography, (2) soils and subsoils, (3) hydrogeology and (4) vegetation and/or land use/land cover. Based on model selection and subsequent requirements, the primary datasets used for hydrodynamic analyses throughout the current study were catchment-specific hydro-meteorological variables including precipitation, evapotranspiration and stream flow data.

The Register of Hydrometric Stations in Ireland (available at: www.epa.ie/pubs/reports/water/flows/registerofhydrometricstationsinireland.html#.VijiZHFViko) has been used to identify and statistically assess the hydrometric network of small catchments.

1.4 Layout of the Report

The current chapter (Chapter 1) presents the necessary background and explicit objectives of the overall study, in addition to setting out the methods and approaches employed throughout the study. Chapter 2 provides a detailed description of the methods and findings pertaining to a statistical assessment of the current and historical hydrometric network of small catchments in Ireland. In Chapter 3, study catchment selection is described, followed by presentation of the results of hydrodynamic analyses. Chapter 4 presents the methods and findings from an expert elicitation survey (network users and stakeholders). Finally, Chapter 5 summarises the study findings in addition to presenting the primary conclusions and recommendations for future work.

2 Assessment of Hydrometric Network of Small Catchments

2.1 Introduction

Effective hydrological monitoring is vital 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). In addition, a functional hydrometric network is central to national compliance with the EU Water Framework Directive [2000/60/EC (EU, 2000)] and provision of data pertaining to current and projected effects of climate change at multiple scales. Mishra and Coulibaly (2009) recommend that local and national hydrometric networks be periodically reviewed to account for the “reduction in hydrological uncertainty brought about by the data since the last network analysis”, in addition to changes related to budget, data requirements and users. Accordingly, the current study sought to undertake a statistical assessment of the small catchment hydrometric network to evaluate the current status of small catchment monitoring in Ireland and place this in a historical context. In addition, it is considered that this assessment may be used to identify current monitoring gaps at the small catchment scale, thus permitting development of recommendations for future network amendments, particularly when considered and assessed together with network user/stakeholder opinions and requirements (see Chapter 4 – Expert Elicitation Survey).

2.2 History of the Hydrometric Network

A hydrometric network comprises a group or set of hydrometric stations, typically designed and operated to record hydrological observations to address a single objective (i.e. water resource assessment, development or design), or a set of inter-related objectives. Early network design was typically based on specific project objectives (e.g. irrigation, dam construction, flood mitigation), with the current Irish hydrometric networks also falling into this category. Subsequently, the “basic pragmatic approach” was employed (Nemec and Askew, 1986), which was characterised by “a rationale for network design based upon quasi-uniform spatial coverage which accounted for the specific characteristics of the element being quantified (e.g. a catchment)”, i.e. more was needed than an ad hoc series of hydrometric stations installed with little (if any) reference to one another. Increasingly, hydrometric networks are designed, amended or optimised for addressing sets of inter-related objectives, e.g. flood-warning networks, with the range of hydrological network objectives and associated data usage expanding in parallel. In addition to traditional hydrological data uses, hydrometric networks and data are now employed for environmental monitoring, transboundary flow accounting, system development (e.g. local hydrological forecasts, flood warning), and management of water allocation and utilisation processes. Previous studies have shown that hydrometric network design and optimisation are slow processes (Hannaford and Marsh, 2008; Mishra and Coulibaly, 2009; Hannah *et al*., 2011), with an optimum network defined as “achieved when the amount and quality of data collected and information processed is economically justifiable and it meets the users’ needs” (Bobrovitskaya *et al*., 2001). Central to this definition are an awareness and appreciation of hydrometric users (and stakeholders) and their current and likely future requirements.

Hydrometric monitoring in Ireland dates back to the 20th century, with the network formally initiated in the early 1940s, driven primarily by arterial drainage works, electricity generation, infrastructural development and extreme event warning/management (MacCárthaigh, 2002). Currently the EPA and the OPW are responsible for the collection and provision of hydrometric data and, as such, represent the primary network managers. The primary objective of the EPA–local authority (LA) network is low-flow monitoring; conversely, the overarching objective of the OPW network is high-flow monitoring, which has largely targeted effective flood risk management (i.e. flood monitoring, mitigation strategies, arterial drainage and development of early warning systems). The EPA-LA hydrometric network was initially established as a direct response to the drought experienced in Ireland and the UK in 1976, which served to highlight the need for more rigorous monitoring of river flows, and particularly low flows, for sustainable water provision. The EPA-LA network is currently maintained and managed under the auspices of the Environmental Protection Agency Act 1992, requiring the EPA, in consultation and collaboration with several agencies including local authorities (county and city councils), the OPW, the ESB, the Geological Survey of Ireland (GSI), the Marine Institute, Met Éireann and the Northern Ireland Rivers Agency (NIRA), to develop and manage a national programme for the collection, analysis and distribution of surface water quantity data. The Local Government (Water Pollution) Act 1977 placed responsibility for monitoring, management and control of water quality with local authorities (MacCárthaigh, 2002), resulting in significant increases in network density and coverage during the late 1970s and early 1980s. The EPA also has an advisory capacity in the development of local authority river flow networks, which are primarily focused on smaller catchments.

A recent review of the EPA-LA hydrometric network (EPA, 2011) proposed a contraction of the network, to be achieved via removal of the majority of staff gauge-only stations, resulting in a network comprising 267 stations, 87% ($n=231$) of which would be characterised by high-quality continuous recording, and 79% ($n=211$) of which would be associated with continuous discharge monitoring. Removal of stations from the hydrometric network will be based on expert consultation and results of a developed quantitative assessment (EPA, 2011). Similarly, Murphy *et al.* (2013) undertook a review of the Irish river hydrometric network to identify suitable benchmark stations for monitoring and detection of climate-driven hydrological change. This work employed hydrometric record length and rating curve quality for flow value estimation as the two primary assessment parameters. Typically, while OPW hydrometric stations tend to have longer records, many of these stations have been adversely affected by the impacts of arterial drainage (i.e. river channel widening and deepening). Furthermore, and of particular significance within the context of the current project, OPW stations have been more frequently installed in large catchments and basins to monitor flooding occurrences and arterial drainage. Notably, neither of the recent hydrometric network reviews focused on small catchments.

2.3 Hydrometric Network Assessment Method

To effectively assess the small catchment hydrometric network in Ireland, statistical analyses were conducted for all active and inactive hydrometric stations associated with a catchment area ≤30 km^2 during the period 1942–2015. As previously outlined, the primary data source used was the updated Register of Hydrometric Stations in Ireland (updated August 2015); the EPA currently maintains the Register of Hydrometric Stations in Ireland, which comprises all active and retired/inactive hydrometric stations since initiation of the hydrometric monitoring network in 1932 ($n=2384$). Where catchment areas were not available, all possible efforts were made to discretise and/or update the area via consultation with the EPA Hydrometric and Groundwater Section and the OPW, in addition to direct analyses of available digital terrain models (DTMs). The complete register includes 33 variables per station; as part of the current study, 29 variables were extracted, derived and coded for the determination of spatial and temporal trends pertaining to:

- hydrometric network size;
- catchment (water body) type;
- agencies responsible for monitoring/management;
- operational status;
- range of mean annual rainfall;
- range of 50th and 95th percentile flows, and dry weather flow (DWFs);
- station type and data availability;
- geographic distribution at varying scales;
- monitored catchment size.

Following collation of all available data from the Register of Hydrometric Stations, statistical analyses were undertaken within the R statistical environment (FactoMineR, compareGroups and MVN packages). Pearson's chi-squared tests of independence were used to determine the presence of associations between categorical (dichotomous and nominal) variable pairs (χ^2 statistic). Odds ratios (ORs) and associated 95% confidence intervals (CIs) were calculated and used to examine the level of association between dichotomous pairs. Independent sample *t*-tests (difference of means with equal variance assumed) were used to test for the presence of associations between dichotomous and continuous variables (*t* statistic), while one-way analysis of variance (ANOVA) was used to test for relationships between continuous variables and categorical variables with > 2 levels of classification (*F* statistic). Spearman's non-parametric measure of rank correlation was used to examine relationships between continuous variables with non-linear distributions (R_{sp} statistic). A *P*-value < 0.05 was used by convention. All data collation and numerical coding were carried out in Microsoft Excel 2010 using conditional formatting and specifically developed macros.

2.4 Results and Discussion

2.4.1 *Descriptive summary*

The most recently updated Register of Hydrometric Stations in Ireland comprises a total of 2384 currently or previously monitored catchments on the island of Ireland, with 329 stations not assigned an explicit catchment area. As a result, the total number of stations with a known catchment area becomes 2055. Of these 2055 stations, 750 (36.5%) have a catchment area ≤ 30 km^2 and are considered small catchments as defined in the current study. Furthermore, to ensure an unbiased and representative assessment of the national network, a number of exclusion criteria were developed and implemented in consultation with the EPA Hydrometric and Groundwater Section. These included exclusion of private or commercial stations for which data are not readily and/or publicly available (Table 2.1), and stations associated with measurement of uncharacteristic discharges for specific timeframes and/or objectives (Table 2.2). Upon exclusion of unsuitable stations, the primary dataset for network assessment of small catchments was populated by 703 hydrometric stations associated with a catchment size of ≤ 30 km^2.

The majority (85.5%, n = 601) of the 703 hydrometric stations are currently inactive, equating to a currently active small catchment hydrometric network of 102 stations. Irrespective of catchment size, the total active hydrometric network in Ireland currently comprises 1265 stations, with the small catchment network thus constituting 8.1% of the active network. This also equates to a national small catchment density of one station per 832.57 km^2. Within the currently active small catchment network, the mean catchment area is 12.59 km^2 [standard deviation (SD) 8.56 km^2; minimum 0.1 km^2; maximum 29.4 km^2], compared with 12.11 km^2 among all (active and inactive/suspended) stations (t = –0.643, P = 0.52).

As a direct result of the previously mentioned network assessment and resulting recommendations by Murphy *et al.* (2013) (i.e. removal of staff gauging stations), the majority of the 102 active hydrometric

Table 2.1. Number of small catchment hydrometric stations excluded based on station ownership and data availability

Hydrometric station owner	Number of stations excluded
Dún Laoghaire Port	2
Foras Forbartha	1
Private	1
Environmental Research Unit	1
Iarnrod Éireann	1
Siúicre Éireann	1
New Ross Port Company	8
Bord na Móna	4
Irish Distillers	3
Cork Port Company	6
Golden Vale Foods	2
Central Fisheries Board	5
National Parks and Wildlife	1
Shannon and Foynes Port Company	1
Total	37

Table 2.2. Number of small catchment hydrometric stations excluded based on monitored discharge type

Water body/discharge type	Number of stations excluded
Manhole	1
Influent stream	1
Effluent stream	1
Discharge outlet	2
Intake	1
Adit	2
Reservoir	1
Drain	1
Total	10

stations are characterised as recorder stations (98%, *n* = 100), with only one staff gauging station and one spot recorder station currently in use. Overall, 76% (*n* = 76) of the 100 currently active recorder stations monitor both discharge (flow) and water level, with the remainder (*n* = 24) providing continuous water level measurements. These proportions have been altered significantly by both recent and historical amendments (primarily via removal of stations); since network initiation, 99.8% of level-gauging stations have been removed or suspended.

There is a notable paucity of annual mean rainfall, 50th percentile flow, 95th percentile flow, and DWF data currently available for small catchments (Table 2.3). Overall, 10.8% (*n* = 11) of 102 active stations reported zero DWFs. A recent hydrometric registry update has resulted in the provision of revised instantaneous flow measurements; revisions with respect to 50th percentile, 95th percentile and DWF are currently available for 51 (50%), 5 (4.9%) and 34 (33.3%) of 102 actively monitored small catchments, respectively. This trend mirrors a recently reported global pattern characterised by a marked decline in the volume of river flow data being collected and made available (Mishra and Coulibaly, 2009). Typically, this has been driven by insufficient funding, inadequate institutional framework and a lack of appreciation of the worth of long-term hydrological data (Stokstad, 1999; Mishra and Coulibaly, 2009) among non-technical decision makers.

As shown (Table 2.4), almost three-quarters (69.6%) of 102 active stations of small catchments are associated with small river catchments, with monitored river and lake catchments combining to account for approximately 94% of the currently active small catchment network.

As previously outlined (section 2.2), the majority of stations are and traditionally have been operated by the EPA jointly with local authorities, with approximately 71.6% of currently operational stations managed by the relevant county council (Table 2.5).

Structured small catchment hydrometric data measurement was initiated in 1942 (Figure 2.1) with the construction of the Torc Weir by the OPW at Owengariff, Co. Cork. A significant network size increase began in 1975 with the installation of 28 stations; this increase largely continued over the ensuing 5- to 6-year period. A peak occurred in 1998 when 65 individual stations (10% of total) were

Table 2.3. Descriptive statistics for instantaneous hydrological variables associated with active stations (*n* = 102)

Variable	*n* (%)	Minimum	Maximum	Mean	SD
Pmm_61–90 (mm)	83 (81.4)	725	2332	1188.35	356
50% flow (m^3/s)	51 (50)	0.007	0.642	0.224	0.155
95% flow (m^3/s)	34 (33.3)	0	0.230	0.050	0.049
DWF (m^3/s)	41 (40.2)	0	0.200	0.017	0.034

Notes: Pmm_61–90, mean 30-year (1961–1990) annual precipitation (Pmm_61–90); 50% flow, 50th percentile (median) flow; 95% flow, 95th percentile flow.

Table 2.4. Catchment type assigned to all (active and inactive) small catchments

Catchment type	Active and inactive (%)	Active (%)
River	616 (87.4)	71 (69.6)
Lake	52 (7.4)	19 (18.6)
Tidal	6 (0.9)	3 (2.9)
Groundwater	7 (1)	3 (2.9)
Unknown	24 (3.4)	6 (5.9)
Total	705 (100)	102 (100)

Notes: Inactive stations include currently suspended stations (*n* = 4); Groundwater catchments include categorical “Spring” and “Well” water body types

installed nationwide, followed by a steady decrease starting in 2000 and continuing over the next decade.

2.4.2 Network distribution

The Shannon (Sh) River Basin District (RBD) is associated with the highest percentage of active stations (28.4%, $n=29$); in terms of hydrometric density, this equates to an unrepresentative proportion, with this RBD accounting for approximately 21.5% of national land surface area (18,000 km^2). The Eastern (E) RBD is also somewhat over-represented, while the South-Eastern (SE), South-Western (SW) and North-Eastern (NE) RBDs are associated with comparatively low levels of monitoring (Figure 2.2). The highest numbers of active small catchment stations are currently operating in counties Westmeath (10.8%, $n=11$), Mayo (7.8%, $n=8$), Leitrim (6.9%, $n=7$) and Donegal (6.9%, $n=7$), while three counties do not presently have an active hydrometric station (Fermanagh, Kilkenny and Tyrone).

The association between geographical location, and data availability and values of annual mean rainfall,

Table 2.5. Institutional operators of small catchment monitoring in Ireland

Agency	Active and inactive (%)	Active (%)
EPA-LA	623 (88.4)	73 (71.6)
OPW	35 (5)	21 (20.6)
NIRA	16 (2.3)	6 (5.9)
Marine Institute	9 (1.3)	1 (0.98)
ESB	10 (1.4)	1 (0.98)
Other	12 (1.7)	–
Total	705 (100)	102 (100)

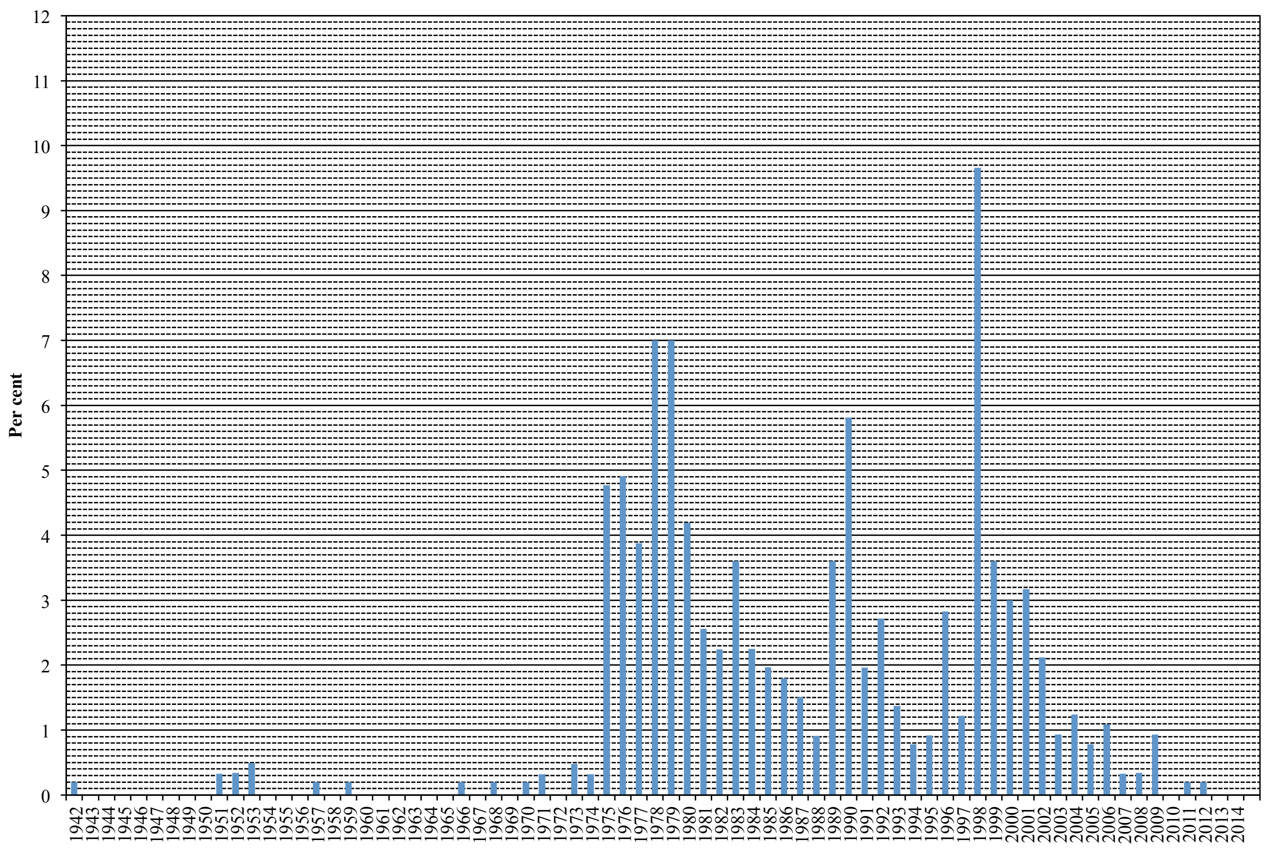

Figure 2.1. Year of installation assigned to (active and inactive) small catchment hydrometric stations in Ireland, 1942–2014 ($n=688$).

50th percentile flow, 95th percentile flow and DWF have been examined using a Bonferroni multiple comparisons post hoc test. The results indicate that higher levels of annual mean precipitation are associated with administrative areas (RBDs and counties) located along the western seaboard, thus reflecting national meteorological patterns. No association between administrative area and the availability of the 50th and 95th flow percentile flows or DWF was found. Similarly, no association was apparent between geographical area and means or SDs of the three flow variables.

Within the total (active and inactive) dataset, a significant association was found between geographical location and catchment/gauged water body type, as confirmed by the result of the chi-squared test ($\chi^2(21) = 43.956$, $P = 0.002$). Interestingly, amendments to the small catchment hydrometric network made since the later 1990s have led to a reduction in the previously evident "lack of proportionality" ($P = 0.510$) (Table 2.6), i.e. catchment location is no longer indicative of gauged water body type and may therefore denote a lack of hydromorphological representivity within the currently active network.

2.4.3 Station inactivation

Since initiation of small catchment monitoring in Ireland, 588 stations have been deactivated, with 563 of these associated with an explicitly reported inactivation year (Figure 2.3). The remaining 25 stations are currently inactive (or suspended) but do not have a specific inactivation year, and therefore it was not possible to calculate an available record period. As shown in Figure 2.4, significant network contraction began in 1999 and has continued unabated since then.

As might be expected, a statistically significant association exists between the occurrence of station inactivation and station type ($\chi^2(4) = 261.087$, $P < 0.001$). While 52.9% of recorder stations, which

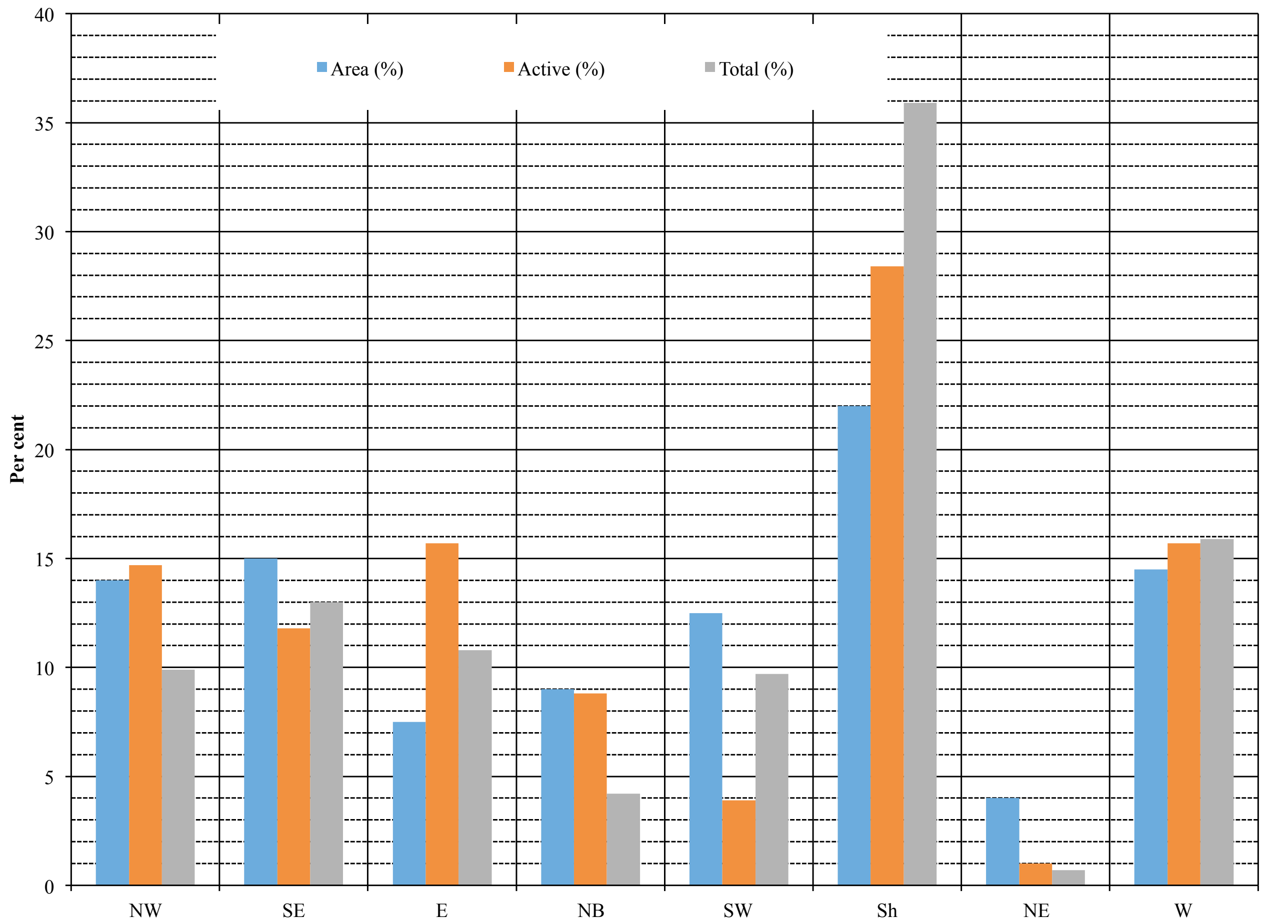

Figure 2.2. Spatial distribution of active and inactive monitored small catchments with known river basin district (*n* = 694). NB, Neagh Bann; NW, North-Western; W, Western.

Table 2.6. Catchment type and RBD associated with actively monitored small catchments

RBD	River	Lake	Tidal	Groundwater	Unknown type
North-Western	11	4	–	–	–
South-Eastern	11	–	1	–	–
Eastern	12	4	–	–	–
Neagh Bann	3	1	–	–	5
South-Western	4	–	–	–	–
Shannon	19	5	2	3	–
North-Eastern	–	–	–	–	1
Western	11	5	–	–	–
Total	71	19	3	3	6

Note: groundwater catchments include categorical "Spring" and "Well" water body types

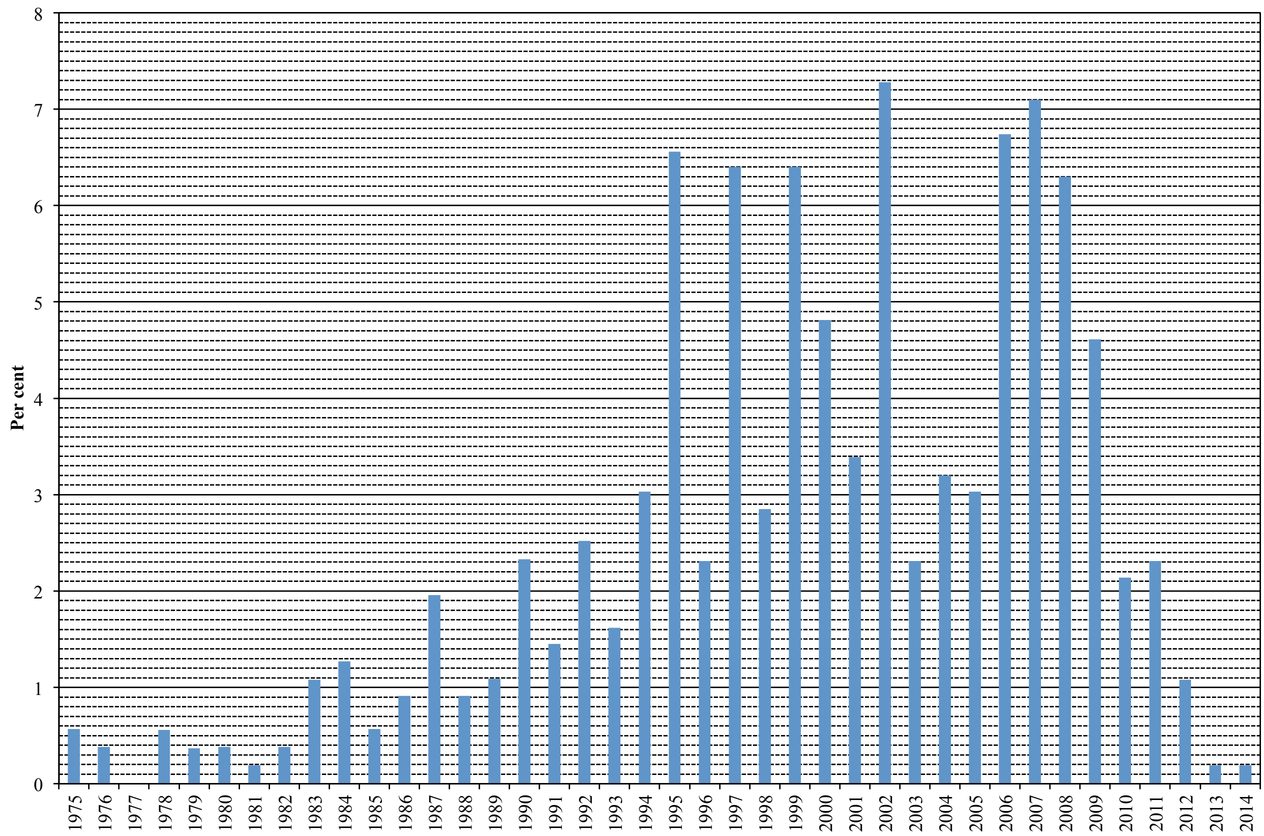

Figure 2.3. Year of station deactivation associated with inactive small catchments in Ireland, 1975–2014.

are stations fitted with a staff gauge and an automatic water level recorder, have been retired over the record period, the equivalent figure is 99.8% for gauge-only stations, i.e. stations fitted with only a staff gauge, (OR 6.2; 95% CI 4.3–8.9) (Figure 2.5). These findings are in agreement with previous findings and recommendations emanating from previous network assessments (EPA, 2011; Murphy *et al.*, 2013). Subsequently, while active network density has decreased substantially, a significantly higher proportion of active stations and associated small catchments are now associated with the availability of continuous level and/or flow data ($\chi^2(4) = 303.915$, $P < 0.001$) than was previously the case.

A significantly greater proportion of stations associated with rivers and lakes have been inactivated during the record period than other water body/catchment types ($\chi^2(6) = 59.651$, $P < 0.001$). For example, presently 88% ($n = 542$) of previously monitored river catchments have been retired from the network, with a further four stations currently suspended. Conversely, 50% of tidal

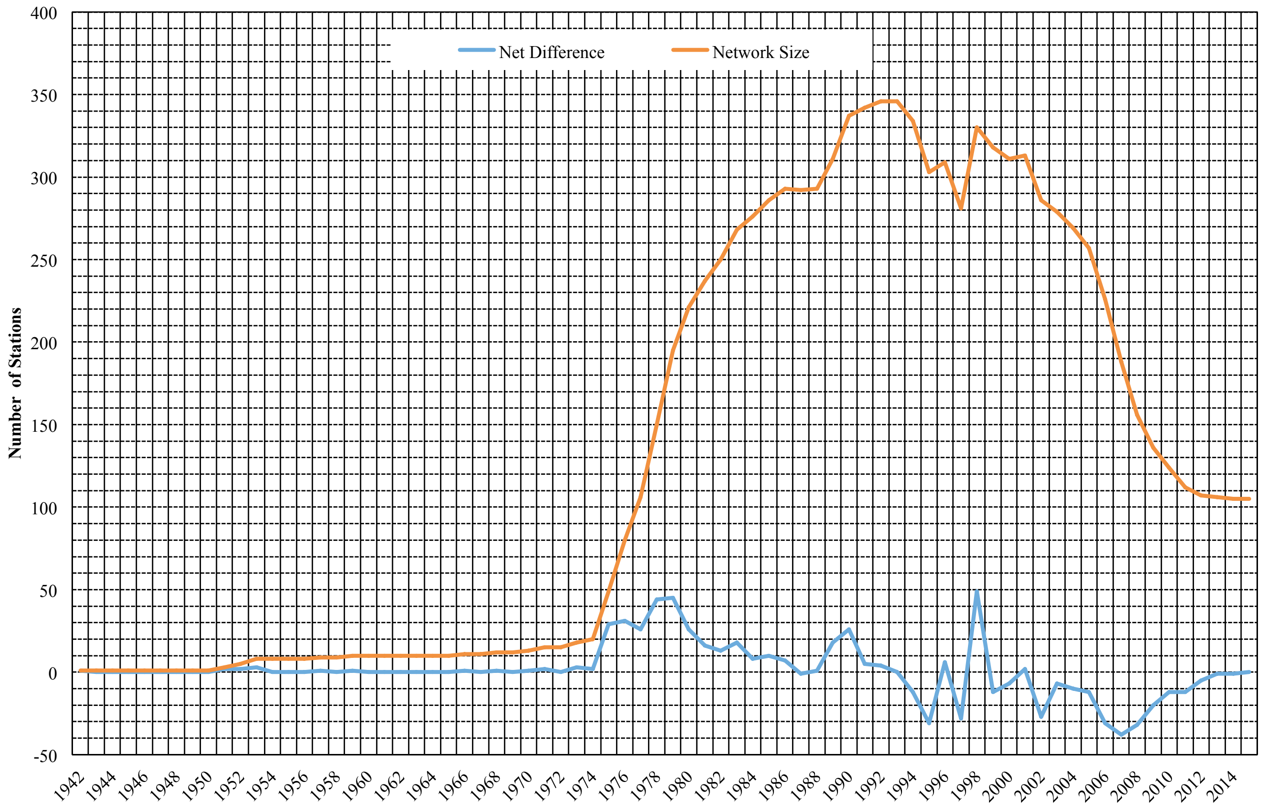

Figure 2.4. Annual net difference between small catchment hydrometric station activations and deactivations, and total annual network size from 1942 to 2014.

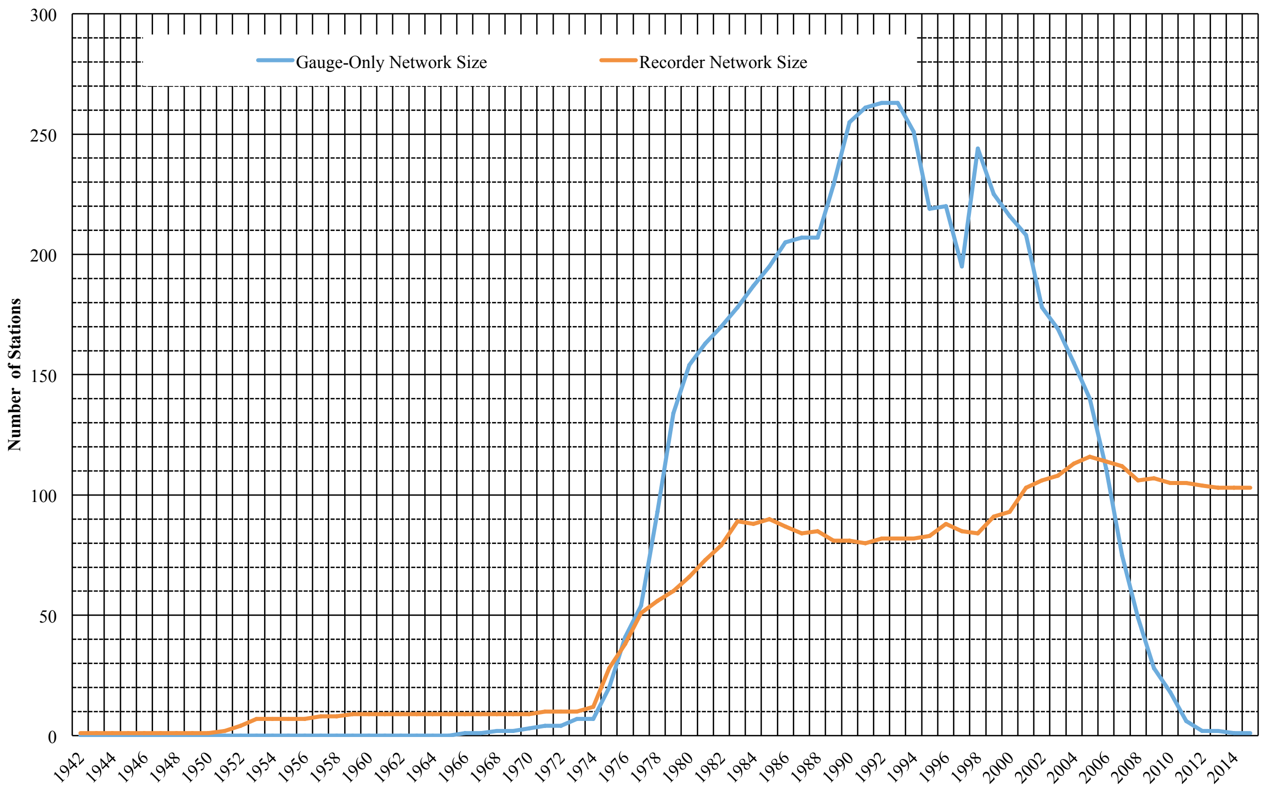

Figure 2.5. Gauge-only and continuous recorder small catchment monitoring network size from 1942 to 2014.

small catchments are still being actively monitored, albeit this proportion represents an extremely small figure ($n=3$).

No significant association was found between operational status (i.e. station active/inactive) and catchment size ($P=0.52$), 50th percentile flow ($P=0.501$), 95th percentile flow ($P=0.201$) or DWF ($P=0.725$). Accordingly, it may be concluded that amendments to the small catchment network, which have typically focused on cost-effective provision of high-quality hydrometric data, have not inadvertently created a hydrometric bias based on catchment size or instantaneous discharges. Network amendments have been more frequent in the Shannon RBD, with the fewest number of station inactivations occurring in the Neagh Bann (NB) (3.4%) and North-Eastern RBDs (0.6%) ($\chi^2(14)=26.373$, $P=0.023$) (Table 2.7). A number of counties including Fermanagh (100%), Kilkenny (100%), Laois (95.5%), Cork (88.6%) and Wicklow (88.5%) are currently associated with a disproportionately high percentage of inactive stations ($\chi^2(62)=84.888$, $P=0.028$).

2.4.4 Available record length

An independent samples *t*-test indicates that a statistically significant difference exists with respect to available record length (calculated based on activation and inactivation year, with all currently operational stations attributed an inactivation year of 2015) and station status (active/inactive) ($t=-8.530$, $P<0.001$). No figures are available for currently suspended stations. Currently active stations are associated with a mean available record of 25.06 years (minimum 3 years; maximum 73 years; SD 14.55 years), while inactive stations have a mean available record of 12.17 years (minimum <1 year; maximum 41 years; SD 9.86 years).

As shown in Figure 2.6, the second, third and fourth quartiles associated with active station record length are all in excess of the median inactive station record length. A significant association was also found between data type and available record ($F(2)=12.784$, $P<0.001$) (Figure 2.7); recorder stations associated with continuous discharge and concurrent discharge/level measurements have mean available records of 12.8 years and 18.2 years, respectively, compared with 16.2 years for gauging (water level only) stations.

Table 2.7. River basin district associated with stations with known inactive status

RBD	Inactive (*n*)	Inactive nationally (%)
North-Western	54	9.2
South-Eastern	78	13.3
Eastern	59	10
Neagh Bann	20	3.4
South-Western	61	10.3
Shannon	218	37.1
North-Eastern	4	0.6
Western	94	16
Total	588	100

Telemetered stations ($n=38$) within the currently active network are associated with a significantly longer record (29.9 years), compared with non-telemetered stations (22.1 years) ($t=-2.696$, $P=0.008$). Monitored water body/catchment type was significantly associated with record length ($F(3)=7.927$, $P<0.001$); lake catchments had a mean record length approximately 15.2 years greater than river catchments and 25.6 years greater than groundwater (spring and well) catchments. No significant correlation was found between available record length and catchment size within the currently active network ($P=0.438$), although a weak positive correlation did exist within the total (active and inactive) network ($R_{sp}=0.184$, $P<0.001$), i.e. larger catchments associated with slightly longer record periods. No correlation was noted with respect to available record length and instantaneous flow data within either the total or current network.

2.4.5 Station type

As a result of recent amendments (EPA, 2011), no association was found between monitored water body/catchment type and station type ($P=0.619$); prior to 2010, a higher proportion of lake (82.4%) and tidal (100%) catchments were associated with installed recorder stations than was the case in river catchments (54.7%) ($\chi^2(4)=11.227$, $P=0.024$). Deactivation of all but one gauge-only stations has resulted in an increasingly balanced network with respect to collected data type and quality. Similarly, findings indicate that recent gauge deactivations have resulted in a lack of association between station type

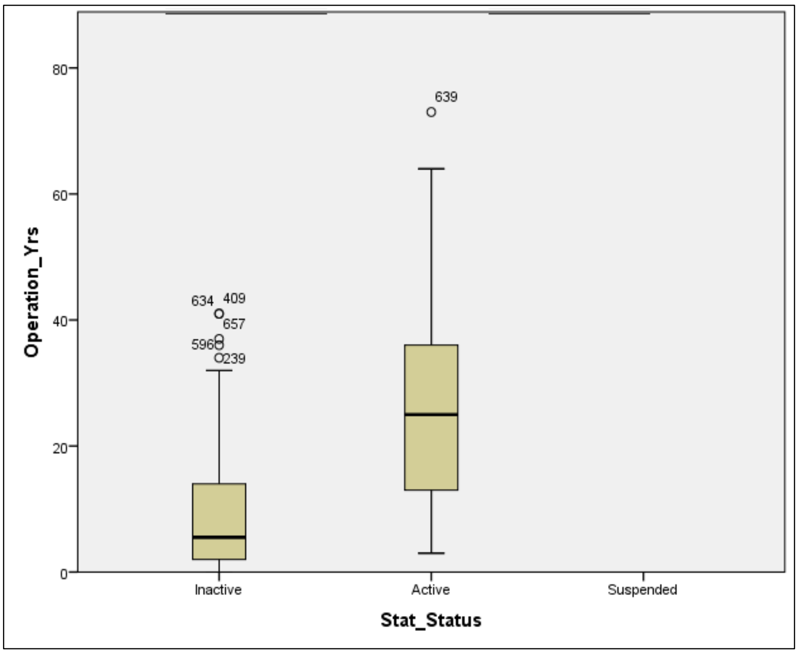

Figure 2.6. Boxplot of station operational years (equivalent to available record length) and current station status (*n* = 687).

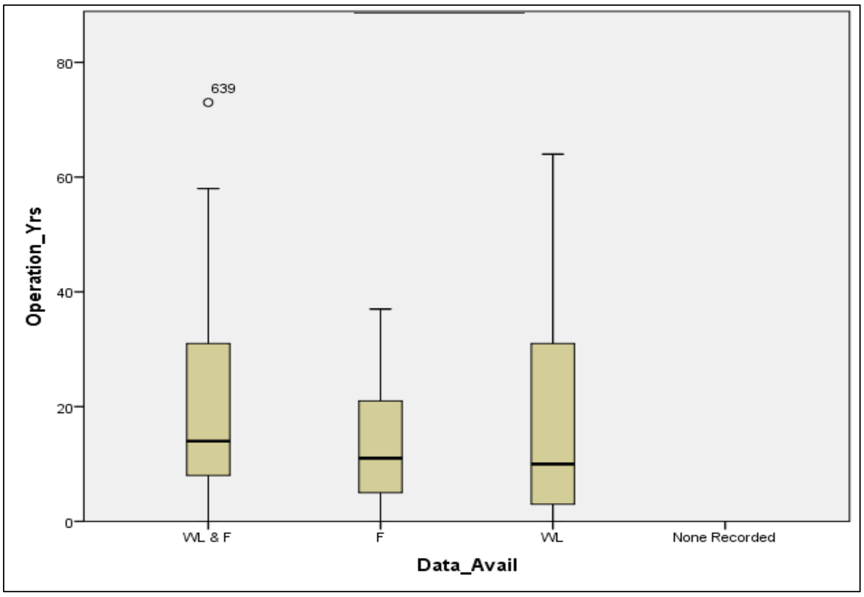

Figure 2.7. Boxplot of station operational years (equivalent to available record length) and available data (*n* = 687). F, recorder discharge; WL, gauged water level; WL & F, recorder discharge and water level.

Table 2.8. Station type associated with actively monitored small catchments stratified by RBD (*n* = 102)

	NW	SE	E	NB	SW	Sh	NE	W
Recorder	15	12	15	9	4	29	1	15
Gauge-only	0	0	1	0	0	0	0	0
Spot recorder	0	0	0	0	0	0	0	1

and geographical/administrative location ($P=0.699$) (Table 2.8); prior to network modifications, there was a marked proportional dissimilarity, with a significantly lower proportion of recorder stations previously employed in the Shannon RBD (41.8%) ($\chi^2(7)=24.346$, $P=0.001$). Accordingly, a relatively consistent level and quality of hydrometric data are now being spatially collated.

Within the active network, no significant mean differences were found between station type and annual mean precipitation, 50th and 95th percentile flows, and DWF. Unsurprisingly, within the entire dataset (including inactive stations), 30-year mean annual precipitation as given in the hydrometric register was significantly higher in small catchments with recorder stations. Unrevised mean DWF among recorder stations and gauge-only stations were 0.0196 m^3/s and 0.0137 m^3/s, respectively ($P=0.195$). No association was found between station type (recorder or gauge-only) and (currently active) station activation year ($P=0.714$); since 1975 (first year during which a station was inactivated), 96 recorder stations, one spot recorder station and 468 gauge-only stations have been deactivated ($\chi^2(78)=351.211$, $P<0.001$).

2.4.6 Catchment area

Analyses indicate that the mean catchment area associated with differing station types (recorder station mean: 11.22 km^2; gauge-only station mean: 12.54 km^2) was not statistically different at the 95% CI level ($t=1.933$, $P=0.054$). The only monitored small catchment currently employing a gauge-only station has a catchment area of 1.8 km^2, while recent network amendments have slightly increased the mean catchment area associated with active recorder stations (12.77 km^2). No difference was found between available continuous data type (water level or discharge) and catchment size ($P=0.154$); recorder stations associated with discharge and water level measurements had mean catchment sizes of 13.36 km^2 and 10.54 km^2, respectively. In terms of catchment size and geographical location, a significant difference previously existed between monitored catchment size and RBD ($F(7)=2.239$, $P=0.030$); catchments previously located within the Western RBD were significantly larger than other small monitored catchments. This was not mirrored within the currently active network ($F(7)=0.959$, $P=0.465$), thus indicating that because of the decreased number of catchments now monitored, actively monitored catchments have a high level of spatial comparability.

Network amendments (station inactivation) have not significantly affected the mean catchment size associated with gauged water body types ($t=-0.643$, $P=0.520$) (Table 2.9). Within the entire dataset (active and inactive stations), the mean river catchment size was significantly larger than other catchment types ($F(3)=4.551$, $P=0.004$); however, recent amendments have resulted in this inequality no longer being present within the active network ($P=0.196$).

Catchment size within the currently active network is not statistically related to precipitation ($P>0.05$), thus exhibiting a lack of geographical bias (30-year mean precipitation from the closest available climate/synoptic station to each catchment is recorded and included in the Register of Hydrometric Stations). Several instantaneous flow values are, however, significantly correlated with catchment size. For example, an increased 50th and 95th percentile flow occurs in concurrence with increasing catchment size, while decreasing (existing) DWF occurs in concurrence with increasing catchment size. Interestingly, recently updated DWFs exhibited a significant, negative non-parametric relationship with catchment area; however, as this correlation is based on a low number of summary measurements, it should be interpreted with caution.

2.4.7 Network management

A significant pattern exists between catchment type and hydrometric station management ($\chi^2(9)=17.239$, $P=0.045$); the EPA jointly with local authorities currently manage 76% ($n=73$) of the active small catchment hydrometric network, comprising 76%

Table 2.9. Catchment type and mean catchment area associated with monitored small catchments ($n=693$)

Catchment type	Active mean area (km^2)	Total mean area (km^2)
River	13.2	12.5
Lake	10.1	8.8
Tidal	7.6	8.6
Groundwater	5.6	7.2
Total	12.6	12.1

Table 2.10. Catchment type and management agency associated with actively monitored small catchments ($n=102$)

Agency	River	Lake	Tidal	Groundwater	Unknown
OPW	16	2	3	–	7
Marine Institute	1	–	–	–	–
ESB	–	1	–	–	–
EPA	54	16	–	3	1
Total	71	19	3	3	8

($n=54$) and 84.2% ($n=16$) of monitored rivers and lakes, respectively (Table 2.10). The only gauge-only station currently operating is managed by the ESB, while the only spot recorder in use is operated by the EPA. 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 ESB are traditionally larger than those operated by other agencies ($F(5)=2.899$, $P=0.013$). Within the active small catchment hydrometric network, no association exists between management agency and mean catchment size ($P=0.071$).

2.5 Summary

- The Register of Hydrometric Stations currently comprises 750 stations located in catchments <30 km^2. Only 705 stations of these 750 stations have been found suitable for the purpose of this study. Of these suitable stations, 85.5% are currently inactive, equating to an active small catchment hydrometric network of 102 stations and an active network density of one station per 832.57 km^2.
- Small catchment monitoring began in Ireland in 1942, with significant network increases occurring during the mid-1970s as a direct result of the nationwide drought experienced during 1976 leading to increased data requirements.
- Network size has contracted significantly (and relatively constantly) since the late 1990s, with the current network predominantly associated with river (85%) and lake (10%) catchments.
- The network is characterised by a lack of available continuous-flow data, for example, low-flow data (95th percentile) is available for just 45% of active stations.
- Within the currently active network, 98% of stations are classified as recorder stations, and are thus associated with collection of continuous data.
- A disproportionately high network density has historically been associated with the Shannon RBD, while low monitoring levels are associated with the North-Western, South-Western and Neagh Bann RBDs. Recent network amendments via station deactivations have served to remove this apparent disproportionality; however, this has been at the expense of data volume.
- Recent network amendments have resulted in a relatively consistent level and quality of hydrometric data now being spatially collated; however, this is an artefact of significantly lower volumes of data collation due to widespread deactivation of river gauging stations. This trend mirrors a recent global pattern characterised by a marked decline in the volume of river flow data being collected and made available.
- Results suggest that recent network amendments have resulted in an apparent decrease in data "representivity" with respect to topographical, morphological and meteorological catchment characteristics, i.e. network density and topographical/morphological/meteorological representivity are negatively correlated.
- Previous assessments and amendments of the small catchment network have typically focused on cost-effective provision of high-quality hydrometric data, and have not inadvertently created a hydrometric bias based on catchment size or instantaneous discharges.

3 Hydrodynamic Evaluation of Study Catchment

3.1 Introduction

Small catchments are frequently characterised by high levels of (geological and hydrological) heterogeneity; thus, flow pathways are typically sensitive to prevailing local climatic conditions and the primary physical catchment characteristics (Chiverton *et al.*, 2015). Therefore, to successfully evaluate catchment behaviour under varying climatic and hydrological conditions, the most reasonable approach is to undertake in-depth hydrological analyses and modelling, via integration of all available hydrodynamic elements. This requires extensive hydrometric, meteorological and catchment-related physical data availability to ensure appropriate representation of small catchment hydrodynamic complexity.

In this chapter, a review of conceptual representation of flow pathways in a catchment is presented (section 3.2), followed by a description of the hydrodynamic evaluation methods employed in the current study (section 3.3). The study catchment selection methodology is outlined (section 3.4), and, finally, results of hydrological analysis and modelling of the selected catchments are presented (section 3.5).

3.2 Flow Pathways in a Catchment

The temporal and spatial response of stream flow to precipitation has traditionally been attributed to variation in the importance of several hillslope processes and pathways (Kirkby, 1978). The hydrodynamic behaviour of any river catchment is typically characterised by the water balance equation, which describes the relationships between inflow, outflow and water storage in a catchment, as follows:

$$\Delta S = \text{Inflow} - \text{Outflow} = P - (Q + E) \pm N \qquad (3.1)$$

where ΔS is change in surface and subsurface storage; P is precipitation; Q is runoff; E is evapotranspiration; and N is groundwater exchange (inflow (+) or outflow (–)).

As shown (Figure 3.1), the natural inflow of water into a typical catchment occurs in the form of precipitation (rainfall or snowfall), which is subsequently subjected to three main processes of loss, namely infiltration, evaporation and transpiration. The second and third processes are combined as evapotranspiration, with all water lost through this process subsequently released back into atmospheric water storage, thus addressing the saturation deficit. A proportion of infiltration water satisfies any deficit in the soil water storage of the catchment, with the remainder further percolating to recharge the groundwater storage. The volume of precipitation not utilised by evapotranspiration or infiltration is classified as surface runoff, which eventually reaches the catchment river channel, thus feeding its flow for a period equal to the catchment travel time. Groundwater storage actively feeds baseflow, which maintains river flow during prolonged dry periods; this occurs as a result of the rate of baseflow typically being substantially lower than that of surface runoff. Interflow or rapid flow represents an additional source of river flow, originating from the unsaturated soil and subsoil layers and flowing relatively laterally to the river channel by following the direction of the subsurface slope gradient.

Typically, it is possible to divide the hydrological catchment pathways into surface flow (runoff) and subsurface flow, with subsurface flow comprising lateral soil water flow (interflow) and groundwater flow (baseflow). In the case of Irish catchments underlain by bedrock aquifers, the groundwater flow component has been further subdivided into three distinct components, namely shallow groundwater flow, discrete fault (conduit) flow and deep groundwater flow (RPS, 2008). A framework for catchment hydrodynamic analyses in Irish catchments has been developed (Jennings *et al.*, 2007; Archbold *et al.*, 2010), comprising five primary pathways for transport of precipitation to surface water: (1) overland flow, (2) interflow, (3) shallow groundwater flow, (4) discrete fault or conduit flow, and (5) deep groundwater flow. Recent studies of the pathways actively contributing to stream flow in an Irish setting have considered four primary contributors: overland flow (runoff), interflow, shallow groundwater flow and deep groundwater flow (Mockler *et al.*, 2013; O'Brien *et al.*, 2013) (Figure 3.2). Under the auspices of this conceptual approach, overland flow and interflow agree with the widely used (international) definitions,

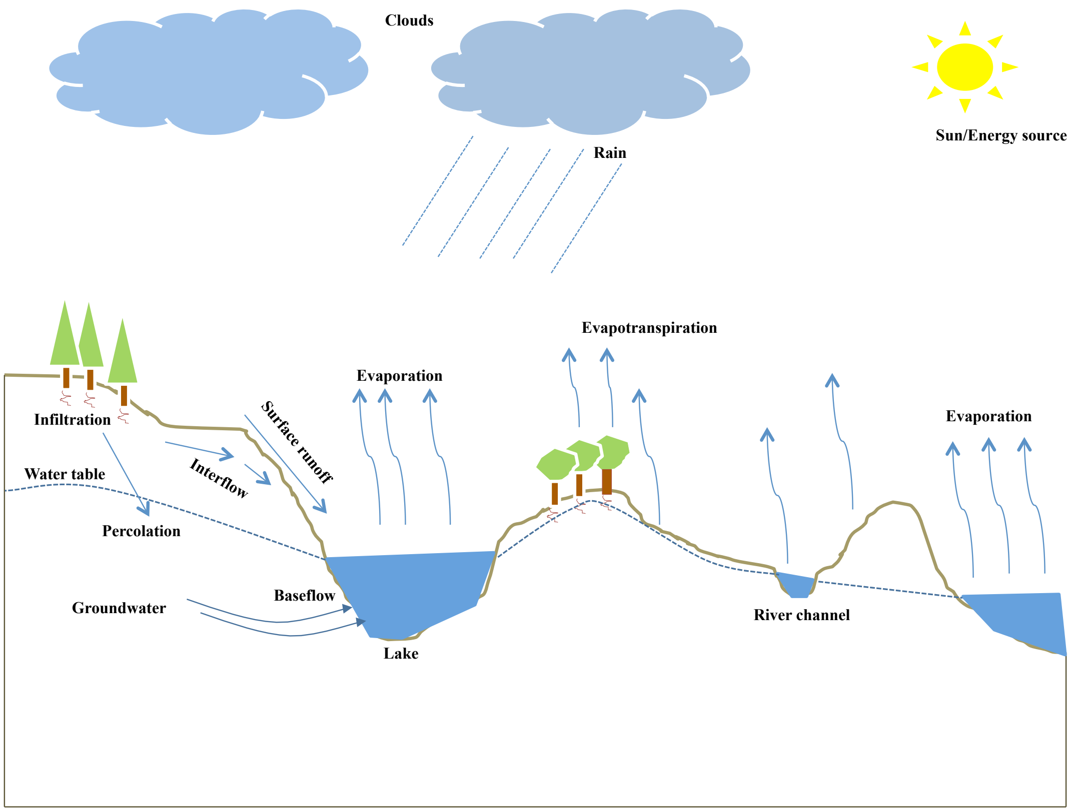

Figure 3.1. Physical processes involved in stream flow generation.

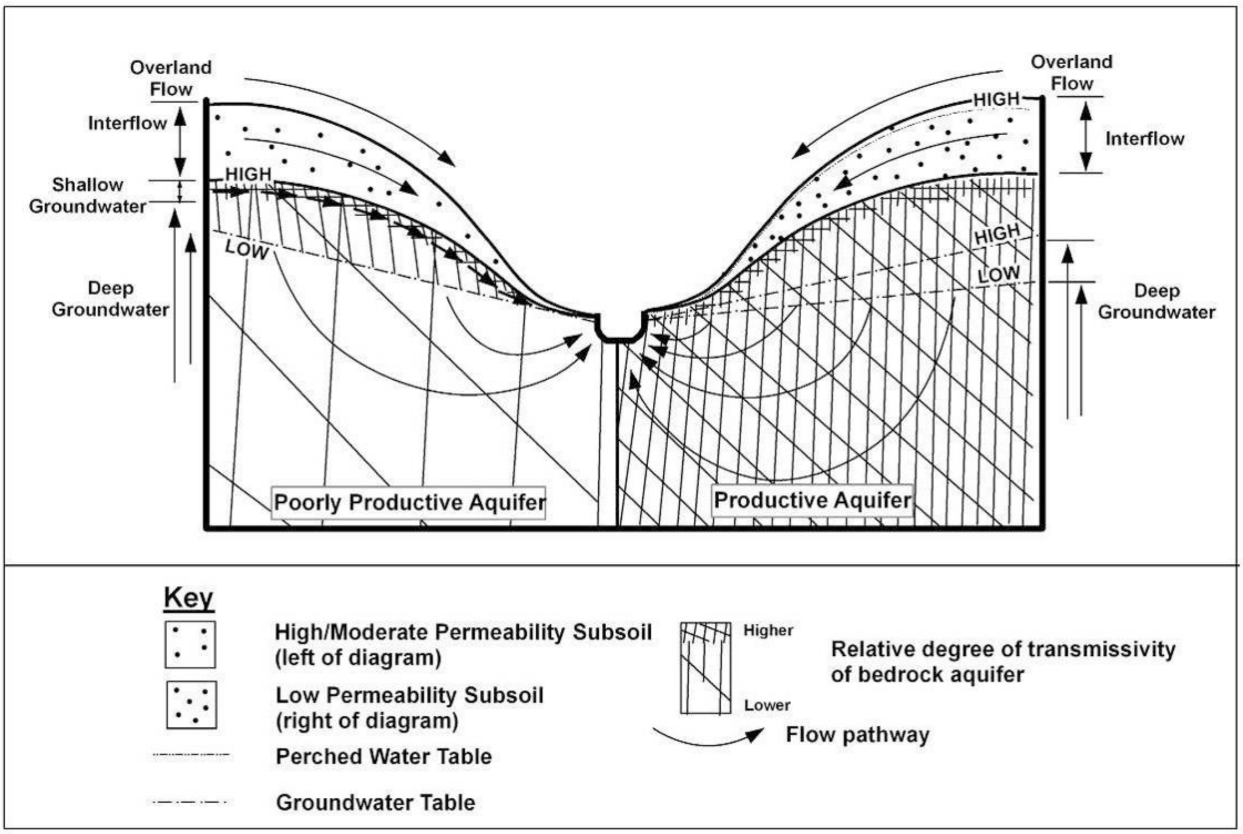

Figure 3.2. Four flow pathways (overland flow, interflow, shallow groundwater, deep groundwater) in poorly productive (left) and productive aquifers (right) (from Archbold *et al.*, 2010).

whereas shallow groundwater and deep groundwater have been more explicitly defined. The shallow groundwater zone comprises the transmissive upper portion of the fractured-bedrock aquifer, characterised by extensive weathering and an increased frequency and concentration of water-bearing fractures. The deep groundwater zone is represented by the less transmissive section of the aquifer, below this upper layer (O'Brien *et al*., 2013).

Quantification of these hydrological pathways in a small catchment is significantly influenced by the physical characteristics of the catchment and spatio-temporal climatic distributions (rainfall and evapotranspiration) (Peters, 1994). Thus, the availability of accurate physical characteristic and hydro-meteorological data for selected small study catchments is critical. Estimation of water storage and transport within these pathways subsequently facilitates the relevant water balance calculations for a catchment to be undertaken. Water flux between these pathways and characterisation of catchment hydrodynamic behaviour may be estimated by one of two approaches, namely hydrograph separation techniques and mathematical/numerical modelling techniques (section 3.3).

3.3 Catchment Hydrodynamic Evaluation Methods

3.3.1 Hydrograph separation techniques

A thorough review of hydrograph separation techniques is presented in the RPS (2008) report on quantification of groundwater and surface water contributions of stream flow in Irish rivers. Typically, hydrograph separation techniques only necessitate the availability of continuous daily river flow data, with the total flow hydrograph separated into surface and subsurface flow components. The surface flow component is typically considered to be the sum of overland flow and interflow while the subsurface flow component comprises the shallow and deep groundwater flows (O'Brien *et al*., 2013; Mockler *et al*., 2013). Four hydrograph separation methods have been employed in previous Irish hydrological studies: (1) the unit hydrograph (UH) method, (2) the Boughton "two-parameter" algorithm, (3) the Institute of Hydrology (IoH) method, and (4) the master recession curve (MRC) method. Additional approaches available for hydrograph (baseflow) separation include the fixed and sliding interval methods and numerous recursive filtering methods (Sloto and Crouse, 1996). All of the above-mentioned methods have been employed in the current study.

3.3.2 Mathematical modelling techniques

Mathematical modelling techniques attempt to estimate water fluxes between the four primary catchment pathways (runoff, interflow, shallow groundwater and deep groundwater) at varying temporal scales. This is achievable through data-driven or numerical modelling approaches to catchment water balance quantification. Unfortunately, in-depth data are frequently unavailable because of the difficulty of monitoring the flow of water within various catchment pathways, and particularly subsurface water flows.

Potentially suitable hydrological models vary considerably with respect to a number of features, including conceptual structure, parameter estimation methods and spatio-temporal model resolution (Nasr and Bruen, 2006). Nasr and Bruen (2006) previously examined the efficacy of three distinct hydrological models for quantification of diffuse phosphorus pollution in three Irish agricultural catchments. This study highlighted the ease with which simple empirical hydrological models can be managed in comparison with conceptual hydrological models. However, empirical models are typically not capable of accurately elucidating catchment dynamics. In addition, it is considered that conceptual modelling of small catchments may permit results to be employed within a semi-distributed (lumped) framework as a basis for large catchment modelling, thus contributing to an improved understanding of the hydrological behaviour and interactions of these catchments. Presently, numerous conceptual models are available for and have been employed to elucidate the hydrodynamic behaviours of Irish catchments. These include the Hydrologiska Byrans Vattenavdelning Model (HBV) (Steele-Dunne *et al*., 2008), the Nedbør-Afstrømnings Model (NAM) (DHI, 2009), and the Soil Moisture Accounting and Routing for Transport (SMART) model (Mockler *et al*., 2016).

The hydrodynamic behaviours of small catchments exhibit significant levels of seasonal variation as evidenced by river flow hydrographs at catchment outlets. Frequently, hydrographs associated with extended time periods exhibit condensed and indistinct patterns due to seasonal effects. Accordingly, seasonal hydrodynamic behaviours in small catchments may be more accurately examined through use of graphical approaches based on the traditional hydrograph (Peters, 1994). The most frequently employed of these approaches is flow duration curve (FDC) development. In addition, several indices are available for characterisation of the hydrodynamic behaviours within small catchments during seasonally associated flow regimes. The baseflow index (BFI) is widely used to characterise low flow regimes in catchments influenced by hydrogeological setting. However, it is important to note that the use of a single index for seasonal catchment characterisation (e.g. flooding) is undesirable, as catchment responses (e.g. flood events) tend to be specific to individual rainfall event characteristics, including frequency, duration and intensity.

3.4 Selection and Characterisation of Study Catchments

An initial assessment of potentially suitable small catchments was undertaken with two overarching conditions: (1) an available record length > 10 years; and (2) catchments were not nested within tidally or anthropogenically influenced large catchments. In addition, it was considered essential that selected catchments be representative of the complex physical settings that influence the hydrodynamic behaviours of small catchments in Ireland. A significant proportion of surface water catchments are characterised by heterogeneous groundwater flow regimes, and thus comprise diverse aquifer (and subsoil) types with respect to both lithology and productivity (RPS, 2008). Accordingly, dominant aquifer type, soil drainage group and land use/land cover classification were employed as the primary criteria for final study catchment selection (Table 3.1). Analysis of collated data led to the selection of four small catchments for the current study, namely the Ballygoly (Co. Louth), Frankfort (Co. Dublin), Rochfort (Co. Westmeath) and Ballyhaunis (Co. Mayo) catchments associated with hydrometric station numbers 06030, 09011, 25034 and 30020, respectively (Figure 3.3; Table 3.1). Based on the developed selection procedure, the selected catchments are characterised by a diverse range of aquifer types [PI, LI and Rkc, among others (see Table 3.1 for definitions)], Corine (Coordination of Information on the Environment) land cover usage categories (231, 112 and 412), and soil drainage groups (poorly drained, well drained and made/urban fabric) (Table 3.1). The Ballygoly and Frankfort catchments have previously been included in the development of the flow duration model (Bree *et al.*, 2010). Catchment details pertaining to hydrometric and rain gauge and synoptic stations (i.e. primary data sources) are presented in Table 3.2a,b. Catchment-specific maps associated with subsoils, aquifer type and recharge coefficient are presented in Appendix 1.

3.5. Evaluation of Catchment Hydrodynamics

To investigate and improve understanding of the hydrodynamic behaviour of selected catchments, several hydrograph/baseflow separation techniques were employed. These have been divided into two main approaches, namely "interval-based" techniques [fixed interval and sliding interval, IoH (local minima)] and recursive filtering techniques (Boughton one-parameter algorithm, Boughton two-parameter algorithm, Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data (IHACRES) three-parameter

Table 3.1. Area, dominant aquifer type, soil/subsoil type and land cover/land use associated with selected small catchments

Station number	Catchment name	Area (km^2)	Dominant aquifer type[a]	Dominant soil drainage group	Dominant land cover/land use code[b]
06030	Ballygoly	10.40	PI	Poorly drained	412/231
09011	Frankfort	5.46	PI	Made	112
25034	Rochfort	10.77	LI	Well drained	231
30020	Ballyhaunis	21.41	Rkc	Peat/well drained	231/412

[a]LI, locally important aquifer – moderately productive only in local zones; PI, poor aquifer – generally unproductive except for local zones; Rkc, regionally important karstified aquifer dominated by conduit flow.

[b]112 discontinuous urban fabric; 231 pasture; 412 peat bogs.

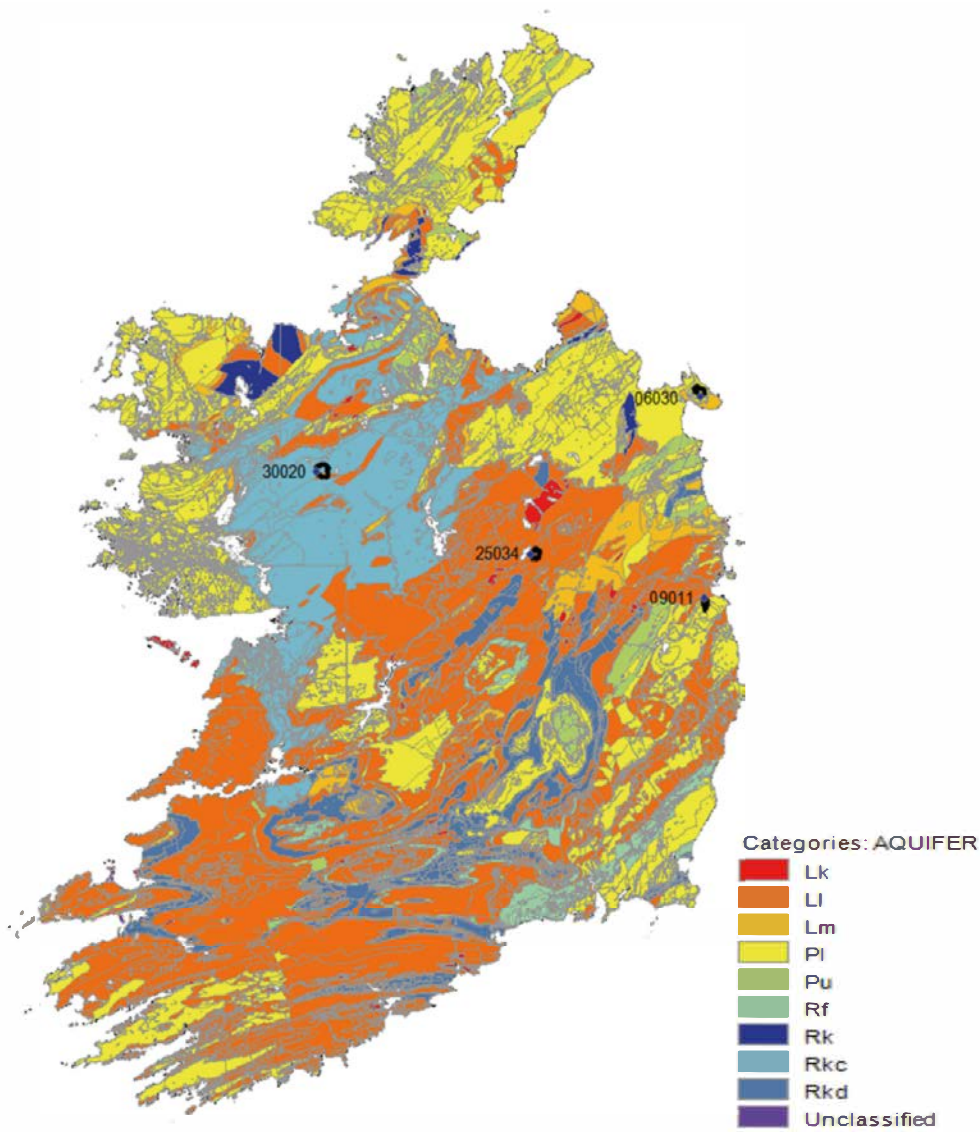

Figure 3.3. Selected study catchment locations shown on the GSI aquifer importance map of Ireland.

algorithm, Chapman algorithm, Lyne and Hollick algorithm (BFLOW) and exponential smoothing (EWMA)). The EcoHydRology baseflow separation package for R, and the BFI+3.0 module in HydroOffice 2015 were utilised. Prior to analyses, a scoping review of available peer-reviewed literature was carried out to calculate appropriate parameter values for each method (Table 3.3).

Hydrological modelling was considered essential to complement the solely data-driven hydrodynamic analyses. As previously mentioned, in addition to quantification of catchment water balances, hydrological modelling also simulates and thus elucidates flow pathways within the catchment, thereby permitting characterisation of catchment hydrodynamics. Prior to hydrological model initiation, parameter optimisation for each individual catchment was undertaken, with three conceptual/semi-distributed models employed, namely the HBV, NAM and SMART models. All available daily rainfall, evaporation and flow data were employed for calibration and validation of hydrological models within each of the four selected catchments. Approximately two-thirds of the data (available record) were used for model calibration, with the remainder used for model validation (Table 3.4). Rainfall data were taken from the closest operational rain gauge to the catchment centroid with record length > 10 years. A number of alternative options were considered, including the use of numerous gauges via interpolation, Thiessen polygons and the Met Éireann national dataset of gridded daily rainfall. However, primarily as a result of

Table 3.2a. Hydrometric stations associated with the four study catchments

Station number	Location	River	Catchment	Easting	Northing
06030	Ballygoly	Big	Piedmont	315108	309990
09011	Frankfort	Slang	Liffey	316908	228850
25034	Rochfort	Little Ennell Tributary	Shannon	241597	246359
30020	Ballyhaunis	Dalgan	Corrib	149616	279434

Table 3.2b. Rain gauge stations associated with the four study catchments

Station number	Location	Easting	Northing
Nearest rain gauge			
3438	Riverstown (Glenmore Upper)	315500	311000
8023	Dublin (Dundrum)	316700	227900
1222	Mullingar (Belvedere House)	242000	247700
3027	Milltown	141000	262800
Nearest synoptic station			
2437	Clones	250000	326300
3723	Casement Aerodrome	304100	229500
2922	Mullingar	242300	254300
2727	Claremorris	134500	273900

Table 3.3. Employed parameter values for hydrograph/baseflow separation methods

Separation method	Parameter number	Parameters
Fixed interval	1	$N=5$
Sliding interval	1	$N=5$
IoH (local minima)	2	$N=5$, $f=0.9$
Boughton one-parameter algorithm	1	$k=0.95$
Boughton two-parameter algorithm	2	$k=0.95$, $C=0.05$
IHACRES three-parameter algorithm	3	$k=0.97$, $C=0.03$, $\alpha=0.01$
Chapman algorithm	1	$\alpha=0.925$
Lyne and Hollick algorithm (BFLOW)	1	$\alpha=0.925$
Exponential smoothing (EWMA)	1	$\alpha=0.004$

***C*, fit constant ("free variable"); *f*, turning point factor; *k*, recession constant (during periods with no direct runoff); *N*, interval size (days); *α*, filter/smoothing factor.**

Table 3.4. Calibration and validation periods for catchment hydrological modelling

Station number	Catchment name	Calibration period	Validation period	Total record (years)
06030	Ballygoly	Dec 1989–Dec 2000	Jan 2000–Jan 2008	17
09011	Frankfort	May 1983–Jan 2005	Feb 2005–Jan 2015	31.5
25034	Rochfort	Jul 1976–Jun 2006	Jul 2006–Dec 2014	38.5
30020	Ballyhaunis	Dec 1989–Dec 2005	Jan 2006–Jan 2015	25

time constraints, the simplest approach was used. The exception is the Ballygoly Station (06030) catchment, where shorter rainfall records from Riverstown (the nearest rainfall station) and longer rainfall records from Clones (the nearest synoptic station) were tested for modelling this catchment. The shorter Riverstown record was used for final model development as a result of higher calibration and validation accuracy.

Hydrological modelling results in the four study catchments were further substantiated with FDCs. The FDC 2.1 module in HydroOffice 2015 was used for the development of characteristic river (m^3/s) and catchment (mm/day) FDCs (Tallaksen and van Lanen, 2004). Primary input data for FDC development were measurement date, river discharge and catchment size; weekly, monthly, annual and total record FDCs were developed for all four study catchments. In addition, a number of key flow indices (5th, 10th, 50th, 90th and 95th percentiles), ratios (Q5/Q95, Q5/Q50) and slopes (high flow: 0–10th percentile, mid-range: 10th–90th percentile, low flow 90th–100th percentile) were extracted from developed catchment FDCs and statistically analysed in terms of absolute values and distributions (Nasr and Bruen, 2014).

The BFI Visual Basic application within Excel 2013 was used for BFI calculation using the IoH algorithm (IoH, 1980) (M. Morawietz, University of Oslo, 4 June 2015, personal communication), in concurrence with catchment discharge values. Seasonal, annual and whole series BFIs were calculated for all study catchments, with annual and seasonal means, minima and maxima also compared. Sensitivity analysis (model tuning) was undertaken via primary parameter (N) variation to refine and optimise catchment BFI estimation; Misstear *et al.* (2009) have previously reported that appropriate values for N will depend on catchment size.

As for hydrograph/baseflow separation, a scoping review of existing literature was used to develop working ranges and distributions for model parameters, with model calibration conducted using automated calibration modules for determination of an optimised set of parameters. A 12-month warm-up period was selected for all model calibration and validation to aid comparative analyses, both within catchments and among models. For quantification of the performance of calibrated and validated models the coefficient of determination (R^2) and Nash–Sutcliff criterion (R_{eff}) were selected for use. The R_{eff} is given by the following equation:

$$R_{eff} = \left(1 - \frac{\sum_{i=1}^{n}\left(Q_{obs_i} - Q_{sim_i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs_i} - Q_{mean}\right)^2}\right) \times 100 \qquad (3.2)$$

where Q_{obs} is the observed discharge (m^3/s); Q_{sim} is the simulated discharge (m^3/s); Q_{mean} is the mean of the observed discharge (m^3/s); and n is the number of days in the record.

As a result of the volume of hydrological analyses and modelling undertaken during the current project, an investigation of groundwater recharge estimation reliability in the four study catchments was undertaken. The currently utilised weighted-mean method of estimation was compared with an approach developed using primary catchment water balance components from optimised SMART models, based on expectations arising from physical catchment indicators (e.g. aquifer importance, soil drainage category). In summary, a catchment groundwater recharge map for each catchment was first extracted from the GSI recharge map via ArcGIS (Figure 3.4). Then an overall recharge coefficient for the entire catchment was calculated using a weighted average method. In this method the total polygonal area corresponding to all recharge coefficients in the recharge map of each catchment was represented as a percentage of total catchment area, and a weighted-mean recharge coefficient thus calculated for the entire catchment based on the resulting spatial proportions.

Conversely, catchment water balance components calculated from long-term modelling results (i.e. simulation over full period of record) were used to calculate alternative recharge coefficients using equations 3.3 and 3.4:

$$\text{Total precipitation} - (\text{Runoff} + \text{Evaporation}) = \text{Recharge} \qquad (3.3)$$

$$\frac{\text{Recharge}}{\text{Effective Precipitation}} = \text{Recharge Coefficient} \qquad (3.4)$$

Normalisation (i.e. conversion of river discharge to catchment discharge) was employed for all hydrodynamic analyses to enable direct comparison between catchments via reduction of catchment area effects, i.e. catchment discharge used as opposed to river discharge.

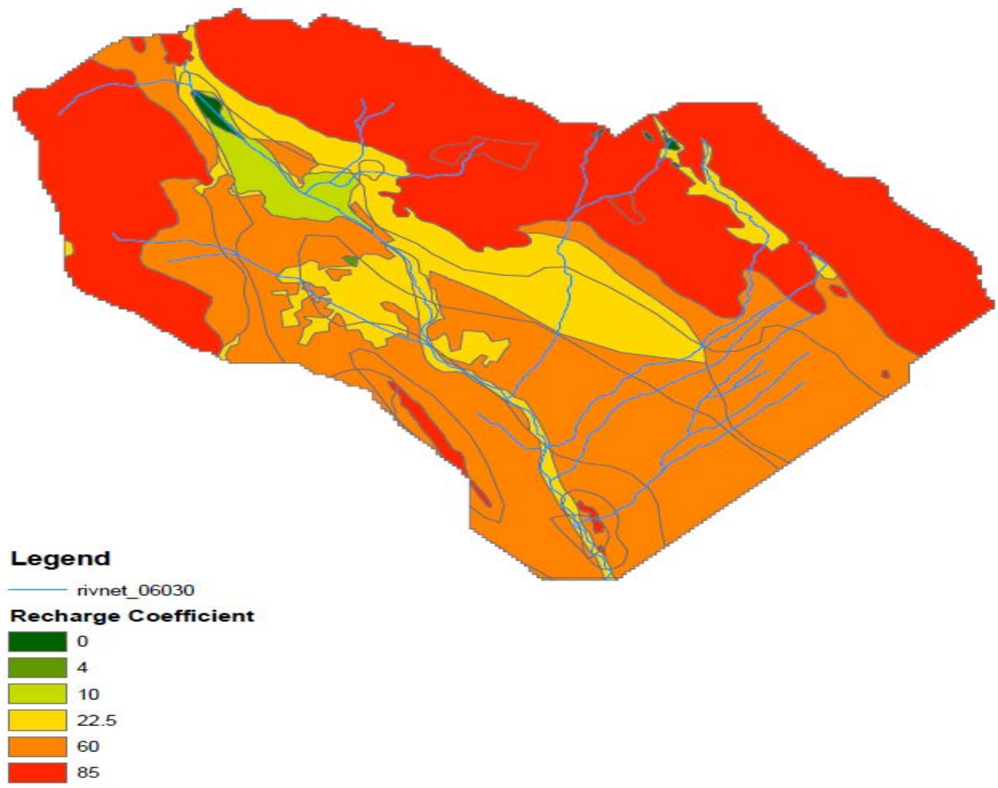

Figure 3.4. Delineated recharge coefficient map for the upland Ballygoly (station 06030) catchment.

3.6 Results

3.6.1 Hydrograph separation

The range of estimated subsurface contributions to stream flow (expressed as BFI) resulting from utilisation of multiple separation techniques was significant (Table 3.5), with two primary data clusters observed, namely those associated with interval-based methods, and those resulting from recursive filtering. Typically, interval-based techniques were shown to result in a wider range and significantly higher baseflow estimates than recursive filtering techniques; for example, within the primarily urban Frankfort (station 09011) catchment, an estimated range of 0.407 to 0.831 was encountered, with no cluster intersect (interval-based: 0.551–0.831; recursive filtering 0.407–0.500). Misstear *et al.* (2009) have previously reported that hydrograph separation frequently results in high baseflow estimates where physical catchment indicators (e.g. aquifer importance, soil drainage group) suggest significantly lower groundwater contributions; this would seem to be the case in this catchment. Based on the physical characteristics of the four study catchments, the simpler interval-based separation techniques [including the frequently employed IoH (local minima) technique] provided reasonable results within the Frankfort (station 09011) and Ballyhaunis (station 30020) catchments, while the Lyne and Hollick algorithm (BFLOW) and IoH methods were found to provide reasonable results within the Rochfort (station 25034) catchment (Figure 3.5). The IoH method seems to be most reasonable within the Ballygoly (station 06030) catchment.

3.6.2 Hydrological modelling

Values of R^2 and R_{eff} resulting from all calibrated hydrological models (HBV, NAM, SMART) for the four study catchments are presented in Table 3.6. As a result of the nature of this study (12-month desk study), one set of calibrated parameters was identified for each model and catchment, thus representing a limitation given the parsimonious nature of conceptual models. As shown, based on both employed objective functions, the SMART model outperformed the HBV and NAM models in all four catchments with the exception of the Ballygoly (station 06011) catchment, where the R^2 of the HBV model was slightly higher than the SMART model, although this difference is not considered significant. Statistical analyses found

Table 3.5. Estimates of BFI in the four study catchments

Separation method	Ballygoly (station 06030)	Frankfort (station 09011)	Rochfort (station 25034)	Ballyhaunis (station 30020)
Fixed interval	0.585	0.777	0.867	0.806
Sliding interval	0.637	0.831	0.913	0.853
IoH (local minima)	0.399	0.551	0.727	0.662
Boughton one-parameter algorithm	0.507	0.500	0.531	0.526
Boughton two-parameter algorithm	0.507	0.500	0.531	0.526
IHACRES three-parameter algorithm	0.474	0.488	0.542	0.547
Chapman algorithm	0.581	0.498	0.517	0.509
Lyne and Hollick algorithm (BFLOW)	0.381	0.430	0.730	0.530
Exponential smoothing	0.401	0.407	0.608	0.541

Table 3.6. Calibrated hydrological model efficiencies in the four study catchments

Model	Ballygoly (station 06030)		Frankfort (station 09011)		Rochfort (station 25034)		Ballyhaunis (station 30020)	
	R^2	R_{eff}	R^2	R_{eff}	R^2	R_{eff}	R^2	R_{eff}
HBV	0.82	0.65	0.78	0.55	0.92	0.82	0.77	0.54
NAM	0.81	0.66	0.74	0.54	0.87	0.74	0.84	0.4
SMART	0.83	0.69	0.77	0.58	0.92	0.84	0.85	0.73

Table 3.7. Summary of annual water-balance components estimated by SMART model

Water-balance components (mm)	Ballygoly (station 06030)	Frankfort (station 09011)	Rochfort (station 25034)	Ballyhaunis (station 30020)
Observed rainfall	1131	680	943	1192
Evaporation	536	436	556	450
Overland flow	429	155	70	153
Interflow	169	99	199	137
Upper groundwater	127	201	218	430
Lower groundwater	46	19	71	70

no evidence of association between validated model efficiencies and record length; however, a significant rank correlation was found between model efficiency and catchment size ($P=0.041$), with increasing model efficiency concurring with increasing catchment size. As shown in Figure 3.6 (a–d), actual and simulated hydrographs exhibited high levels of homogeneity within the four catchments, while overall, model efficiencies were adjudged moderate (Rochfort and Ballyhaunis) to low (Ballygoly and Frankfort). Lowest model efficiencies were associated with the urban Frankfort (station 09011) catchment for all three models (R_{eff} 0.54–0.58). Interpretation of modelling results suggests that adjacent catchments may contribute to overland flow within this urban catchment during low-frequency, high-intensity rainfall events, thus highlighting both a catchment delineation and modelling limitation. An overall summary of the annual water balance components in the four study catchments is presented in Table 3.7; all presented water balance components are estimated using the SMART model, which showed the best performance in the four study catchments, excluding rainfall, which was calculated from observed data.

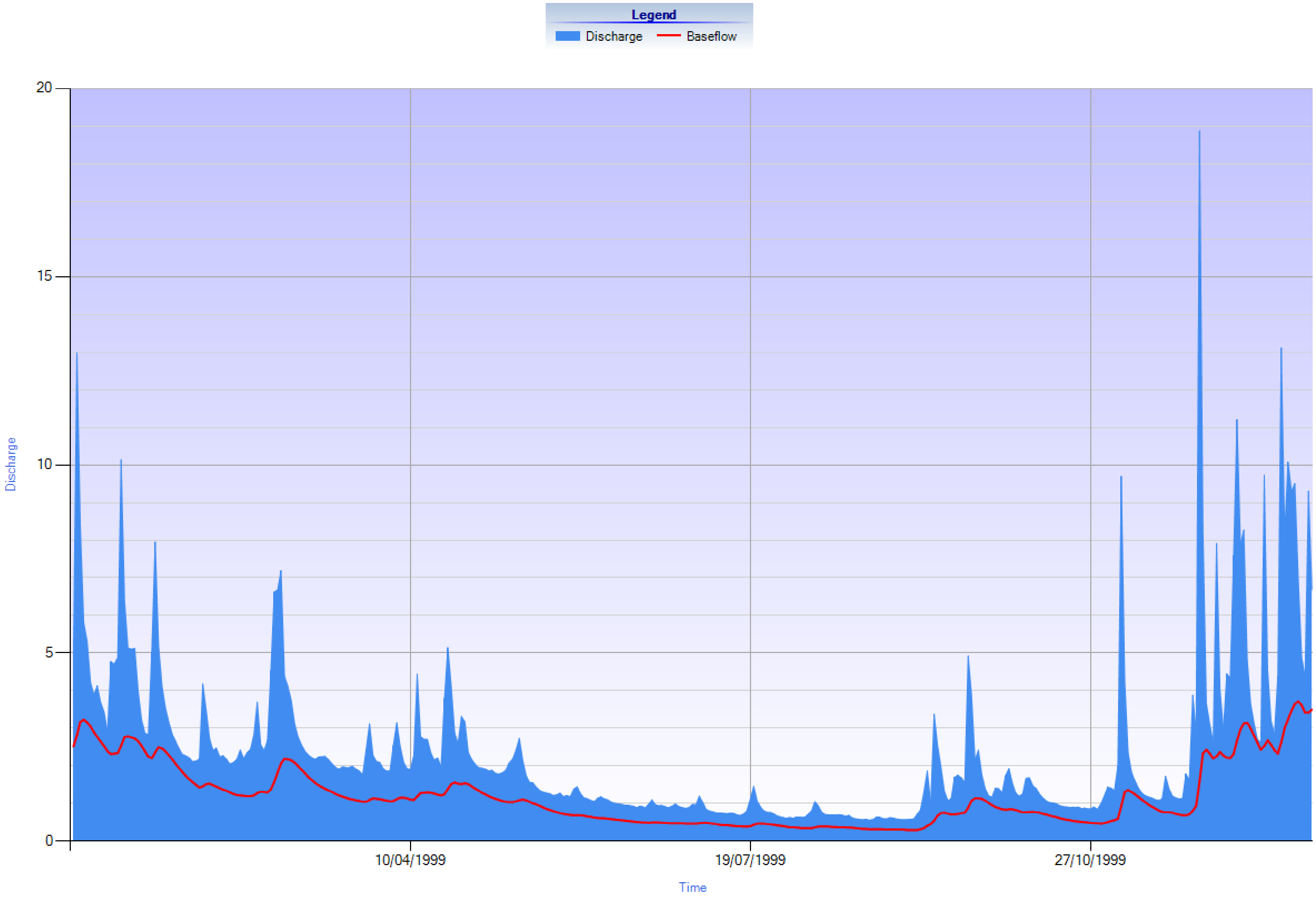

Figure 3.5. Lyne and Hollick (BFLOW) baseflow separation algorithm employed within the groundwater-dominated Rochfort (station 25034) catchment.

Interpretation of daily time-step (i.e. low resolution) rainfall runoff simulation results highlighted significant modelling limitations, including adjacent catchment runoff contributions and generally poor simulation of low-frequency, high-intensity rainfall events. Accordingly, the effect of high-resolution (hourly) rainfall data on hydrological model accuracy using three conceptual models (HBV, NAM and SMART) was examined. The hourly rainfall data were taken from the closest operational synoptic station to the catchment centroid (Table 3.2). As a result of the inherently large volume of data, specific discharge years were modelled as opposed to entire records; individual years were selected based on overall classification (i.e. above average annual rainfall), number of significant rainfall events occurring during the year and results from daily time-step models. Two catchments were selected based on results from daily time-step models, namely Rochfort (station 25034, moderate to high daily simulation accuracy) and Frankfort (station 09011, low daily simulation accuracy). High-resolution 12-month models were run using a 365-day warm-up period, with modelling structures and model parameters analogous to those employed for daily time-step modelling. As data resolution associated with discharge (15 min) and rainfall data (60 min) differed, a data consolidation approach was employed using hourly maximum values and the three classical Pythagorean (arithmetic, harmonic and geometric) means.

As shown in Table 3.8, daily modelling of the primarily rural lowland Rochfort (station 25034) catchment resulted in a reasonable level of accuracy (R_{eff} = 0.84–0.88); all consolidation approaches resulted in relatively analogous forecasting results. Hourly modelling of the 12-month period from January to December 2013 resulted in slightly improved results, with use of the arithmetic mean providing the highest level of accuracy (R_{eff} > 0.938) via enhanced baseflow prediction. Daily modelling of the urban Frankfort catchment during 2010 and 2013 resulted in moderate (R_{eff} > 0.572) and poor (R_{eff} > 0.299) simulation efficiencies, respectively. Hourly modelling was not shown to offer significant overall simulation improvements in this catchment; during 2010, hourly modelling resulted in lower levels of simulation accuracy for all approaches barring the maximum hourly flow volume. During 2013, hourly modelling resulted in analogous efficiency values to those of daily modelling.

Hourly modelling of discrete rainfall events was also undertaken; hourly simulations in the rural lowland Rochfort (station 25034) catchment systematically underestimated event peaks (mm/h) by 30–100%, with higher levels of underestimation prevalent during periods characterised by similar potential and actual evaporation. However, event timing and (to a lesser extent) duration were modelled with reasonable accuracy. Hourly models were shown to incorrectly attribute the majority of flow within the urban catchment to the subsurface (70–95%) (Figure 3.7a); thus, discharge peaks were underestimated by up to 500% (Figure 3.7b), with peak duration (Figure 3.7c) and timing (Figure 3.7d) also shown to be poorly predicted in some instances.

3.6.3 Recharge estimation

A summary of recharge coefficient estimates from the weighted-mean and model-based approaches is presented in Table 3.9. For the hydrological model-based approach, the SMART model was used as it had generally higher validated model efficiency (R_{eff} calculated based on the entire record period). Based on physical catchment indicators (e.g. aquifer importance, soil drainage category), it is considered

Table 3.8. Best-fitting hourly time-step model efficiencies in concurrence with differing data consolidation approaches and best-fitting daily time-step modelling results

Parameter	Rochfort (station 25034) 2009	Rochfort (station 25034) 2013	Frankfort (station 09011) 2010	Frankfort (station 09011) 2013
Arithmetic mean	0.838	0.938	0.371	0.287
Harmonic mean	0.842	0.878	0.378	0.315
Geometric mean	0.846	0.881	0.375	0.314
Maximum	0.843	0.871	0.623	0.303
Daily mean	0.846	0.881	0.572	0.299

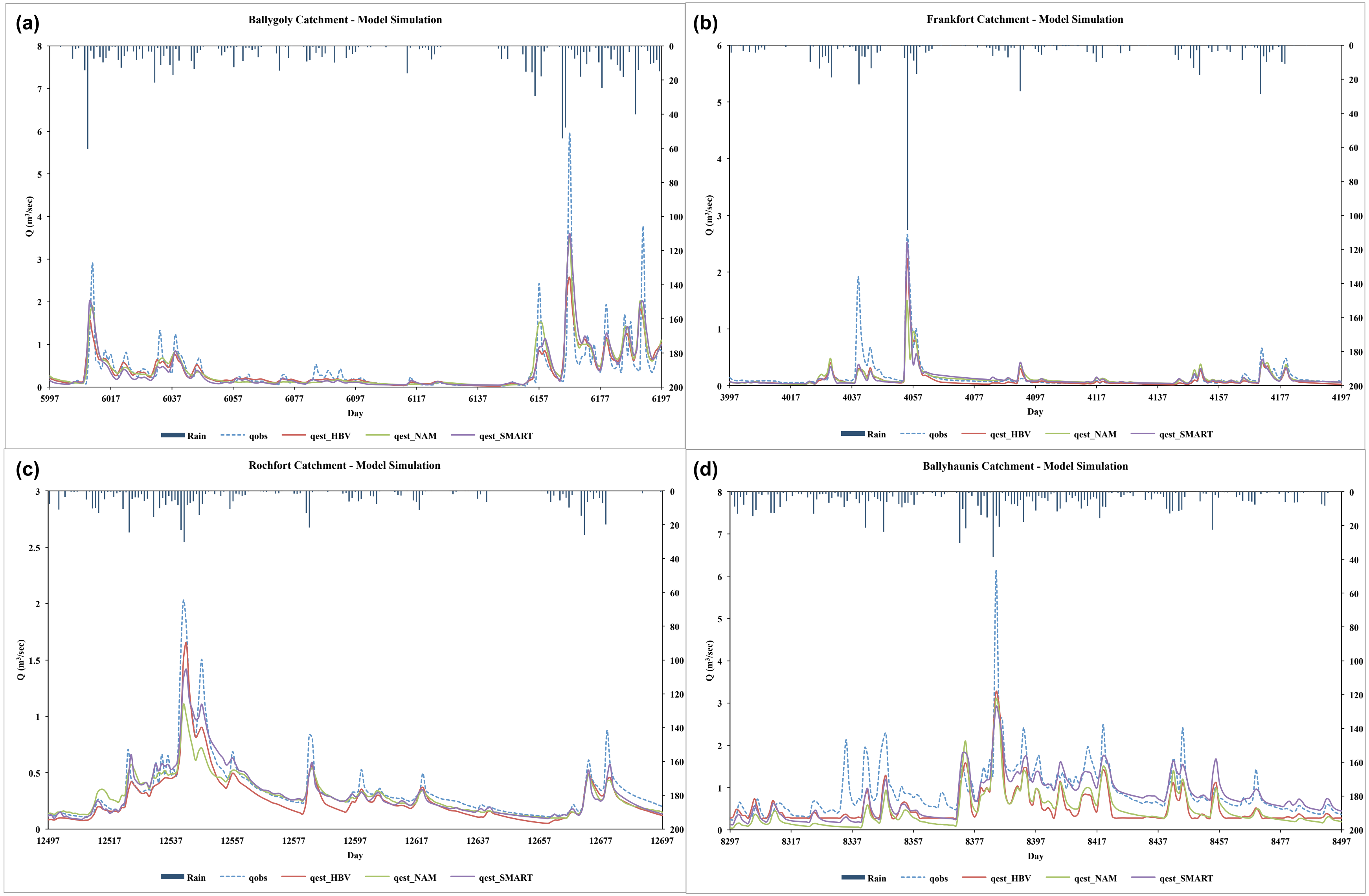

Figure 3.6. Comparison of calibrated (conceptual) hydrological models in the four study catchments. (a) Rural upland [Ballygoly (station 06030)] catchment; (b) urban [Frankfort (station 09011)] catchment; (c) lowland rural [Rochfort (station 25034)] catchment; (d) groundwater-dominated [Ballyhaunis (station 30020)] catchment.

Table 3.9. Summary of recharge coefficient estimates from the weighted mean and calibrated hydrological model-based (2001–2006) approaches

Catchment	Weighted mean		Model-based	
	Polygon Number	Estimated RC (%)	SMART model Efficiency	Estimated RC (%)
Ballygoly (station 06030)	95	63.8	0.71	67.9
Frankfort (station 09011)	135	34.0	0.57	71.8
Rochfort (station 25034)	70	53.2	0.83	59.1
Ballyhaunis (station 30020)	351	34.1	0.68	68.8

likely that both methods overestimate the catchment recharge coefficient in the Ballygoly (station 06030) catchment, which is characterised by poorly drained soils. As a result of the primarily urban character of the Frankfort (station 09011) catchment (i.e. high runoff and subsequent low recharge), the weighted-mean recharge coefficient estimate is considered more accurate than the model-based estimate; notably, the level of efficiency associated with the calibrated hydrological model for this catchment was low ($R_{eff} = 0.57$). Conversely, the model-based recharge coefficient estimate is thought to be more accurate than weighted-mean estimation in the karst catchment [Ballyhaunis (station 30020)]. Finally, based on physical indicators (well drained soils and a locally important aquifer), recharge coefficient estimates from both methods are considered reasonable in the lowland rural Rochfort (station 25034) catchment.

3.6.3 Hydrodynamic seasonality

Flow duration curves

Based on developed catchment FDC indices (Figures 3.8 and 3.9; Table 3.10), all four catchments are characteristically “flashy” because of the significant difference ($P < 0.05$) between observed high and mid-level flows. The Q5/Q95 ratio and high-flow slopes associated with the Ballygoly (station 06030), Frankfort (station 09011) and Rochfort (station 25034) catchments indicating that these respond particularly quickly to rainfall. The Q5/Q95 ratio in Ballygoly (station 06030) catchment was extremely high (Q5/Q95 = 42.882) indicating a flashy catchment. This dimensionless ratio summarises the magnitudes of the infrequent fifth percentile (high flow) discharges and the frequent 95th percentile (low flow) discharges and so is a practical way of comparing the runoff response between gauged catchments. Catchments with a higher ratio have flashier responses to rainfall primarily as a result of the predominance of faster runoff flow paths (Jordan *et al.*, 2005). The magnitude of calculated FDC slopes in the low-flow range implies that the baseflow contribution within the four catchments is not significantly different, with Q5/Q50 ratios suggesting relatively analogous low-flow behaviour within the Frankfort (station 09011), Rochfort (station 25034) and Ballyhaunis (station 30020) catchments. Larger high-flow slope values were associated with the upland [Ballygoly (station 06030)] and (primarily) urban [Frankfort (station 09011)] catchments, thus reflecting steeper land gradients and a high runoff coefficient, respectively. The lowest high-flow slope was associated with the lowland agricultural catchment [Rochfort (station 25034)], as might be expected.

Baseflow Indices

Results of BFI development from all four study catchments are presented in Table 3.11. Findings indicate that the Rochfort (station 25034) catchment is characterised by the highest mean (entire record) BFI (0.727), and may thus be considered a groundwater-dominated catchment, i.e. catchment geology exerts significant effects, particularly during low-flow periods. Conversely, Ballygoly (station 06030) catchment had the lowest estimated BFI (0.399), with stream flow within the catchment therefore significantly influenced by surface runoff due to catchment topography. As shown in Table 3.11, no marked temporal pattern was observed with respect to estimated minimum and maximum annual BFI, i.e. no one record year was significantly associated with minimum or maximum BFI, thus reflecting the local nature of temporal hydrodynamic regimes. Based on the utilised

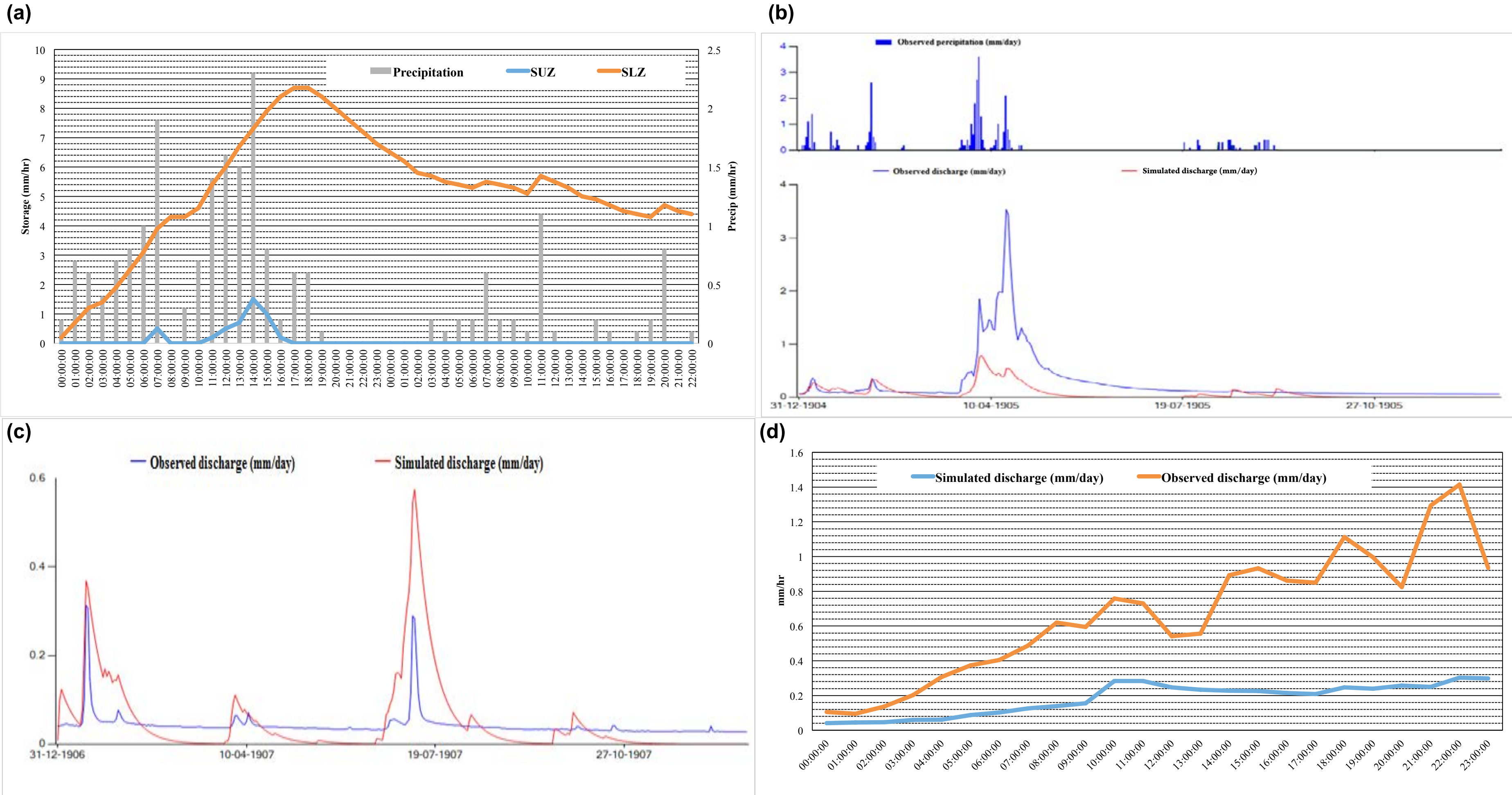

Figure 3.7. (a) Hourly simulated subsurface infiltration/storage and runoff in urban Frankfort catchment, 18–19 January 2013 (NAM); (b) hourly observed/simulated catchment discharge in Frankfort, early/mid-March 2013 (HBV); (c) observed/simulated catchment discharge in Frankfort, late April 2013 (maximum percolation rate = 0) (HBV); (d) hourly observed/simulated catchment discharge in Frankfort catchment, 18 January 2013 (SMART).

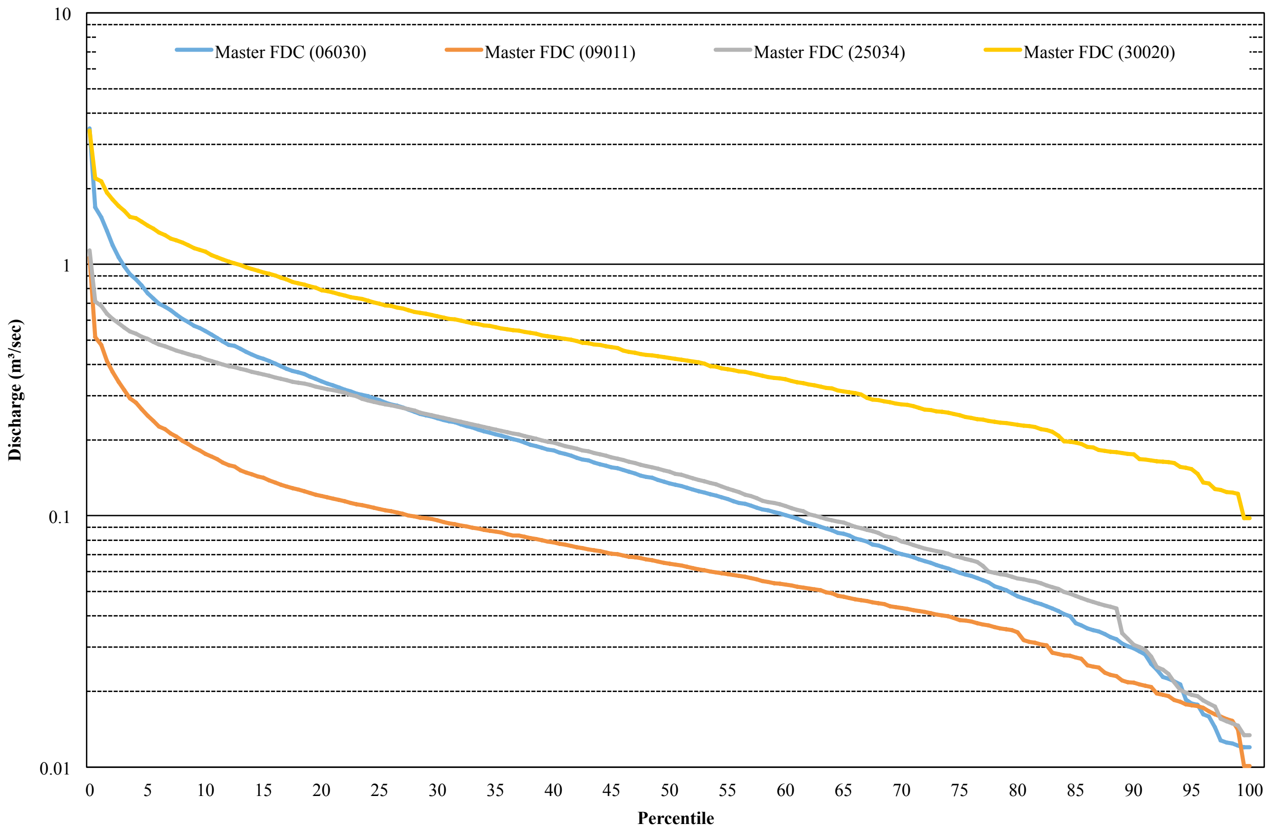

Figure 3.8. Characteristic master (entire available record) river (m^3/s) FDCs for selected study catchments.

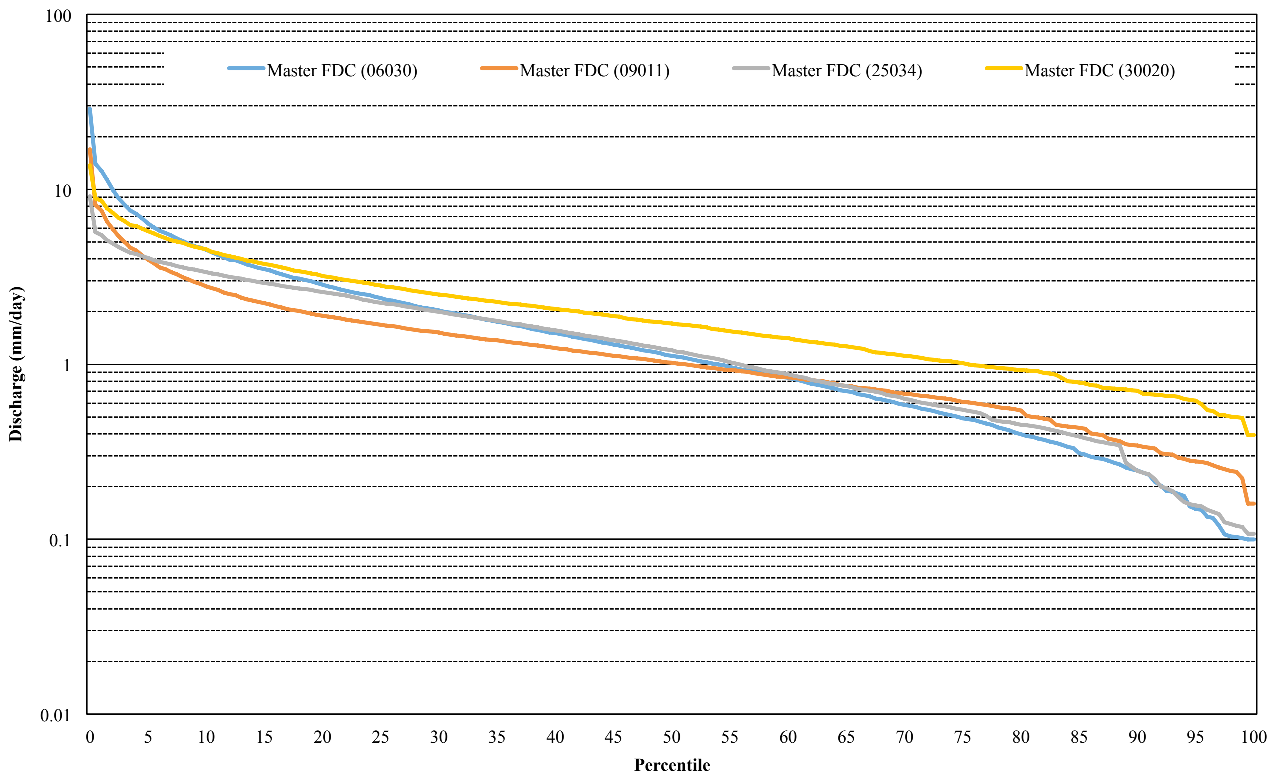

Figure 3.9. Characteristic master catchment (mm/day) FDCs for selected study catchments. Note: catchment FDCs based on normalised discharge data.

Table 3.10. Distribution of key catchment FDC indices

Percentile	Ballygoly (station 06030)	Frankfort (station 09011)	Rochfort (station 25034)	Ballyhaunis (station 30020)
5th (high flow)	6.376	3.954	4.049	5.3767
10th	4.508	2.791	3.366	4.530
50th (median)	1.119	1.020	1.201	1.710
90th	0.246	0.343	0.245	0.707
95th (low flow)	0.148	0.278	0.155	0.619
Q5/Q95	42.882	14.198	26.020	9.310
Q5/Q50	5.698	3.874	3.369	3.371
High-flow slope[a]	–1.31	–0.75	–0.32	–0.56
Mid-range flow slope[b]	–0.042	–0.02	–0.03	–0.04
Low-flow slope[c]	–0.015	–0.01	–0.01	–0.03

[a]0–10th percentile.

[b]10th–90th percentile.

[c]90th–100th percentile.

Table 3.11. Annual mean, annual maximum, annual minimum and seasonal mean calculated values for BFI using the IoH (1980) method

Parameter	Ballygoly (station 06030)	Frankfort (station 09011)	Rochfort (station 25034)	Ballyhaunis (station 30020)
Mean	0.399	0.551	0.727	0.662
Min (year)	0.279 (2010)	0.440 (1999)	0.538 (2009)	0.621 (2011)
Max (year)	0.509 (1977)	0.669 (1990)	0.835 (1989)	0.712 (2001)
Spring mean	0.411	0.551	0.77	0.696
Summer mean	0.461	0.622	0.809	0.802
Autumn mean	0.326	0.567	0.678	0.633
Winter mean	0.397	0.578	0.720	0.605

Note: as a result of missing record values, the 5-year period 1996–2000 was not used for BFI calculation for Ballygoly (station 06030) catchment; instead periods 1975–1995 and 2001–2015 were used for calculation.

IoH method, all catchments exhibit peak levels of groundwater storage during the summer period, followed by a gradual decline during the autumn and winter, with storage then increasing during the spring. This general pattern was particularly evident within catchments characterised by high BFIs [i.e. Rochfort (station 25034) and Ballyhaunis (station 30020)].

3.7 Summary

- Study findings suggest that numerous approaches to baseflow estimation provide a wide range of estimates. Accordingly, a range of hydrograph separation methods should be tested when estimating baseflow contribution to stream flow in small catchments. While the overarching use of one method may provide greater levels of comparability, it may also result in highly inaccurate baseflow estimation in specific catchments or catchment types.
- Generally, small catchments with poor subsurface drainage characteristics have a flashier response to rainfall events due to inherently shorter flow paths to the catchment outlet.
- Hydrological modelling represents the best tool to simulate flow pathways in small catchments when necessary data are available.
- The efficiency of conceptual hydrological models was shown to improve approximately linearly with catchment size, probably due to "buffering" (averaging) of catchment heterogeneity.
- Generally, high flows are poorly simulated in small catchments by conceptual hydrological models, while low and medium flows are reasonably simulated.

- High-resolution modelling of annual records at an hourly time-step was not shown to significantly improve model efficiency, i.e. based on results presented in Table 3.8, daily models explained a larger fraction of the variance in the daily data than it did of the variance in the hourly data. This is understandable since the variance in the hourly data is likely to be larger than in the daily data. It is important to note that daily simulations are more accurate (or better) at modelling actual flows than hourly simulations.
- Significant issues were highlighted with respect to data synchronicity, i.e. discharge and climatic data are not measured at the same temporal resolution, necessitating data consolidation, which introduces an additional level of model input uncertainty. Further consideration should be given to data measurement, synchronicity and collation.
- Event-based analysis at an hourly time-step resulted in underestimation of discharge, with peak duration and timing also shown to be poorly predicted in some instances, particularly with respect to the urban study catchment.
- The majority of existing hydrological models have been developed and tested to simulate large catchment hydrodynamics, and thus may not necessarily perform well in small catchments. Accordingly, it is recommended that further work be undertaken to investigate the underlying cause(s) of poor performance, e.g. conceptual model structure and spatial distribution of model input variables. Furthermore, it is recommended that future work examine the potential efficacy of new semi- or fully-distributed models that accurately mirror small catchment behaviours and responses, and thus appropriately represent the complexity of small catchment hydrodynamics.
- Seasonal behaviour of small catchment hydrodynamics may be predicted based on parallel consideration of validated models and catchment characteristics.
- Catchment instrumentation is vitally important in the medium to long term for provision of necessary data leading to an increased understanding (and ability to predict and/or manage) of small catchment hydrodynamics in Ireland.
- Based on a scoping review of international literature and hydrological analyses undertaken in this study, we conclude that hydrological (up)scaling is not currently feasible in Ireland. Our current understanding of small catchment hydrodynamics is not sufficiently advanced to permit appropriately accurate hydrodynamic upscaling at a regional or national level. Moreover, within an Irish context, it is likely that small catchment heterogeneity, which is more pronounced in Ireland than in many other regions, represents an additional contributory limitation, and perhaps, in the long term, an over-riding one.

4 Expert Elicitation Survey

4.1 Introduction

This chapter describes an expert elicitation survey conducted as part of the current study to inform the process of developing recommendations pertaining to future monitoring of small catchments in Ireland. Expert elicitation is characterised as a “scientific consensus methodology”, which seeks to synthesise the knowledge and opinions of subject authorities where uncertainty exists as a result of insufficient or unobtainable data. Involving both experts and stakeholders from relevant fields represents a time- and cost-effective method of data collation, increases overall perspective and understanding, and aids development of holistic models and/or solutions in a data-scarce environment (Drew and Perera, 2012; Krueger *et al*., 2012). Expert elicitation permits utilisation of aggregated knowledge from many years of experience, including expertise and experience derived from outside the study region (Martin *et al*., 2012), and frequently results in information for which no measured data equivalent is available or accessible (Krueger *et al*., 2012). Moreover, including stakeholders in the process of solution development increases the likelihood that findings and subsequently developed tools are actively employed. Expert elicitation has previously been employed within a number of environmental and hydrological fields, including groundwater recharge modelling of regional flow systems (Lu *et al*., 2015), hydroelectricity and ecosystem services (Locatelli *et al*., 2011), and lake water quality (Van Houtven *et al*., 2014). As with any data measurement and collation approach, expert elicitation also has several disadvantages that must be considered and accounted for; these include potential inaccuracy, overconfidence and occurrence of biases (O’Hagan *et al*., 2006). For example, Burgman *et al*. (2011) report that perceived level of expertise (i.e. qualifications, years of experience, track record) was not correlated with performance in terms of quantity, frequency or probability estimation.

Within the context of expert elicitation, it is important to suitably and clearly define the roles of “expert” and “stakeholder”. As previously outlined by Drew and Perera (2012), an expert is classified based on their expertise, while a stakeholder is, inter alia, involved in decision making. Accordingly, throughout the current study, an expert refers to survey respondents in possession of specialised, in-depth working knowledge of the Irish hydrometric networks, irrespective of the source of knowledge (i.e. research, practise or both). A stakeholder is characterised as a respondent with the authority to influence processes/actions or who is affected by them.

To successfully realise stated project objectives, this study employed an expert elicitation approach to collate and analyse hydrometric network user and stakeholder opinions, knowledge and experience to elucidate current usage, strengths, requirements and limitations of the Irish hydrometric network of small catchments. Furthermore, based on a recent EPA Office of Environmental Assessment review (EPA, 2011), it was recommended that “The hydrometric programme ... be externally reviewed in relation to site selection, uses of the data ...”; it is considered that data and findings from the current study may be used to provide a baseline for future studies investigating the Irish hydrometric network and associated data. Finally, based on the work presented in Chapter 3 of the current report, numerous conclusions pertaining to our understanding of small catchment hydrodynamics have been developed, based on results of hydrodynamic analyses, and mathematical and statistical modelling. Accordingly, these are considered to be idealised in terms of current and future data requirements, i.e. what *should* be done. However, not all recommendations may be nationally achievable in the short and medium term because of financial, operational, knowledge- and/or data-based constraints. Thus, the findings from expert elicitation will be used to bridge the gap between the optimal and the achievable, i.e. what *can* be done. Accordingly, evidence-based recommendations, achievable in the context of current resources, knowledge and operational requirements, will be formulated. Moreover, expert elicitation will be used to prioritise current and future requirements of the current hydrometric network.

4.2 Expert Elicitation Survey Methodology

4.2.1 Development of research questions

Integration of project objectives, a scoping review of relevant published international literature and a recent review of the EPA hydrometric network (EPA, 2011) resulted in development of 11 research questions that will be answered, either wholly or partially (in concurrence with network assessment) via analyses of data elicited from relevant experts and stakeholders.

1. Who are the primary hydrometric data users?
2. What are Irish hydrometric data currently used for and how frequently?
3. Are the network and associated data fit for purpose?
4. Is small catchment hydrometric network amendment/optimisation required?
5. Is data availability currently fit for purpose/adequate?
6. What general improvements are required (i.e. not pertaining to direct network amendments)?
7. What are the perceived user-based gaps/deficiencies with respect to data (e.g. representivity, density, event-based) and catchment types?
8. Where should future catchment monitoring projects be focused/located?
9. What/where are the high-quality, long-term "benchmark" small catchments?
10. Do redundant and/or low-quality stations exist?
11. What new technology (e.g. telemetry, wireless sensors) may be employed to improve the network?

4.2.2 Questionnaire design

A cross-sectional questionnaire entitled "The Hydrometric Network in Ireland: Uses, Efficacy, Strengths and Improvements" was developed for expert elicitation. The survey was characterised by a 10- to 12-minute mean completion time and a maximum of 30 questions. Closed-format questions were favoured to minimise completion time, avoid response patterns and simplify data coding and analyses (de Vaus, 2002). Response bias was minimised via exclusion of questions or lines of questioning considered overly probing or sensitive.

Following consultation with the project steering committee (September 2015) and the two primary hydrometric network stakeholders (EPA's, Hydrometric and Groundwater Section and the OPW), a final questionnaire draft was completed and piloted with 21 non-experts so that all language, questions and overall framing/structure were suitable for general release. The survey was developed offline using the Survey Monkey Survey Design application (www.surveymonkey.net). The survey was developed with a number of filter questions to appropriately classify respondents and exclude those with little or no experience of actively working with Irish hydrometric data. A number of questions also had inbuilt response logic included to appropriately direct respondents to suitable prioritised questions. The final survey comprised 27 questions, including dichotomous ($n=1$), open-format ($n=3$), sole-response multiple choice ($n=12$), relevance-based multiple choice ($n=6$) and ranking-/ordinal-style ($n=5$) questions.

4.2.3 Survey protocols

Based on relevant published literature, together with project structure and existing expertise within the project team, an online mode of completion was used (de Leeuw and Collins, 1997; Dillman, 2000; Nonnecke *et al.*, 2003; Nulty, 2008). A previous EPA-funded small-scale study (2013-W-SS-10) employed online surveying to successfully achieve high response rates and data quality (Naughton and Hynds, 2014). For the current project, surveying took place over a 3-month period from mid-December 2015 to mid-February 2016. Initial contact (including the active survey link) was made with potential respondents in mid-December 2015, followed by monthly reminders in early January and February, with the survey taken offline on 12 February 2016. The sample population for expert elicitation was defined as "any person over 18 years of age, permanently employed in a public or private position which previously or currently necessitates an understanding and use of data collated from the Irish hydrometric network". A survey overview approved by the Dublin Institute of Technology (DIT) Ethical Review Board was developed into an introductory email outlining the research team, overarching study objectives and concise survey objectives. The introductory email also highlighted the purpose of the survey and outlined the eligibility criteria, in addition to assuring potential respondents that survey completion was entirely voluntary and that all responses would be treated confidentially. The online surveying tool was configured to exclude IP addresses from data collation or storage, thus complying with current data protection standards (www.dataprotection.ie). No financial reward was offered to respondents. Owing to the nature of the target audience and the non-personal nature of the questionnaire, formal written consent was not considered necessary, with a positive response deemed adequate evidence of consensual completion. Members of the project steering committee and research team were not considered eligible for survey completion. Expert elicitation invitations were subsequently sent to all potentially suitable respondents (target audience members), including:

- OPW employees (stakeholder);
- EPA employees (stakeholder);
- ESB employees (stakeholder);
- National Roads Authority employees (expert);
- Met Éireann employees (expert);
- Inland Fisheries Ireland employees (expert);
- Waterways Ireland employees (expert);
- GSI employees (expert);
- members of the International Association of Hydrogeologists (Irish chapter) (expert);
- Marine Institute employees (stakeholder);
- Teagasc employees (expert);
- NIRA employees (stakeholder);
- National Parks and Wildlife Service employees (expert);
- local authority employees (stakeholder);
- Council for Forest Research and Development (COFORD) employees (expert);
- members of the Environmental Science Association of Ireland (expert);
- all members of the Association of Consulting Engineers of Ireland (ACEI) with (1) > 10 employees and/or (2) a stated interest/specialisation in water engineering or a related field (expert).

4.2.4 Survey analyses

Following survey completion, all collated data were exported to Excel 2010. Data formatting and cleaning, in addition to development of derived (dummy) variables were carried out using conditional formatting and specially developed macros. Analyses were undertaken within the R statistical environment, using several sub-packages (FactoMineR, compareGroups, and MVN). Respondents were categorised based on (1) level of experience with hydrometric network and data (cut-off value = 5 years), and (2) expert/stakeholder classification (see above).

Since 2009, 1039 people have registered with the EPA HydroTool; however, it is not possible to ascertain how many individuals have actively downloaded and used data during this period (C. Quinlan, EPA, 19 March 2016, personal communication). Similarly, the OPW Hydro-Data website received 3696 visitors during the 12-month period December 2014 to December 2015; however, data pertaining to data download/usage are not available (O. Nicholson, OPW, 19 March 2016, personal communication). Accordingly, it is not possible to accurately calculate or estimate an overall survey response rate.

4.3 Results

4.3.1 Profile of survey respondents

In all, 203 respondents completed the survey, of which 67.5% (n = 137) were male. The majority of respondents were categorised within the 30- to 40-year-old (33.7%) and 40- to 50-year-old (28.2%) age brackets, respectively. Responses were acquired from 28 of 32 Irish counties (Cavan, Donegal, Longford and Tyrone were not represented), with Dublin (28.4%), Cork (13.2%) and Galway (8.8%) the most frequently represented counties. Overall, 4.9% ($n = 10$) of respondents resided outside of Ireland at the time of taking part in the survey, but had previously worked with Irish hydrometric data. Professions and areas of professional expertise of respondents are shown in Figures 4.1 and 4.2, respectively.

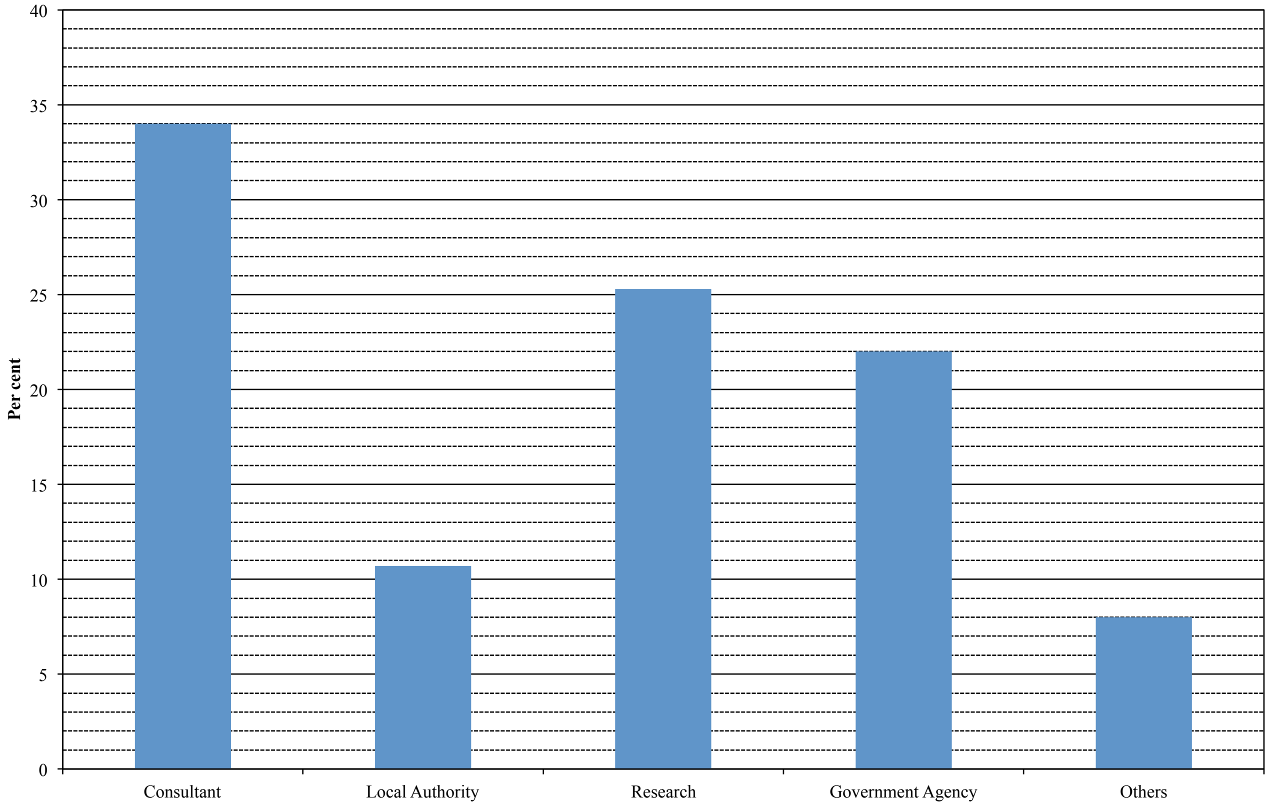

Figure 4.1. Self-reported professional categories among expert elicitation respondents.

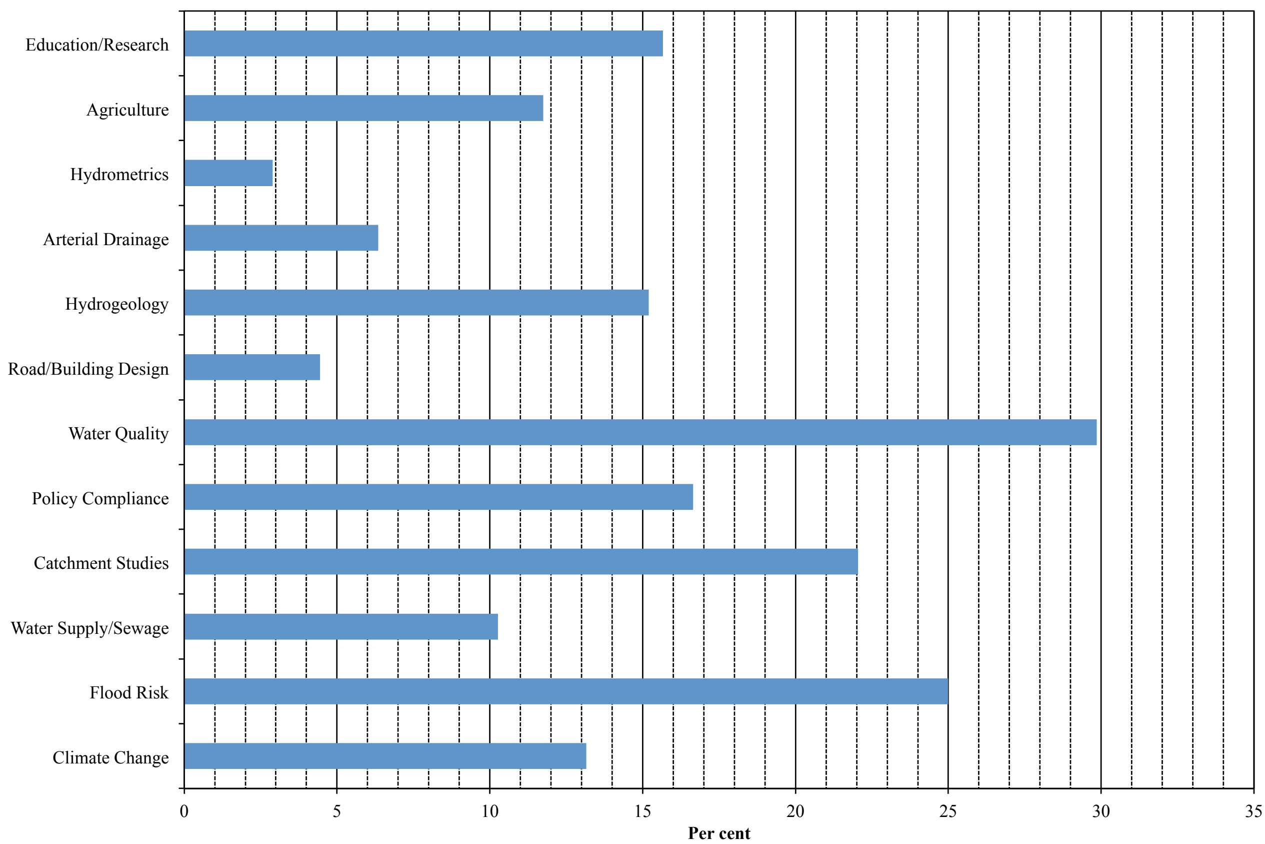

Figure 4.2. Self-reported areas of professional expertise among respondents.

4.3.2 Hydrometric network usage

Upon exclusion of respondents who had not previously used hydrometric data, 52.3% reported being current users, with the remainder (47.7%) reporting previous use. Data derived from EPA-LA (41.7%) and OPW (41.2%) managed stations were most frequently used, thus accurately representing current network management patterns. Overall, 43.3% of respondents reported sporadic data usage (annual or less than annual), with the majority of respondents (32.3%) typically utilising data on a monthly basis; 7.1% and 17.3% reported daily and weekly use, respectively. No statistically significant difference was found between usage frequency and hydrological experience or stakeholder/expert classification. In all, 71.2% of hydrometric data users indicated that they download the most recently updated data on a site- or catchment-specific basis as required, while 28.8% employ previously acquired data; less frequent users were more likely to employ previously acquired (i.e. less current) data.

As shown in Figure 4.3, of those respondents whose professional work is typically focused on one catchment size, 51%, 29% and 17.6% of data users indicated that their work concentrated on small catchments (< 30 km^2), large catchments (> 30 km^2) and larger hydrological basins (> 1000 km^2), respectively. The rest of the respondents indicated the use of the hydrometric data in two and three catchment sizes. Respondents working in larger catchments (> 30 km^2) reported more frequent use of hydrometric data ($\chi^2(4) = 13.062$, $P = 0.011$). Experienced users (> 5 years) were approximately twice as likely to work in smaller catchments (OR 2.066; 95% CI 1.085–3.921). Similarly, network stakeholders were just over 2.5 times more likely than experts to work on larger hydrological regions ($\chi^2(1) = 5.556$, $P = 0.018$).

Sub-daily (15-min interval) data were employed when available by 44% of data users, with 43.1% utilising daily data, 5.5% utilising monthly/seasonal data and 7.3% employing annual summary data (Figure 4.4).

As shown in Figure 4.5, river (54.4%), urban (19.6%) and tidal (18.1%) catchment data are the most frequently accessed and employed. Where respondents indicated only one catchment type, river catchments (83.8%, $n = 40$) far outnumbered all others. Respondents utilising river catchment data were categorically more experienced ($\chi^2(1) = 11.619$,

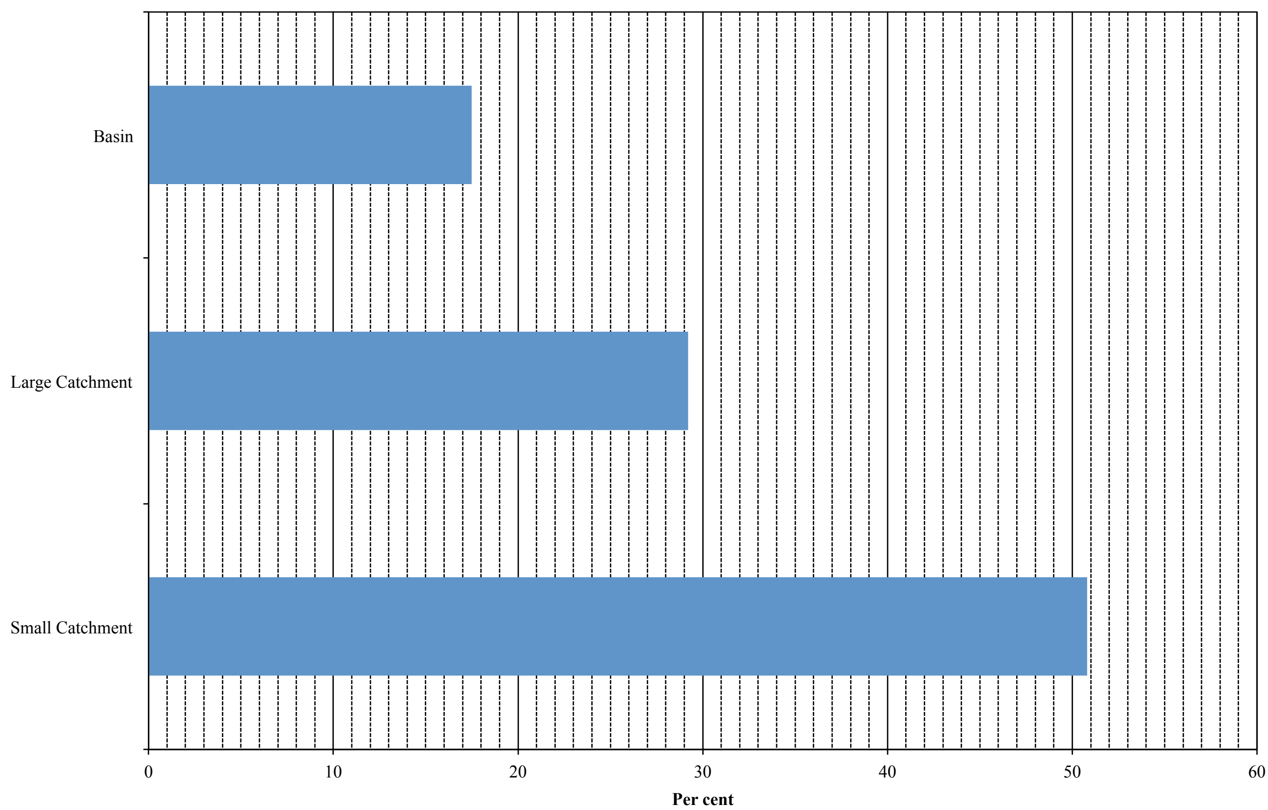

Figure 4.3. Catchment size associated with respondents' professional work.

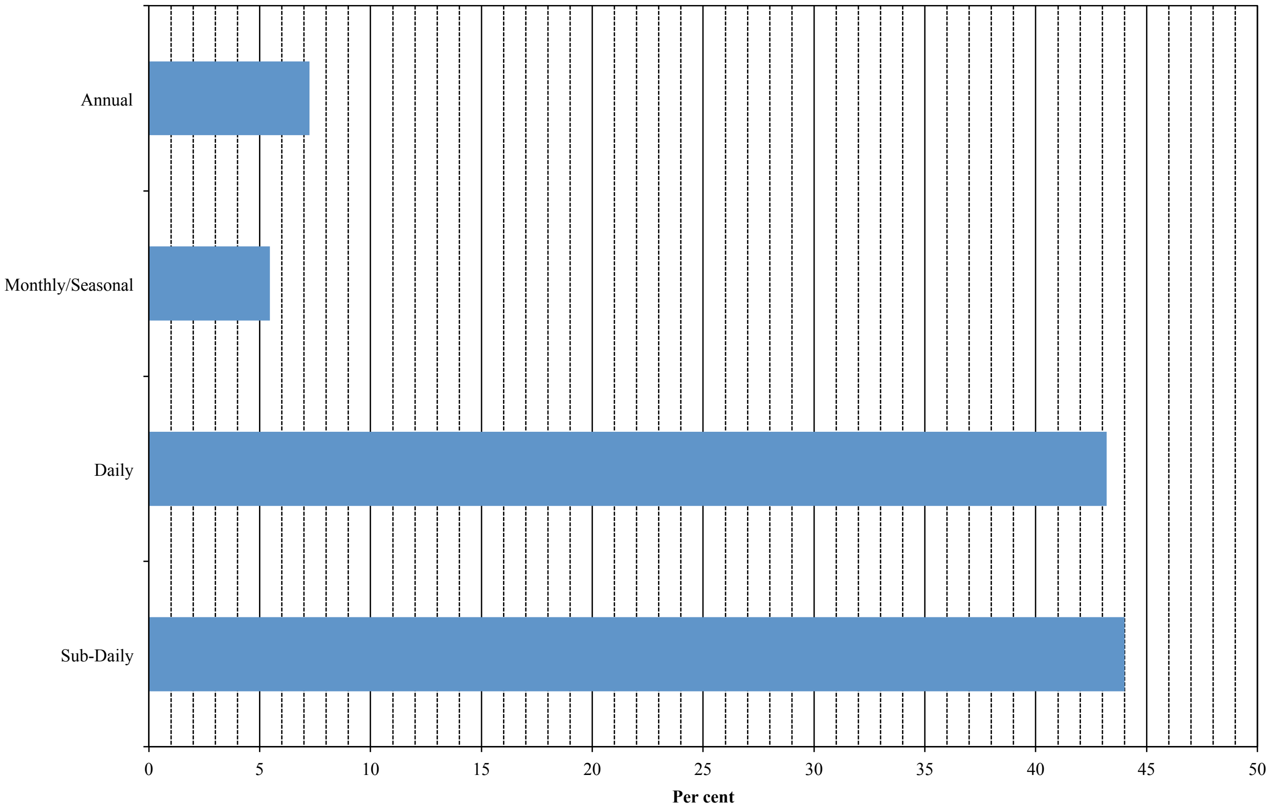

Figure 4.4. Temporal data resolution associated with respondents' professional work.

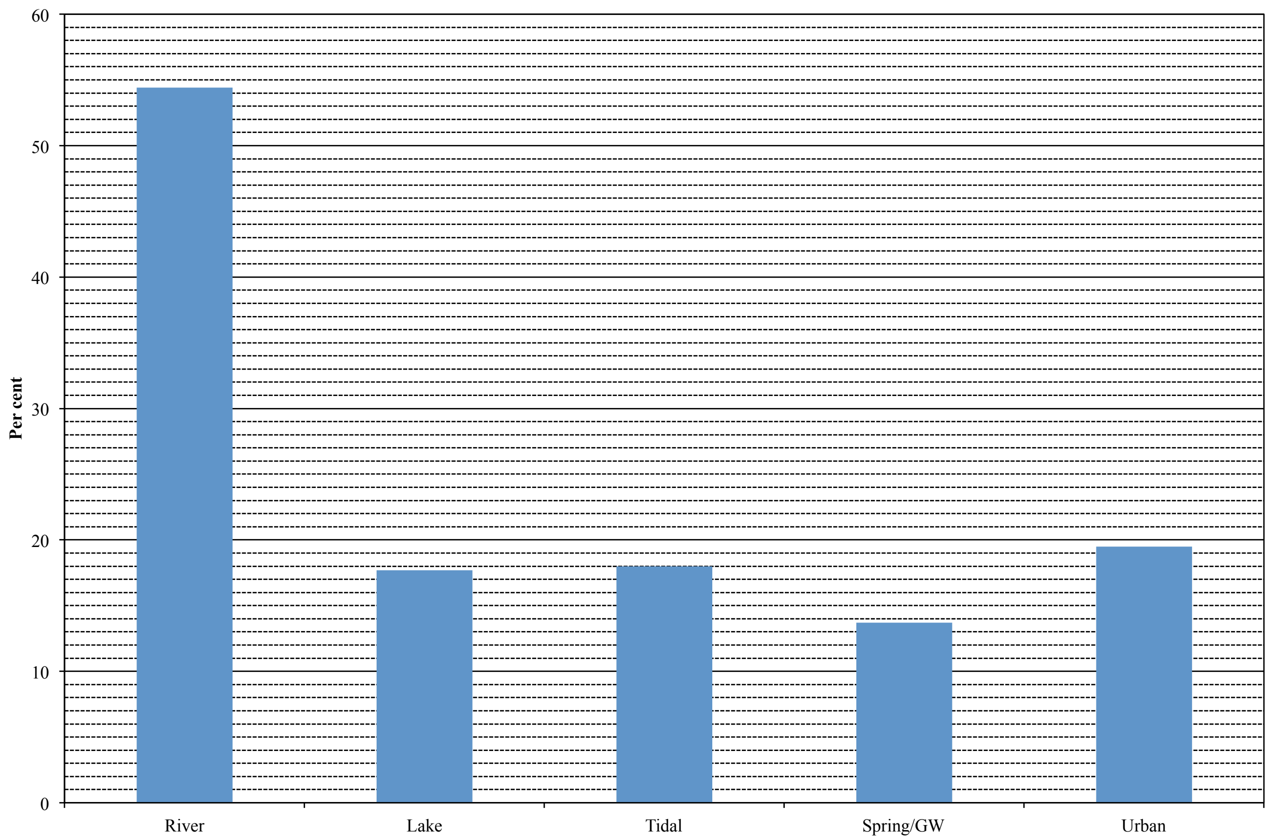

Figure 4.5. Water body (catchment) type associated with respondents' professional work. GW, groundwater

$P=0.001$), used data more frequently ($\chi^2(4)=32.377$, $P<0.001$), were more likely to download updated data ($\chi^2(4)=13.492$, $P=0.009$) and more likely to utilise sub-daily data ($\chi^2(4)=19.136$, $P=0.001$).

With respect to data type, perhaps surprisingly, water level (m) data (37.3%) were more frequently employed than discharge (m^3/s) data (34.3%), with these two data fields, along with summary statistics (32.4%), representing the primary network data requirements among surveyed users (Figure 4.6). When only one data type was employed, water level data (41.9%) remained the most frequently utilised, followed by summary statistics (30.2%), discharge (18.6%) and instantaneous data (7%).

Additional analyses found no discernible association between the use of a particular data type and expert/stakeholder classification ($P>0.05$). However, a significantly greater proportion of "experienced" network users (>5 years) reported using instantaneous hydrometric data ($\chi^2(1)=5.738$, $P=0.017$); 81.1% of instantaneous data users had 5 or more years of hydrological data experience (OR 3.036; 95% CI 1.195–7.714). Similarly, the use of instantaneous data was significantly associated with small catchment studies ($\chi^2(1)=5.196$, $P=0.023$); 94.6% of respondents who reported current or previous work in small catchments had used these data. Current network users were more likely to utilise discharge ($\chi^2(2)=10.960$, $P=0.004$) and flow duration curves ($\chi^2(2)=8.735$, $P=0.013$) than previous users. Moreover, increased frequency of usage was associated with both discharge ($\chi^2(4)=14.531$, $P=0.006$) and flow duration curves ($\chi^2(4)=10.111$, $P=0.039$); for example, 72.8% of respondents reporting at least monthly hydrometric data usage (i.e. daily, weekly and monthly) employed discharge data, with an equivalent figure of 41.2% among more sporadic users (greater than monthly). Network users that reported downloading the most recent hydrometric data for each job/project were more likely to employ discharge data ($\chi^2(4)=11.765$, $P=0.019$), while those reporting the use of previously acquired data (i.e. less current) were more likely to employ instantaneous measurements ($\chi^2(4)=10.523$, $P=0.032$).

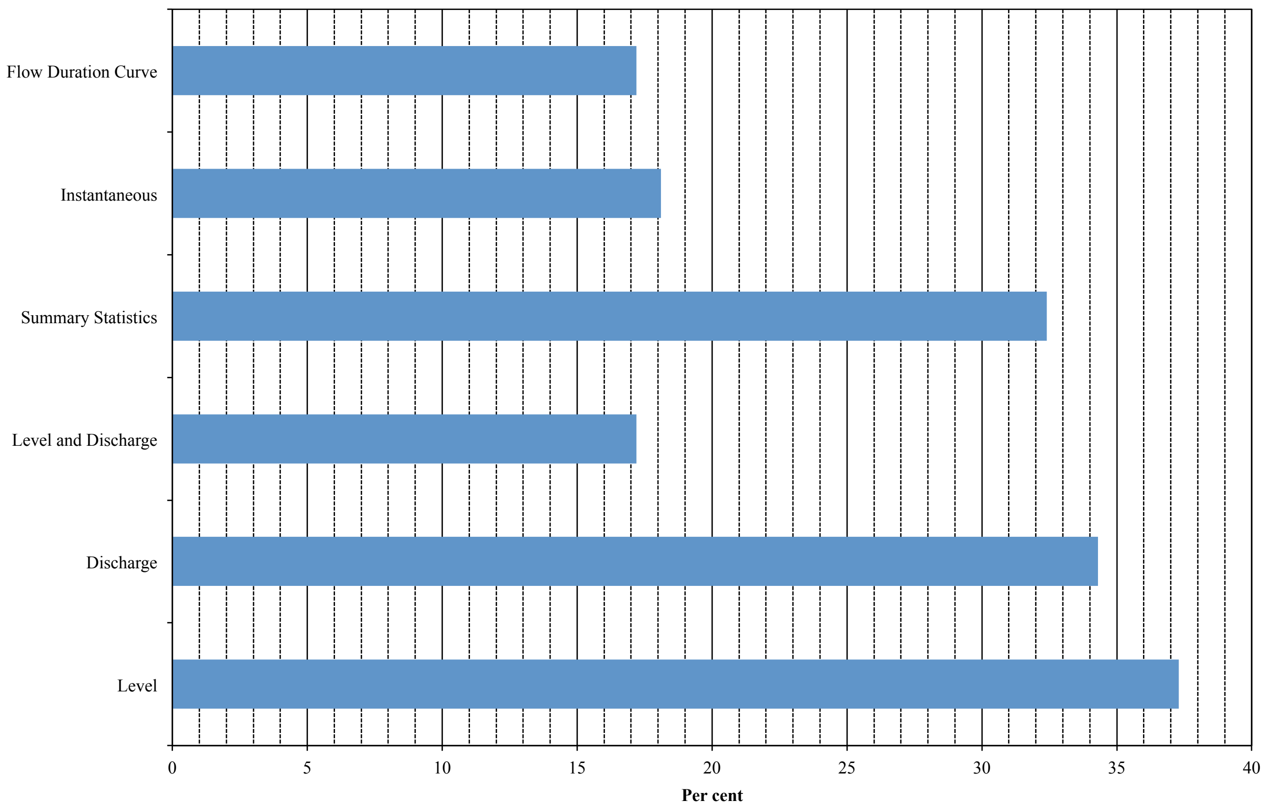

Figure 4.6. Hydrometric data type associated with respondents' professional work.

4.3.3 Perceived hydrometric network efficacy

Network users were asked if the current network and associated data are adequate within the context of their professional work; 50.5% of respondents indicated that the network is not adequate for their requirements. A further 17% indicated that efficacy was station dependent (8.5%) or they remained undecided (8.5%) and 32.4% stated that the network is currently adequate. Neither hydrological experience ($P=0.188$) nor expert/stakeholder classification ($P=0.368$) were found to be associated with self-reported levels of adequacy. Previous users were more likely than current users to classify the current network as being adequate for their professional requirements ($\chi^2(6)=16.261$, $P=0.012$). Neither frequency of usage nor the data source utilised were associated with perceived network efficacy. Similarly, respondents associated with small catchment work did not display a significantly different perception of network adequacy ($P=0.546$), nor was reported network adequacy associated in any way with catchment size, catchment type, management agency or hydrometric data type. Almost 82% of respondents stated that missing hydrometric data (i.e. incomplete time series) had previously represented a limitation in the context of their professional work; these respondents were significantly more likely to attribute a low level of efficacy to the network and associated data ($\chi^2(6)=23.139$, $P=0.001$). Missing data were reported as having previously occurred among 82.1% of small catchment data users, with highest levels of missing data attributed to urban catchments (85.7%).

The majority of respondents reported that, in their opinion, the overall efficacy of the hydrometric network and associated data had improved (53.2%) or remained unchanged (26.6%) over the course of their professional careers, while 13.8% reported a decline in overall network efficacy (Figure 4.7). A significant difference was found between temporal network efficacy and respondents' level of hydrological experience ($\chi^2(3)=11.956$, $P=0.008$), with experienced network users more likely to report both network improvements and declines. While similar proportions of experts (52.9%) and stakeholders (54.8%) reported an overall network improvement during their professional careers, 19.4% of stakeholders were

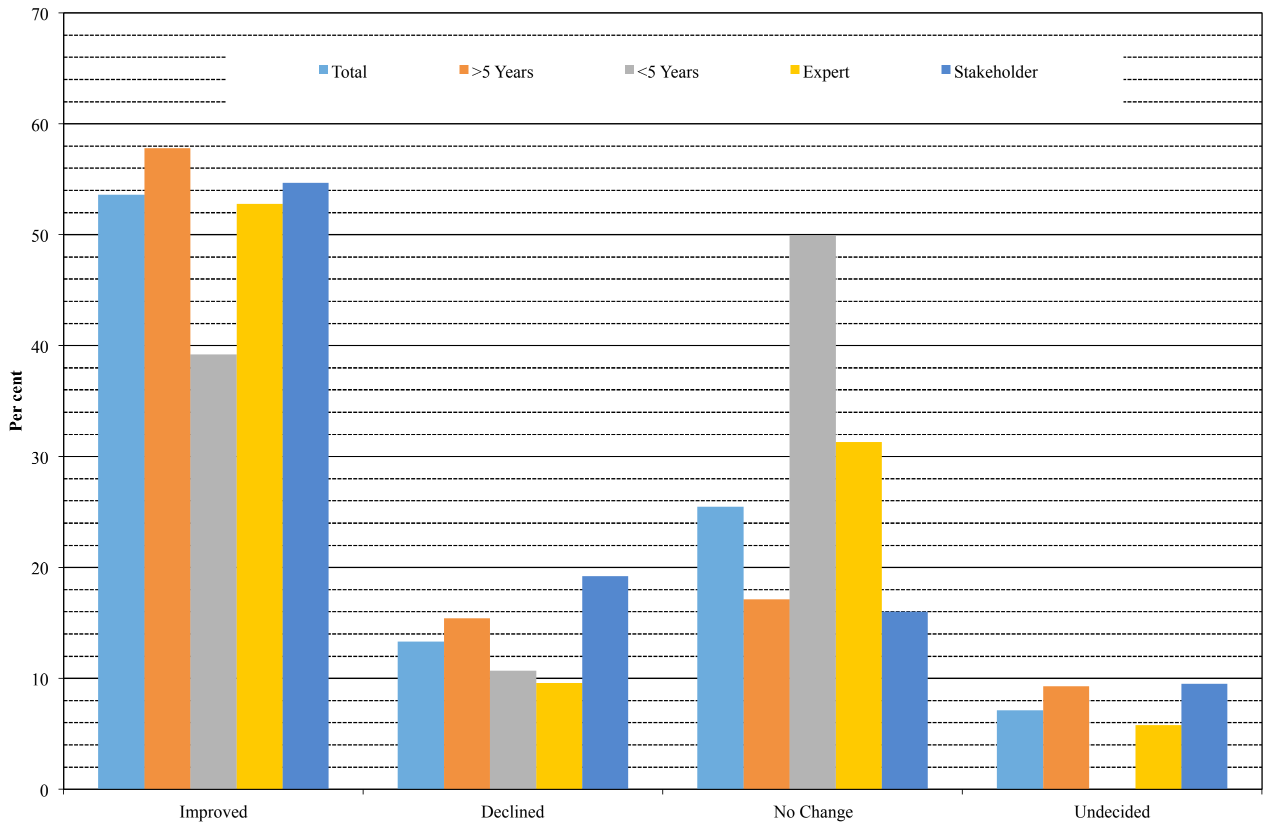

Figure 4.7. Respondent reported changes in hydrometric network efficacy stratified by respondents' experience and expert/stakeholder classification.

of the opinion that network efficacy has declined, compared with 9.8% among classified experts. No significant difference was found between respondents' perception of temporal network efficacy and catchment size ($P = 0.367$).

To further examine the specific factors associated with perceived network adequacy, respondents were asked to rate the level of quality they personally ascribed to the current network and associated data under six generalised headings. As shown in Table 4.1, a low overall level of efficacy was attributed to current network density (7.5%) and network representivity (9.9%). Rankings assigned to network density and representivity were not significantly associated with catchment size (i.e. poor ranking independent of catchment scale). Likewise, expert/stakeholder classification was not associated with data- or network-based ranking; however, level of respondent experience was associated with ranking of network data availability ($\chi^2(2) = 7.396$, $P = 0.025$), current network density ($\chi^2(2) = 12.626$, $P = 0.002$) and network representivity ($\chi^2(2) = 6.889$, $P = 0.032$). In all cases, lower levels of satisfaction were exhibited by more experienced network users.

4.3.4 Hydrometric network improvements

Based on findings from the previous questionnaire section (Table 4.1), respondents were asked if current network density and representivity require amendment, and, if yes, where should amendments be focused. Overall, 85.4% of respondents agreed that network density should be amended as a priority; 60.2% of respondents favoured focused network density increases (i.e. specific catchment types, catchment sizes, geographical areas, etc.), while the remaining 39.8% preferred a general network density increase. Notably (and unsurprisingly), no respondents were in favour of decreasing the current network density. Further questioning sought to elucidate where amendments might be focused to concurrently improve both network density and representivity (Figure 4.8).

Respondents were subsequently asked to identify and rank which hydrometric and climatic variable measurements should be improved to maximise overall network utility. As shown in Figure 4.9, flows (33.3%) and discharges (34.1%) were the hydrometric variables most frequently selected for improvement. Respondents characterised by lower levels of professional experience were more likely to prioritise an increase in groundwater level measurements ($\chi^2(5) = 12.021$, $P = 0.035$). A higher proportion of network experts (22.2%) prioritised improved rating curves than network stakeholders (12.0%); however, this was not significant at a 95% level ($P = 0.060$).

To further explore the perception of "network efficacy" and thus aid development of recommendations for future network optimisation, respondents were asked to prioritise (high, moderate or low) potential amendments that could be used to improve the level of utility associated with the current hydrometric network and associated data in terms of (1) data quality, (2) available record period, (3) network density, (4) network representivity (i.e. adequate proportion of gauged catchment types and sizes), (5) data availability, and (6) data formatting. As shown in Table 4.2, highest priority levels were attributed to data centralisation (65.5%), increasing overall network representivity (61.2%) and increasing the number of gauged small catchments (60.2%). As shown (Table 4.2, column 5), the issues most significantly associated with the likelihood of a respondent perceiving the network to be inadequate were hydrometric record periods ($P = 0.030$) and small catchment network density ($P = 0.039$).

Table 4.1. Ordinalised "level of quality" attributed to the current hydrometric network by expert elicitation respondents

Measure	High (%)	Moderate (%)	Low (%)
Data quality	33.3	59.1	7.5
Data availability	20.4	59.1	20.4
Data formatting	23.6	61.8	14.6
Network density	7.5	58.8	33.8
Network representivity	9.9	56.8	33.3

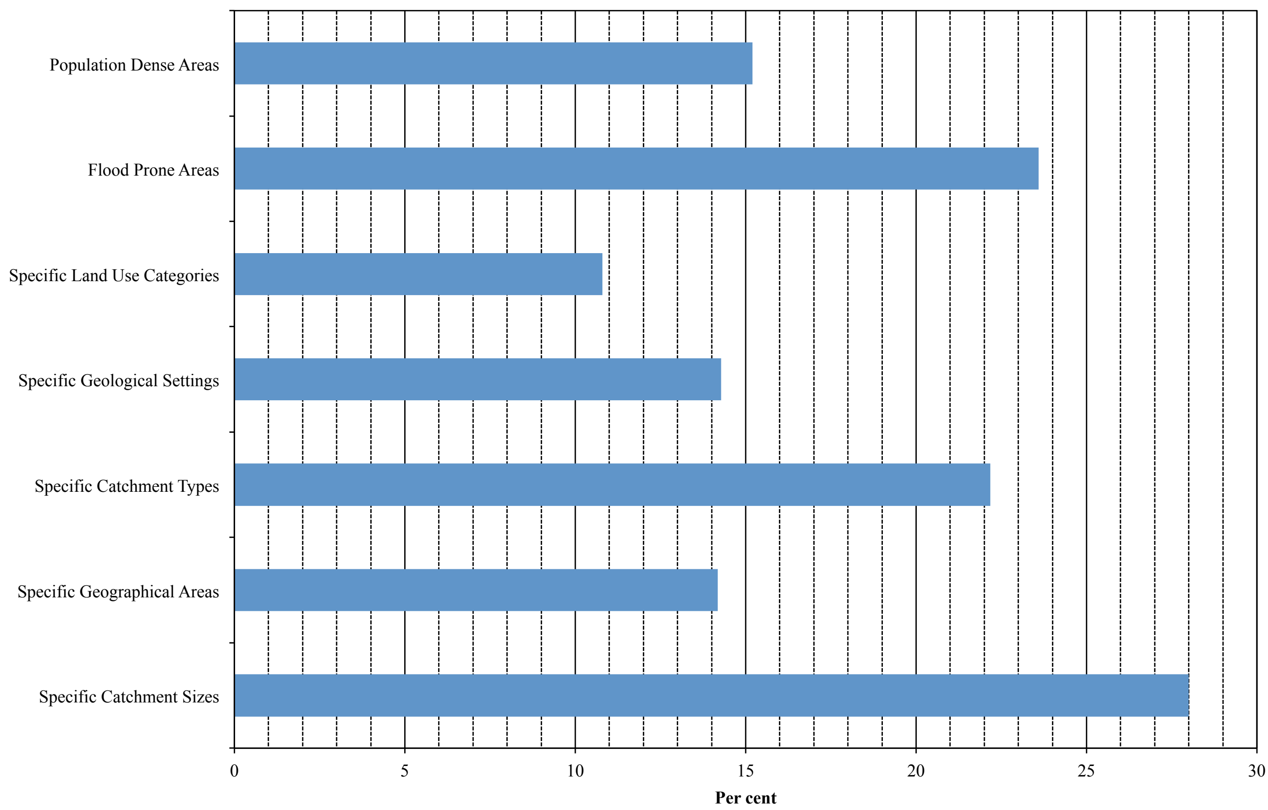

Figure 4.8. Prioritised categorical areas for future hydrometric network density increases.

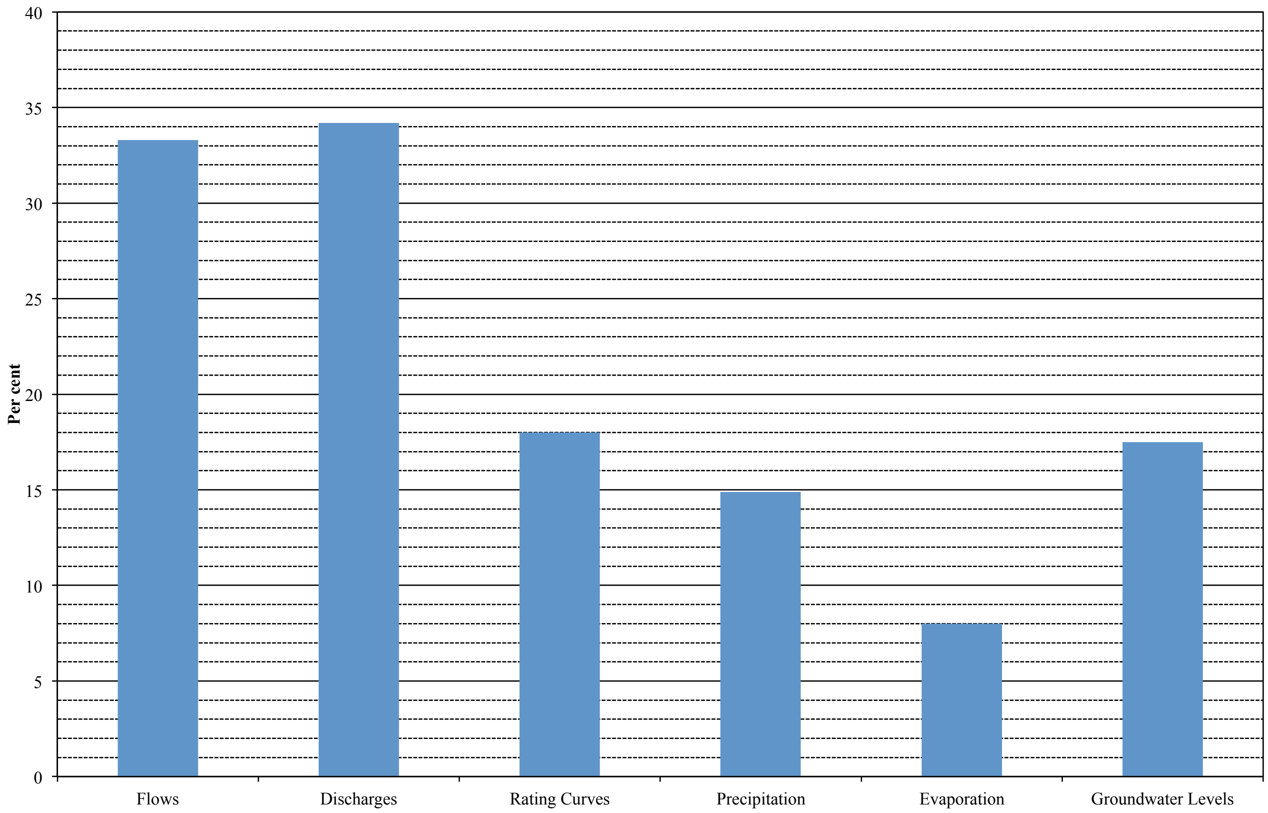

Figure 4.9. Hydrologic/climatic variables requiring improvement to maximise hydrometric network utility.

Table 4.2. Prioritised potential amendments for improving current hydrometric network

Amendment	High (%)	Moderate (%)	Low (%)	Network efficacy association *(P)*
Increase record periods	33.7	47.7	17.4	0.030
Improve data quality	38.4	39.5	19.8	0.057
Increase large catchment network	43.5	40	14.1	0.320
Increase small catchment network	60.2	26.1	12.5	0.039
Increase network density	58.9	32.2	6.7	0.260
Increase network representivity	61.2	31.8	4.7	0.162
Improve data availability	65.5	24.1	5.7	0.079
Improve data formatting	34.1	34.1	28	0.184

4.4 Summary

An expert elicitation survey was conducted to assist in the development and prioritisation of recommendations pertaining to small catchment monitoring in Ireland. Following survey completion and statistical analyses, the primary conclusions are outlined below.

- Small catchments represent the most frequently examined catchment type/size in Ireland in terms of hydrometric data usage.
- Over half of surveyed respondents (50.5%) reported that the current network is not adequate for their professional requirements and has represented a limitation to their work, with a further 8.3% indicating that efficacy is station dependent.
- User-defined efficacy is complicated and multivariate, with no individual predictor identified; however, general data quality, network density and contraction/size of the small catchment network are important issues among the majority of network users.
- Most respondents indicated that network efficacy had improved (53.2%) or remained stable (26.6%) over the course of their professional careers; however, based on perceptions pertaining to current adequacy, these improvements have not occurred sufficiently quickly, i.e. there is a notable disparity between current adequacy and historical amendments.
- Less experienced network users were more likely to report a network decline over the course of their professional careers.
- Based on respondent opinions, temporal efficacy (increased/decreased efficacy over time) of the small catchment network has kept pace with the overall network, i.e. no disparity was found between temporal efficacy and catchment size.
- Small catchment data users were more likely to cite rating curves and groundwater measurements as variables requiring future amendment.
- A significant majority (85.4%) of respondents indicated that network density requires amendment, with no marked difference found with respect to catchment size (87.5% of small catchments data users support a density increase).
- A majority of respondents (60.2%) exhibited a preference for geographically and/or categorically focused network increases, as opposed to a more general national increase.
- Small catchments and areas characterised by previous/recent flooding were prioritised for network amendments.

5 Summary, Conclusions and Recommendations

5.1 Summary

Quantification of flow pathways in small catchments is vitally important for planning and designs related to various challenges associated with water resource management in Ireland, such as river water abstraction, environmental flows and groundwater recharge. Achieving good quantification of flow pathways requires comprehensive understanding of the temporal and spatial dynamics of key water balance components (e.g. rainfall, evaporation, stream flow and groundwater recharge) in small catchments. This should also be associated with identification of benchmark catchments for providing long-term monitoring to ensure continuation of hydrological investigation in the future. In addition, transferring knowledge gained about detailed hydrological processes from small-scale catchments to large-scale catchments is also important, particularly when dealing with water resources at a large scale. These aims have been translated into the following four objectives for this study, namely:

1. reviewing and assessing the existing Irish hydrometric network of small catchments, thus aiding identification and selection of suitable small-scale study catchments;
2. quantifying, from existing measured data, the temporal and spatial hydrodynamics of selected small catchments;
3. examining current hydrometric data usage, perceived network and data efficacy and limitations, and potential (prioritised) network improvements among users of the Irish hydrometric network;
4. using the findings of the above three objectives to develop recommendations relating to hydrometric monitoring requirements for small catchments in Ireland.

These objectives have been achieved by applying a methodology that consisted of a number of steps. Firstly, a small catchment hydrometric station database was derived from the EPA Hydrometric Register using a ≤30 km^2 catchment size benchmark, followed by a statistical assessment of the spatial and temporal patterns associated with all (active and inactive) hydrometric stations within the derived network. To ascertain perceived current network efficacy and projected (prioritised) future requirements, expert opinion was sought from hydrometric network data stakeholders and users via an online expert elicitation survey, the first of its kind to be undertaken.

Secondly, using a multicriteria approach, four study catchments characterised by appropriate record lengths, diverse land use, topology and/or morphology were selected from the Irish small catchment network to go forward for hydrological analyses. These were Ballygoly (station 06030), Frankfort (station 09011), Rochfort (station 25034) and Ballyhaunis (station 30020). The hydrodynamic behaviours of these four study catchments were characterised using a combination of hydrograph separation methods and hydrological (mathematical) modelling, with nine hydrograph separation approaches and three existing hydrological models employed, namely the HBV Model, the NAM, and the SMART model. Hydrological modelling was undertaken at two distinct temporal resolutions to examine the effects on simulation accuracy and efficiency. In addition, hydrodynamic seasonality was characterised and examined via BFI comparison, FDC development and analyses of FDC-derived indices. Finally, preliminary work pertaining to the development of a potentially effective approach for recharge estimation in small catchments was undertaken and has been presented.

The main objective of this study, which is the investigation of hydrodynamic behaviour of small catchments, has been achieved. However, as a result of the complexity of hydrodynamic behaviour of the study catchments and limitations in modelling such complexity, it was not feasible to carry out further investigation on upscaling hydrological processes from small-scale catchments to large-scale catchments. Moreover, the findings from the assessment of small catchment hydrometric network and the expert elicitation survey have shown a considerable gap in hydrometric monitoring in small catchments. Hence, a formal list of benchmark catchments could not be suggested but instead recommendations have been made to inform future strategy in hydrometric monitoring in small catchments.

5.2 Conclusions

The overarching conclusions emanating from the current study may be defined and presented under three primary headings, namely (1) assessment of the small catchment hydrometric network, (2) hydrodynamic evaluation of study catchments and (3) elicitation of expert opinion.

1. Assessment of hydrometric network of small catchments

- As a result of data gaps, the actual number of monitored small (and large) catchments in Ireland is not currently known. The Register of Hydrometric Stations currently comprises 744 stations located in catchments < 30 km^2, of which 102 stations are active (network density: one station per 832.57 km^2).
- The small catchment hydrometric network was initiated in the early 1940s, increased significantly during the mid-1970s as a result of the nationwide drought experienced during 1976; network size (and density) has been characterised by a significant contraction since the mid-1990s, thus mirroring global trends.
- To date, hydrometric network development in Ireland has occurred on a reactionary basis to respond to new challenges whenever such challenges arise.
- The current small catchment network is predominantly associated with river (85%) and lake (10%) catchments, which may be considered representative of the current national catchment type distribution.
- Network contractions have been primarily associated with deactivation of river gauging stations; thus, current monitoring is focused on the measurement and collation of continuous discharge data. However, assessment reveals a paucity of available continuous flow data (e.g. low flow data (95th percentile) is available for just 45% of active stations), thus representing significant data limitations with respect to hydrological modelling and elucidation of hydrodynamic behaviour.
- Within the active network, approximately 98% of stations are classified as recorder stations, with the remainder being gauge-only stations.
- The majority of small catchment monitoring is managed by EPA jointly with local authorities.
- While network representivity (geographical, catchment type, climate) has apparently improved over recent years, this is an artefact of an overall decrease in network density. Extremely low (or absent) monitoring levels are associated with the North-Western, South-Western and Neagh Bann regions.

2. Hydrodynamic evaluation of study catchments

- As a result of the range of methods and associated results, it is concluded that a range of hydrograph separation methods should be tested when estimating baseflow contribution to stream flow, followed by comparison with physical catchment descriptors to inform appropriate method selection.
- Typically, small catchments, and particularly those characterised by poor subsurface drainage, were shown to display a flashier response to rainfall than larger catchments, as might be expected on account of inherently shorter flow paths to the catchment outlet.
- While hydrological models may represent the best tool to appropriately simulate flow pathways in small catchments, the efficiency of conceptual models was found to decrease approximately linearly with increasing catchment size. It is considered that this is probably due to the majority of models being based on large catchment hydrodynamic concepts, which are therefore less sensitive to climatic and/or catchment heterogeneity as a result of buffering, i.e. variations are distributed across the entire catchment area.
- Conceptual hydrological models were shown to perform poorly at simulating high flows in small catchments, irrespective of resolution of modelling time-step (daily, hourly), while low and medium flows were reasonably simulated. It is important to note that daily models were calibrated for relatively large flow periods, and, thus, model performance represents a compromise between the low-, medium- and high-flow sections of the hydrograph. Hourly models were calibrated for

significantly shorter flow periods, ranging from 2 to 12 months.

- Generally, small urban and upland catchments were associated with poor model simulations, while relatively larger lowland catchments (< 30 km^2) produced notably better results. This is probably as a result of the time for concentration of smaller runoff-dominated catchments being less than the data input time-step (24 hours).
- High-resolution conceptual modelling did not produce significantly improved simulations when compared with lower resolution daily modelling; where improvements were noted, they occurred in larger lowland catchments. In addition, high-resolution modelling resulted in data limitations associated with synchronicity and aggregation.
- Seasonal behaviour of small catchments' hydrodynamics may be predicted based on catchment characteristics; however, predictions are only possible at a temporally coarse (seasonal) scale.
- Based on results of conceptual modelling, further hydrological modelling and catchment simulation work is required for numerous applications, particularly flood prediction and management, i.e. high flows. In the first instance, it is recommended that other conceptual lumped models be tested and compared within the selected study catchments. The efficacy of alternative model types, including semi- and fully distributed models should also be assessed, necessitating the availability of high temporal and spatial resolution data.
- Catchment instrumentation is vitally important in the medium and long term to provide the required data for improving our current understanding (and ability to predict/manage) of small catchment hydrodynamics in Ireland.
- Recent international efforts have focused on hydrological scaling, i.e. prediction of catchment responses based on responses in other linked or nested catchments. A scoping review undertaken as part of the current study has found that, while this may be possible on an individual catchment basis, it is both time and labour intensive. Moreover, and more fundamentally, our current understanding of small catchment hydrodynamics is not sufficiently advanced to feasibly permit hydrodynamic upscaling at a regional or national level in Ireland. Finally, within an Irish context, it is likely that small catchment heterogeneity, which is more pronounced in Ireland than in many other regions, represents an additional contributory limitation, and, perhaps in the long term, an over-riding one.

3. Expert elicitation survey

- Just over half of elicited experts (50.5%) reported that the current hydrometric network is not adequate within the context of their professional requirements, with a further 8.3% reporting that efficacy is station dependent.
- Network efficacy is inherently difficult to measure as a result of the myriad of cross-disciplinary requirements of data users, and is therefore not accurately represented by any specific individual variable, i.e. network efficacy is multivariate and user specific.
- Overall, results indicate that hydrometric data quality, data representivity, the small catchment network and flooding data are the primary user and stakeholder issues.
- Results suggest that recent network amendments have resulted in an apparent decrease in data representivity with respect to topographical, morphological and meteorological catchment characteristics, i.e. network density and topographical/morphological/meteorological representivity are negatively correlated. Such lack of representivity of small catchments in the network has also been highlighted by the results of network assessment.
- Users of small catchment data frequently cited improved rating curves and additional groundwater monitoring as the variables requiring most improvement.
- Approximately 14% of respondents reported a decline in the network, while 26.6% reported no discernible change over the course of their professional careers, with no discernible difference between small and large catchment data users. However, a difference was found with respect to categorical user experience, with a higher proportion of less experienced users reporting network decline or stagnation, perhaps pointing to increased data requirements in association with enhanced computational approaches and/or power.
- The majority of respondents favoured network density amendments via increased station (re)

activations; almost 90% of small catchment users reported that an increased network density is required.

- Approximately 60% of respondents cited a preference for focused network increases, as opposed to generalised national increases. This approach represents a potentially effective and feasible means of maximising the overall efficacy of the current and future network, with small catchments and flood prone areas cited as a priority among users. Moreover, together with improved data availability via centralisation, this approach would effectively address the prioritised potential network amendments presented in Table 4.2 of the current report.

5.3 Recommendations

Based on findings emanating from this study (section 5.2), the following recommendations have been developed for future consideration and investigation.

- Based on the diversity and heterogeneity of small Irish catchments, and the lack of appropriate modelling tools, it is recommended that a small catchments classification system be developed and employed to formulate distinct "Clusters of representative catchments" based on hydrodynamic regime, physiography, spatial area, population size/density, previous events, etc. It is envisaged that this approach would significantly simplify and aid future elucidation of the hydrodynamic behaviour of ungauged small catchments, thus addressing a number of interdependent issues, including water resource management, hydrological modelling, flood risk management, infrastructural design and climate change.
- Identification of one or more sentinel catchments within each identified catchment cluster, based on data availability, data quality and record length, is recommended.
- Small catchment hydrological models (lumped, semi- or fully distributed) that incorporate the characteristic behaviours of the various clusters should be developed. Such models will lead to an improved understanding (and ability to predict/ manage) of small catchment hydrodynamics in Ireland.
- Increased catchment instrumentation is required. This should be based on cluster membership, representivity, data availability and identified problematic catchments, thus providing enhanced data for improving our understanding of the hydrodynamic behaviour of small catchments, in addition to providing necessary data for hydrological model development. Identified sentinel catchments, based on catchment classification clustering, represent an effective starting point for increased instrumentation.
- Increased monitoring to collect data at the highest possible temporal resolution is required for increased modelling capacity, and particularly with respect to groundwater and climate measurement. Thus, it is recommended that discourse be initiated between the relevant authorities to achieve greater synchronicity and thus data availability across the hydrometric network as a whole. It is important that future discussions and strategies pertaining to the synchronicity and availability of network data be tempered by inherent practical considerations, with the fundamental issue being the information content of the data and its association with temporal resolution.
- A decision-based tool is required to inform relevant authorities with respect to future hydrometric network amendments in Ireland, i.e. avoidance of ad hoc reactionary amendments in favour of proactive decision making. It is envisaged that this tool would comprise all critical drivers, including:
  - catchment classification;
  - catchment class hydrodynamics, i.e. required "catchment class" network density;
  - current and future data requirements;
  - areas of special interest, i.e. flooding, population, etc.

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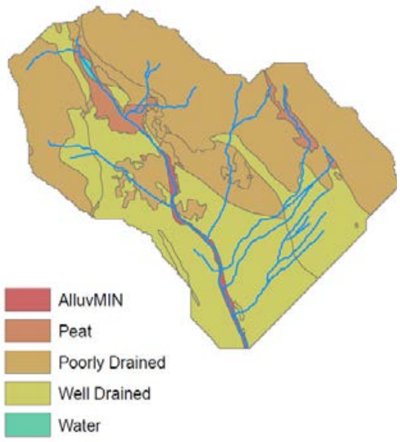
Abbreviations

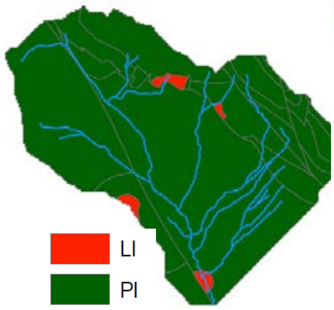
ACP	Agricultural Catchment Programme
ANOVA	Analysis of variance
BFI	Baseflow index
CI	Confidence interval
DTM	Digital terrain models
DWF	Dry weather flow
E	Eastern
EPA	Environmental Protection Agency
ESB	Electricity Supply Board
EWMA	Exponential smoothing
FDC	Flow duration curve
FSU	Flood Studies Update
GSI	Geological Survey of Ireland
HBV	Hydrologiska Byrans Vattenavdelning Model
IHACRES	Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data
IoH	Institute of Hydrology
LA	Local authority
MRC	Master recession curve
NAM	Nedbør-Afstrømnings model
NB	Neagh Bann
NE	North-Eastern
NIRA	Northern Ireland Rivers Agency
NW	North-Western
OPW	Office of Public Works
OR	Odds ratios
R^2	Coefficient of determination
RBD	River Basin District
R_{eff}	Nash-Sutcliff criterion
SD	Standard deviation
SE	South-Eastern
Sh	Shannon
SMART	Soil Moisture Accounting and Routing for Transport
SW	South-Western
UH	Unit hydrograph
W	Western

Appendix 1 Subsoil, Aquifer Type and Recharge Coefficient Maps of the Four Study Catchments

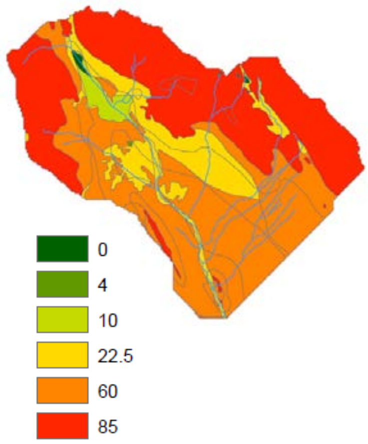
(a) **Ballygoly (06030) catchment**



Subsoil map

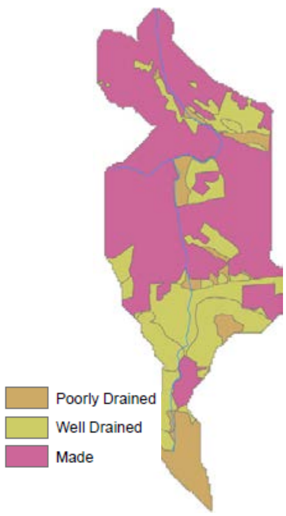


Aquifer map



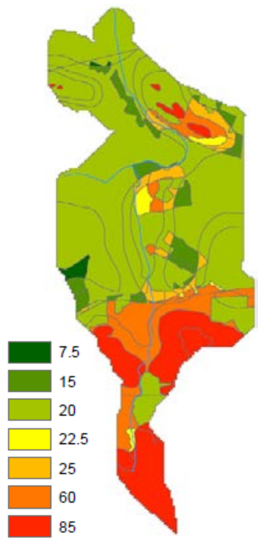
Recharge Coefficient map

(b) **Frankfort (09011) catchment**



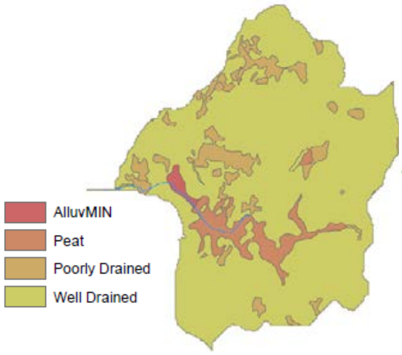
Subsoil map

Aquifer map

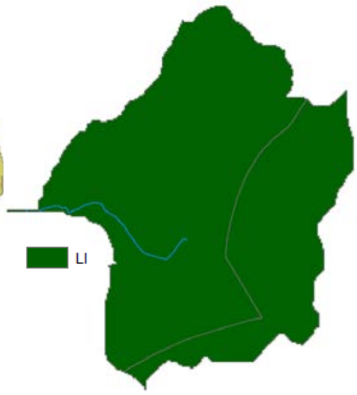


Recharge Coefficient map

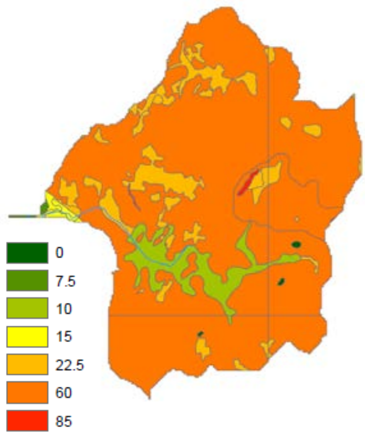
(c) **Rochfort (25034) catchment**



Subsoil map

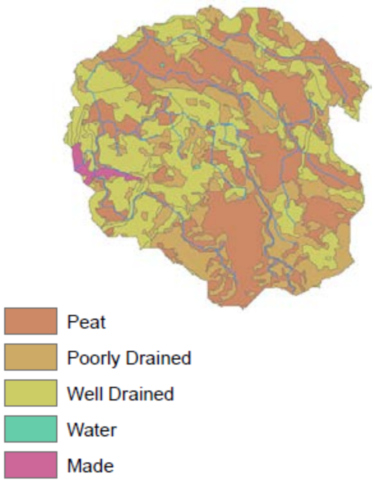


Aquifer map

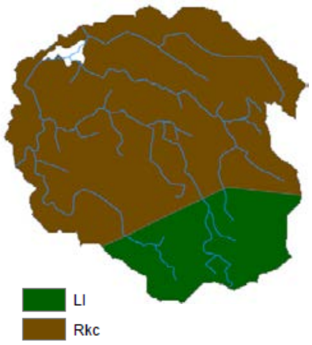


Recharge Coefficient map

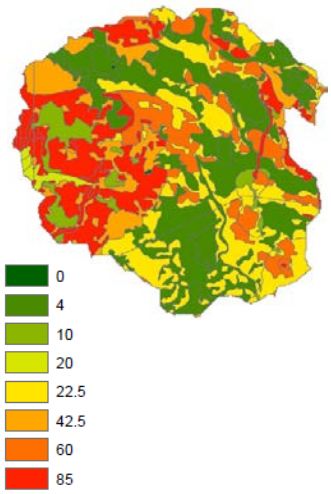
(d) **Ballyhaunis (30020) catchment**



Subsoil map



Aquifer map



Recharge Coefficient map

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report

Assessment of the Hydrometric Network and Hydrodynamic Behaviour of Small Irish Catchments

Authors: Ahmed Elssidig Nasr and Paul Hynds

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Identify Pressures

The combined effects of climate change (natural pressure) and population growth (anthropogenic pressure) represent a significant challenge with respect to water resource management, both nationally and internationally. Recent flood events, in addition to projected urban water shortages, have brought these issues into sharp focus. Improving our understanding of the hydrodynamics of small Irish river catchments is of paramount importance in addressing a range of water resources management challenges including municipal and commercial water abstractions, flood risk management, and water quality. This desk study sought to develop recommendations relating to hydrometric monitoring requirements for small catchments in Ireland via an integrated mixed methods approach. The study design encompassed (i) a statistical assessment of the current and historical small catchment network, (ii) selection of study catchments, (iii) quantification of the temporal and spatial hydrodynamics of selected small catchments via multiple existing approaches, and (iv) examine current hydrometric data usage, perceived network and data efficacy and limitations, and potential (prioritised) network improvements among users of the Irish hydrometric network.

Inform policy

Results of this research project indicate that network amendments over the past three decades have resulted in a significantly contracted small catchment network.. Hydrological modelling of selected study catchments at both daily and hourly time-steps found that existing models provide low to moderate accuracy, with particularly poor simulation accuracy associated with small upland and urban catchments, irrespective of temporal resolution. This study concludes that significant gaps currently exist with regard to our current ability to predict and manage small catchment hydrodynamics.

The key recommendations from this project are threefold:

Firstly, due to the nature of small catchment associated knowledge and data gaps, development of a small catchment classification system based upon existing hydrometric and physical catchment data is required.

Secondly, "sentinel" catchments from each developed cluster should be identified, based upon cluster membership and the availability of high quality continuous hydrometric data, followed by development of representative hydrological models for each small catchment cluster (type).

Finally, a decision-based tool based upon catchment type and associated hydrodynamic behaviour is required in order to inform future catchment instrumentation and overarching network amendments.

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