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Environmental Flow Assessment for Irish Rivers

Authors: Katherine E. Webster, Katie Tedd,
Catherine Coxon and Ian Donohue

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

www.epa.ie

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EPA RESEARCH PROGRAMME 2014–2020

Environmental Flow Assessment for Irish Rivers

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EPA Research Report

Prepared for the Environmental Protection Agency

by

Trinity College Dublin

Authors:

Katherine E. Webster, Katie Tedd, Catherine Coxon and Ian Donohue

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

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DISCLAIMER

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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Project Partners

Katherine E. Webster
School of Natural Sciences
Trinity College Dublin
Dublin 2
Ireland
Tel.: +447 5 0542 6912
Email: katherine.e.webster@gmail.com

Catherine Coxon
School of Natural Sciences
Trinity College Dublin
Dublin 2
Ireland
Tel.: +353 1 896 2235
Email: cecoxon@tcd.ie

Katie Tedd
School of Natural Sciences
Trinity College Dublin
Dublin 2
Ireland
Tel.: +353 8 7687 0429
Email: k.tedd@cantab.net

Ian Donohue
School of Natural Sciences
Trinity College Dublin
Dublin 2
Ireland
Tel.: +353 1 896 1356
Email: ian.donohue@tcd.ie

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Executive Summary

The overarching goal of this research was to evaluate state-of-the-art environmental flow (EFlow) methodology in order to identify best practice, test alternative approaches in catchments of contrasting hydrogeology and provide recommendations to the Environmental Protection Agency (EPA) regarding the establishment of a landscape-based framework for setting EFlow standards that will maintain the ecological status of Irish rivers and the ecosystem services they provide. The objectives of this study were to (1) characterise river flow regimes across a range of landscape settings in Ireland; (2) assess current abstraction pressures; (3) apply abstraction scenarios to identify alterations in hydrologic regimes; and (4) identify information needs and research priorities.

We identified five flow clusters using 34 metrics (representing magnitude, frequency of high/low pulses, duration of high-/low-flow periods, timing and rate of change) generated from long-term daily flow records for 166 hydrometric stations. Flow clusters ranged from those dominated by surface water (flashy) to those dominated by groundwater (more stable); one cluster was lake influenced. Cluster membership was related to elevation, precipitation, subsurface permeability and soil drainage. Agricultural activities appeared to influence the two weakest clusters; these had catchments characterised by high potential land drainage that was related to poorly drained soils and channelisation, which may have increased between-site variability in flow regimes. The identification of reference sites that were representative of “natural” flow in areas subject to centuries of modification as a result of agriculture may require a more appropriate definition of what is “natural” in Ireland.

A national abstraction geodatabase was collated from disparate datasets to assess current abstraction pressures. The geodatabase comprised over 4600 surface water and groundwater abstraction points, which collectively abstract in excess of 5,382,000 m^3 of water per day. Less than 5% of effective rainfall is abstracted from 90% of the catchments analysed. However, more than 10% of the Q95 flow (flow above the rate that was exceeded 95% of the time) was abstracted in 49% of the catchments surveyed. Using the nomenclature of the first cycle of the Water Framework Directive (WFD), these catchments would be classified as “at risk” or “probably at risk” of not achieving the Water Framework Directive’s “good” status, as a result of abstraction pressures that were based on the ratio of abstraction to low flow. An accurate national abstraction database is essential for future work to assess the impacts of abstractions on Irish rivers.

To simulate the potential effects of abstraction on EFlow metrics, we applied 14 abstraction scenarios to daily flow records from stations representing each of the five flow clusters. Scenarios included the proposed UK flow standards, proportional abstraction maintaining low-flow, run-of-river hydroelectric power schemes, and abstraction rates that represented the range quantified in the geodatabase described above. Abstraction scenarios that maintain hands-off flow led to declines in maximum flow rates, which can disconnect rivers from riparian wetlands and floodplains, and in flashiness, which may reduce silt flux and favour organisms that are adapted to more stable flow conditions. Hydroelectric power schemes, although local in effect, led to alterations across all flow metric groups, including barriers to connectivity, because abstracted water is returned downstream. The proportional flow abstraction scenario showed the largest effect on the high-baseflow station, while the flashiest station showed a muted response; flashier stations have higher interannual variability and therefore the signal from abstraction may be swamped by long-term natural variability. Medium to high daily abstraction rates, which are typical of Ireland, led to an increased number of days of zero flow and exacerbated the effects of low flow in the summer in four cases. In agreement with the scientific consensus, our results suggest that, when assessing the effects of abstraction on sensitive ecosystems, a holistic view of flow that extends beyond low-flow assessments should be considered.

We have identified two critical data needs. First, an integrated national database of both abstraction and discharge with adequate temporal resolution and

accurate designations of water sources is essential. Second, long-term records in the hydrometric network should be maintained at a representative set of stations with increased emphasis on under-represented small catchments. A critical research need is to develop ecology–flow relationships for assessing abstraction risk. Our recommendations for abstraction licensing are that this should start in a simple way and use the available data through an integrated approach that prioritises the assessment of rivers that are high-status sites, on the threshold between good and moderate status and most at risk to cumulative abstraction, as well as those for which the qualifying interests may be sensitive to hydrological change. Combining flow assessment with hydromorphology assessment would acknowledge the close link between channel structure and flow regime. Abstraction licensing should remain flexible to adapt to future knowledge from research and monitoring efforts, future novel abstraction pressures and climate change.

1 Introduction to Environmental Flow Assessment

1.1 Environmental Flow and River Management

Freshwater systems provide valuable ecosystem services relating to economic security (e.g. fish, water supply), social security (e.g. flood protection, water purification) and ethical security (rights of people and other species to water) (Acreman and Ferguson, 2010). Globally, the ecosystem services provided by rivers are under threat from pressures caused by catchment disturbance, deforestation and afforestation, water pollution, river corridor engineering, impoundments and water diversion, irrigation, extensive wetland drainage, groundwater depletion, habitat loss and introduced species (Vörösmarty *et al.*, 2010; Arthington, 2012). Vörösmarty *et al.* (2010) estimate that 80% of the world's population lives in areas where either human water security or biodiversity are highly threatened; habitats providing 65% of continental discharge were ranked as moderately to highly threatened.

Twenty years ago, aquatic scientists and policymakers recognised that existing regulations were inadequate to protect rivers and the ecosystem services they provide. Richter *et al.* (1997) posed the ultimate question for river management: how much water does a river need? Despite the long-standing recognition that water flow is a master variable controlling many fundamental ecological processes and functions of river ecosystems, and maintaining valuable ecosystem services (Poff *et al.*, 1997; Petts, 2009), the answer to the question posed by Richter *et al*. (1997) remains complex and is still in contention today. There is consensus that historical approaches towards river regulation focused on maintaining minimum flows, with less attention to retaining natural fluctuations and patterns in flow, are inadequate to protect rivers and the ecosystem services they provide. Consequently, much attention has been focused on the development of environmental flow concepts that account for the requirements of a range of biological communities, life stages and ecosystem processes.

Many definitions of environmental flow (EFlow) have been proposed, but perhaps the most commonly cited is the 2007 definition in the Brisbane Declaration, which is in the summary findings and global action agenda from the 10th International Rivers Symposium held in Brisbane Australia (Arthington, 2012):

> Environmental flow describes the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.

A review of the literature (Webster *et al.*, 2015) highlighted the consensus that environmental flow assessment requires knowledge of multiple components (flow regime, ecology, flowpaths and pressures) and their interactions; uncertainties are caused by limitations in data quality and availability, as well as by the complications of disentangling flow effects from multiple interacting pressures (Figure 1.1).

1.2 Environmental Flow Methodology

Acreman *et al.* (2014a) describe five general trends in environmental flow methodology as it has evolved towards a more comprehensive assessment of natural flow dynamics: (1) simple indices to whole hydrograph analysis; (2) rule-of-thumb to complex models; (3) hydrological to ecohydrological; (4) species-centred to whole ecosystem-based; and (5) site-specific to regional in scale. These trends reflect a transition in the early 1990s from water allocation based on "in-stream flow methods", which were often targeted towards fish or a small number of species, to a more holistic view of environmental flows that was first developed by researchers and managers in Australia and South Africa (Arthington, 2012). Holistic approaches consider flow-related biophysical components and ecological processes of the in-stream habitat within the broader context of connected groundwaters, lakes, wetlands and floodplains, and therefore encompass the understanding of geomorphology, channel morphology, hydraulic habitat and water quality, as well as diverse aquatic and river-dependent communities (Arthington, 2012). Effective management relies on a multidisciplinary approach that integrates expertise from engineering, hydrology, ecology and social sciences, as well as

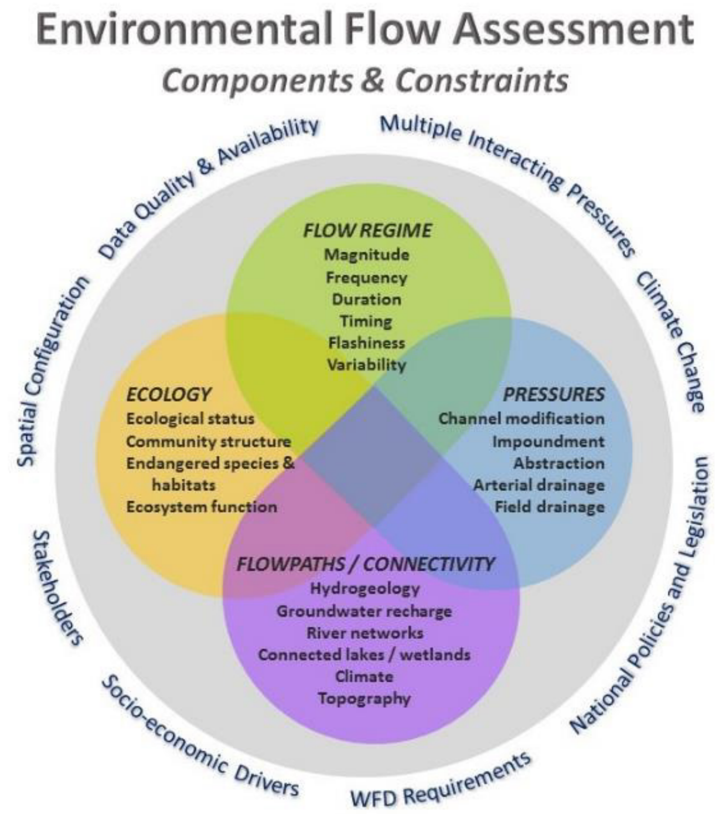


Figure 1.1. Summary of components and constraints in environmental flow assessment.

new disciplines, such as hydroecology, to adequately address environmental flow issues (Vaughan *et al.*, 2009; Acreman *et al.*, 2014a).

Several reviews of environmental flow methods have been published (Dunbar *et al.*, 1998; Tharme, 2003; Acreman and Dunbar, 2004; Arthington, 2012). According to Acreman *et al.* (2014b), more than 250 methods for assessing environmental flow have been developed, most of which fall into one of four main types: hydrological, hydraulic rating, habitat simulation and holistic methods (Table 1.1). These range from rule of thumb methods to intensive site-specific investigations and quantification of discharge–habitat relationships, and to holistic methods that look at relationships across broader spatial scales (catchments or regions). Holistic methods incorporate consideration of the whole ecosystem response, including biophysical, geomorphic, water quality and ecological aspects of rivers and their connected lakes, groundwater and estuarine habitats. Holistic methods can be divided into top-down (i.e. so-called designer flows) and bottom-up approaches that are based on regional assessments of flow regimes. These methods differ in complexity, data requirements, scale of application and certainty of assessments, as well as in their applicability to regulated rivers requiring restoration and to unregulated rivers at risk from pressures altering flow. As many rely on expert judgement and risk assessment rather than quantifiable relationships, they also differ in the certainty of assessment.

1.3 Environmental Flow in the Context of the Water Framework Directive

The European Union (EU) has recently published the Common Implementation Strategy (CIS) Guidance Document No. 31, entitled *Ecological flows in the implementation of the Water Framework Directive* (EC, 2015a). Recognition that over-abstraction was the second most common pressure on the ecological status of river water bodies in the EU, affecting 8% of European rivers, led to the establishment of a working group and to the resultant document and appendices, which were designed to provide a shared understanding of ecological flows for use in the second cycle of River Basin Planning.

Table 1.1. Overview of the main types of environmental flow methodologies with examples, advantages and disadvantages (Arthington, 2012; Tharme, 2003; Acreman and Dunbar, 2004; Linnansaari *et al.*, 2012)

Examples	Advantages	Disadvantages
Hydrological: rule-of-thumb, threshold or standard setting		
Montana or Tennant method (considers seasonal baseflow to maintain habitat and flushing events)	Rapid, cheap, easy to apply; moderate data requirements; desk-based	Requires lengthy flow records to develop relationships; may be inappropriate application to streams outside the study region; often focuses on fish
Flow duration curve (FDC) analysis	Can be elaborated to include flows of any volume or frequency to include a variety of ecological processes	Requires calibration when applied outside original region
Range of variability (RVA); indicators of hydrological Alteration (IHA); Dundee hydrological regime alteration method (DHRAM); sustainable boundary approach (SBA)	Considers more than 34 metrics that characterise components of the natural flow regime	Not specifically ecologically grounded; assumes protecting natural flow regime protects ecosystem integrity
Hydraulic rating: relationships between discharge and habitat		
Wetted perimeter area	Set ecological targets relevant to the specific site being evaluated; scientifically defensible; often precursor to habitat simulation	Assumes sample sites are representative of entire river; intensive field study needed
Habitat simulation: functional models of discharge–habitat relationships for target species		
IFIM (instream flow incremental methodology); PHABSIM (physical habitat modelling platform); FFM (functional flows model)	Considered most scientifically and legally defensible; system specific, linking habitat preferences with target species of interest provides higher certainty; recommended for high-risk projects	Expensive, time-intensive, and requires considerable technical expertise; only applicable to a specific site; focuses on a few target species; criticised as focusing on amount of habitat availability rather than quality or suitability
Holistic or ecosystem: aims to restore the flow-related biophysical components and ecological processes of in-stream, groundwater, floodplains and downstream water bodies		
General characteristics	Can be desk-based and/or field-orientated; focuses on all aspects of the natural hydrologic regime and entire ecosystem; applicable at the regional scale	Often relies on expert panels and workshops to develop ecological relationships with flow regime; may have high levels of uncertainty; relies on existing data that is representative across sites; may not incorporate predictive and quantifiable relationships
Holistic bottom-up: construct a modified flow regime from starting point of zero flow		
Building block methodology (BBM); expert panel assessment (EPAM)	Amenable to simplification for more rapid assessments; Focused on a desired future state for entire river; Flexible, adaptable to either unregulated or regulated rivers.	Demanding to construct; Uncertainties that all flow components captured accurately.
Holistic top-down: acceptable degree of departure from natural or reference flow regime		
Benchmarking: (evaluates ecological implications of potential hydrological alterations using reference and impacted sites)	Whole catchment scale; risk assessments; uses key hydrologic indicators	Uncertainties when extrapolated to larger scales; cumulative uncertainties from each step are difficult to quantify; often relies on expert judgement extracted from expert panels; expensive and requires substantial effort to initiate and develop
DRIFT (downstream response to imposed flow transformation)	Regional scale; uses scenarios and predicts river and sociological responses	
ELOHA (ecological limits of hydrologic alteration)	Regional scale; iterative and flexible framework	

As defined in the CIS document, ecological flows are considered within the context of the EU Water Framework Directive (WFD) (2000/60/EC) as hydrological regimes consistent with the achievement of the environmental objectives of the WFD in natural surface water bodies, as described in Article 4(1). For WFD implementation, the relevant objectives of Article 4(1) are:

1. non-deterioration of the existing status;
2. achievement of good ecological status (GES) in natural surface water body; and
3. compliance with standards and objectives for protected areas, including those designated for the protection of habitats and species where the maintenance or improvement of the status of water is an important factor for their protection, including relevant Natura 2000 sites designated under the Birds and Habitats Directives (BHD).

A river water body (RWB) can be designated as a Heavily Modified Water Body (HMWB) if (a) a substantial physical modification of the channel structure that performs a substantial benefit to society (e.g. flood protection or drinking water) has made it unlikely to achieve GES and (b) the beneficial functions would be compromised by restoration measures and cannot be replaced with a more cost-efficient option. For water bodies designated as HMWB and/or that qualify for an exemption, flow regime requirements take into account technical feasibility and socio-economic impacts on the use that is affected by the implementation of ecological flows.

As a supporting element for the ecological status of natural waterbodies, hydromorphology in Ireland can only influence the ecological status of any waterbody type by downgrading otherwise high ecological status (HES) sites to GES. For rivers, the hydromorphology quality element assessed in determining ecological status includes two subelements of interest here: the dynamic flow regime and connections with groundwater. Many rivers rely on groundwater connections, which are essential for maintaining (a) baseflow during low-flow periods and droughts and (b) specific biological requirements related to differences in water chemistry between surface waters and groundwaters.

1.4 EFlow Project Goals

Even in water-rich countries that do not have a long history of intensive river regulation, such as Ireland, there is concern about maintaining adequate water to protect the functions and biodiversity of river ecosystems, combined with the additional obligation of meeting WFD requirements for environmental flows (EF) as supporting elements for ecological status. Currently, Ireland is in the process of developing abstraction standards to meet WFD mandates and information on abstraction pressures is being compiled by the Department of the Environment, Community and Local Government (DECLG). Therefore, despite abstraction being considered second to nutrient enrichment as a pressure on rivers in Ireland (Shilland *et al.*, 2009; McGarrigle *et al.*, 2010), there are no easily adopted general guidelines for designating environmental flows that support ecological status under the WFD. With the second phase of River Basin Management Plans (RBMP) due in 2017, it is timely for Ireland to develop a national strategy for environmental flow assessment.

The EFlow project described here was funded by the Environmental Protection Agency (EPA) Research Programme 2014–2020 in January 2015 as a desk-based study. The overarching goal of the project was to evaluate state-of-the-art environmental flow methodology to identify best practice, trial alternative approaches in catchments of contrasting hydrogeology with long-term flow data and provide recommendations to the EPA for establishing a landscape-based framework for setting EFlow standards that will help to maintain ecological status and ecosystem services provided by Irish rivers. The scope of this work was to contribute towards development of EFlow assessment for the majority of rivers in Ireland that are not designated under the WFD as HMWBs. We also recognise that there are likely to be different goals of protection versus restoration, depending on ecological status (Figure 1.2).

Following a comprehensive review of the international literature concerning EFlow methodology that was prepared for the EPA (Webster *et al.*, 2015), we focused our research on applying the holistic Ecological Limits of Hydrologic Alteration (ELOHA) methodology depicted in Figure 1.3. ELOHA, the

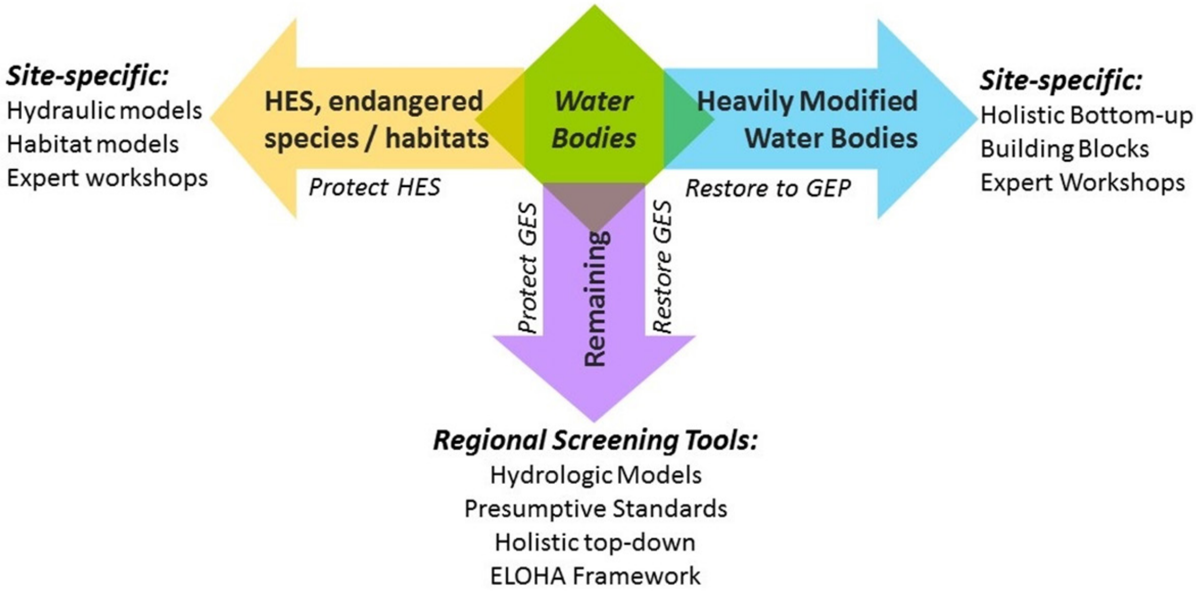


Figure 1.2. Elements of an approach to environmental flow assessment within a WFD context.

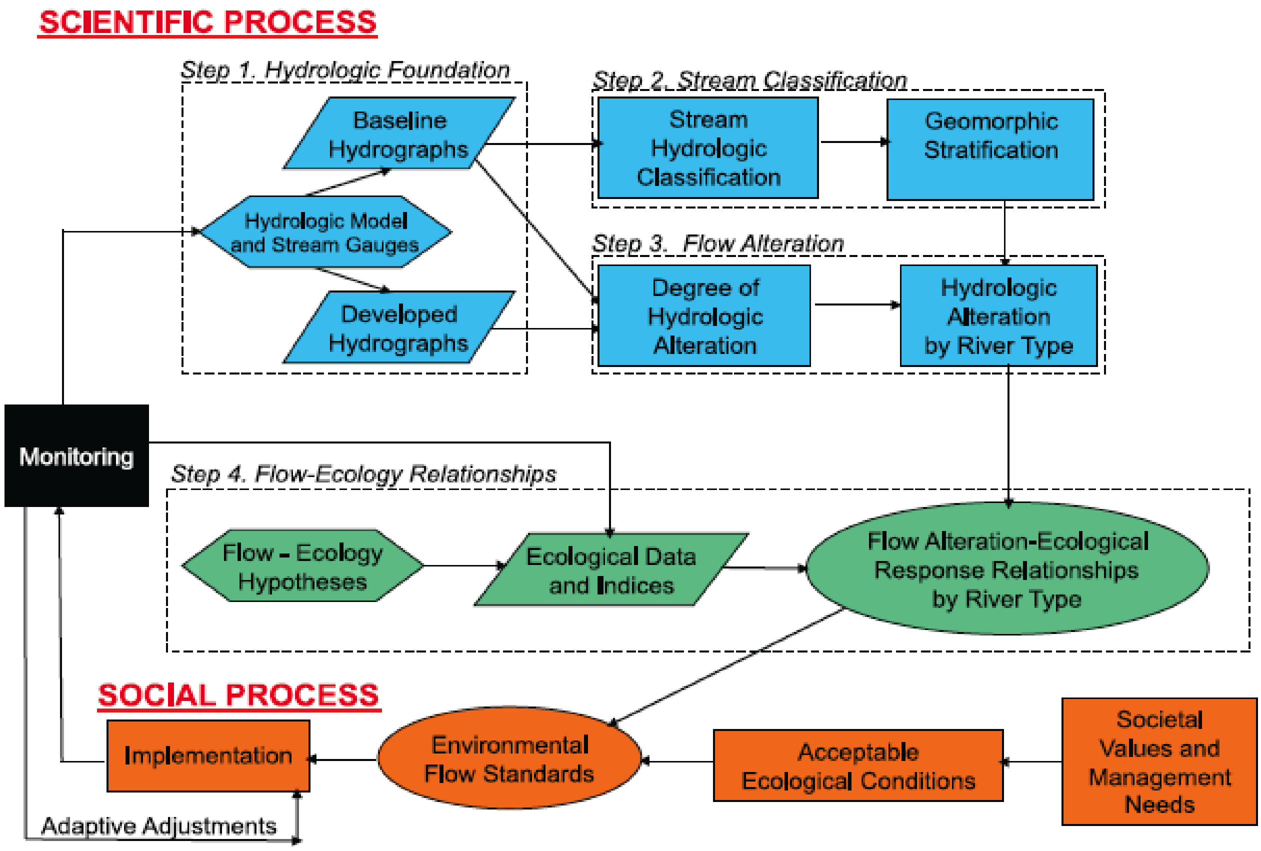


Figure 1.3. ELOHA framework for environmental flow assessment with research areas addressed in this report highlighted in red. Reproduced from Poff *et al.* (2010), with permission from John Wiley and Sons.

outcome of a consensus of international scientists, was developed as a framework for regional quantifiable relationships, designed to avoid costly and time-consuming river-by-river or project-specific approaches to flow assessment (Poff *et al.*, 2010). ELOHA, therefore, meets the challenge of ultimately determining environmental flow standards for many systems simultaneously (Acreman and Ferguson,

2010) and was designed to allow flexibility in its application depending on availability of hydrologic and ecological data, pressure intensity and governance structure (Pahl-Wostl *et al.*, 2013). This flexibility has contributed to its increasing use as a comprehensive top-down approach to environmental flow management across the globe (Arthington, 2012; Kendy *et al.*, 2012).

The first objective of this report, described in Chapter 2, was to develop a flow-type classification system based on long-term daily flow records and landscape characterisation of Irish rivers, corresponding in spirit to the first step in the ELOHA process. Developing ecological flow standards first requires an understanding of (1) natural flow regimes (e.g. the characterisation of magnitude, frequency, duration of flow events, timing, and flashiness) representing contrasting river flow types and (2) the identification of landscape features that can be used to classify the flow type of rivers lacking long-term flow records. Such flow types and their sensitivities provide the basis for assessing the relative risk of abstraction pressures for environmental flow and therefore ecological status.

The second objective was to provide an assessment of current abstraction pressures on Irish rivers (described in Chapter 3). This objective corresponds to the first part of Step 3 of the ELOHA process: assessing the degree of flow alteration. At the time of this work, a comprehensive database of abstraction pressures currently influencing rivers in Ireland was not available. The goals of Chapter 3 were to compile and summarise abstraction pressures in Ireland and provide an initial assessment of the impact of the abstractions on river flow.

The resolution of available abstraction records was as annual totals, so the data did not provide the temporal resolution needed to assess how abstraction pressures may be currently altering the metrics of the natural flow regime of Irish rivers, which is information that provides the basis for developing standards to protect ecological status. Consequently, we took a modelling approach through “data experiments” in Chapter 4 to quantify how existing abstraction rates from Chapter 3, when applied throughout the year, would alter the metrics of the natural flow regime of rivers representing flow types derived in Chapter 2. We also applied flow abstraction standards from the UK to these representative rivers. These abstraction “experiments” provided insight into how existing abstraction rates and a set of existing abstraction standards might influence environmental flows of Irish rivers.

As a result of the short length of time available for this desk-based study, which was combined with data limitations, we were unable to pursue the next step of the ELOHA process (Figure 1.3), which was to develop relationships between flow alteration and ecological response. Such relationships are considered critical for developing abstraction standards to protect ecological status. In lieu of this analysis, we presented the results of this research at a workshop of invited experts representing disciplines of ecology, hydrogeology, hydrology and policy to identify information needs and research priorities for developing abstraction licensing in Ireland. Speakers from the UK provided insights into their experience in developing tools and strategies for developing EFlow methodologies that underpin abstraction regulations. The feedback and comments from that workshop are summarised in Chapter 5.

2 Environmental Flow: Hydrological Foundation

2.1 Goals and Objectives

Many of the hydrologic-based EFlow methods described in Table 1.1 [e.g. Indicators of Hydrologic Alteration (IHA)] classify rivers based on flow metrics that quantify aspects of flow at a range of temporal scales (from daily to annual), consider aspects of both high and low flows, and quantify the degree of flashiness. These methods are based on the natural flow regime paradigm, as formalised by Poff *et al.* (1997), that considers flow dynamics over daily, seasonal, annual and event-based time scales that influence different aspects of ecosystem integrity. The natural flow regime can be summarised by five elements (Poff *et al.*, 1997):

1. *magnitude* of discharge is the amount of water moving past a fixed point per unit time;
2. *frequency* of occurrence is how often flow above a given magnitude recurs over a specified time interval and includes metrics such as the chance of exceeding a 100-year flood and median flow;
3. *duration* is the period of time associated with a specific flow condition, such as the number of days in a year that flow exceeds a specific value;
4. *timing or predictability* refers to the regularity at which flows of a defined magnitude occur, for example the seasonal predictability of annual peak flows;
5. *rate of change or flashiness* is how quickly flow changes from one magnitude to another.

Although the flow regime of each river is, to some extent, unique, Poff and Zimmerman (2010) emphasise the need to classify flow regimes to provide typologies that allow for the development of predictions of ecological–flow relationships, allow extrapolation to ungauged rivers and facilitate management. Natural flow regimes are considered to reflect geographic signatures related to climate (temperature and precipitation), combined with catchment controls on runoff (topography, geology, landcover, position in network) (Poff and Zimmerman, 2010). Because flow regimes are intimately connected to geomorphology, ecological assessments need to consider the pressures that alter flow regime through channel configuration, as well as from abstraction. Understanding the relationships between flow and geomorphology is critical to the science of environmental flows, because geomorphic features can mediate the effects of altered flow regime on ecological processes (Meitzen *et al.*, 2013).

The first objective of this work was to develop a hydrologic foundation (Step 1 in the ELOHA process) for Irish rivers by developing a flow classification system based on metrics derived from long-term daily records followed by class prediction using landscape features. Such an approach has become increasingly common (Olden *et al.*, 2012) and is often the first step in developing an environmental flow framework that provides a foundation for future understanding of ecology–flow relationships, as well as the scientific basis for abstraction rules. The two specific goals were to:

1. create a hydrologic foundation by generating flow regime classes from EFlow metrics derived from long-term daily flow records from hydrometric stations; and
2. predict flow class membership from landscape features to gain an understanding of controls on flow regime in Ireland and provide a framework for extrapolation of flow regime class to unmonitored river locations.

2.2 Methods

The analytical approach used here is considered a "classify then predict" approach, in that flow regime is classified based on flow metrics derived from long-term data records, and classes are then predicted using landscape features (Olden *et al.*, 2012; Peñas *et al.*, 2014). To characterise flow regime, we extracted 34 metrics from daily flow records; these metrics are commonly used in assessments using the IHA method (Table 1.1); they represent flow regimes over long-term climate cycles and are subject to relatively rigorous criteria regarding the length and completeness of the data record (Kendy *et al.*, 2012). Cluster analysis of these metrics was used to generate flow classes with

distinct flow regime signatures. We then developed predictive relationships between flow clusters and landscape features that included natural features (e.g. soil drainage, aquifer and subsurface geology, climate and topography) and anthropogenic features (e.g. features that alter natural drainage patterns and channel configuration). Finally, we applied rigorous statistical techniques to identify the strength of cluster membership in order to assess the ability of the final clusters to provide a predictive approach for assessing unmonitored rivers in Ireland.

2.2.1 Hydrometric station selection criteria

Records for the long-term hydrometric stations used in this analysis are maintained by the EPA and the OPW (Office of Public Works). We note that the Electricity Supply Board (ESB) and the Marine Institute also maintain long-term flow monitoring stations, but these were typically sited near dams or the sea, so were less appropriate to the goals of the study, although they may be suitable for future research. The EPA maintains records from stations that are operated by local authorities and were established for a variety of purposes, including the assessment of exports from waste water treatment schemes. In contrast, the OPW maintains stations that focus on flood protection and warning. It is important to note that data from hydrometric stations maintained by local authorities and the OPW, because of different management goals, are derived from stations where the site geometry provides optimal resolution at low flows (for local authorities) and high flows (for the OPW) (C. Quinlan, EPA, personal communication, September 2015).

Daily flow records for target hydrometric stations were obtained from the EPA's WISKI database or through the OPW (http://www.opw.ie/hydro-data/search.html). Records available from the OPW have recently been revised to account for updating of rating curves (Liam Farrell, OPW, personal communication, June 2015). Records for a subset of OPW-managed stations that have not been updated were obtained from the EPA's WISKI database as part of an earlier effort and are used in this study. Input from the EPA (C. Quinlan and R. Quinn) and the OPW (Liam Farrell) was valuable in avoiding the inclusion of hydrometric stations that were unsuitable or unrepresentative.

Daily flow records were limited to the period 1984 to 2014; we chose this timeframe to avoid known step changes in Ireland's precipitation in the 1970s (Kiely, 1999; Kiely *et al.*, 2010). We then screened data records for completeness criteria recommended in the peer-reviewed literature (Kennard *et al.*, 2010) and in the guidelines in the user manual for the IHA software (Kendy *et al.*, 2012). Each station's flow record was assessed for completeness on a water year basis; water years run from October to September, with the water year set to the calendar year starting in January. Water years that did not meet both of the following completeness criteria were categorised as "missing" in the record:

1. missing daily values for less than 10% of the total year;
2. gaps in the record of less than 10 days.

Using these screened records, hydrometric stations were then selected for further analysis based on the following criteria:

1. They must comprise river stations (i.e. no lake outlet or tidal-influenced stations) with continuous recorders of flow rate.
2. They should represent at least 10 years of data records between 1984 and 2014, meeting the water year completeness criteria described above. Typically, 15–20 year records are recommended for such analyses (Kennard *et al.*, 2010). However, as noted by Olden *et al.* (2012), trade-offs need to be made where sufficient long-term records are unavailable.
3. Their catchment area must not exceed 3,000 km^2; this criterion was set because rivers with larger catchments were either highly regulated by hydroelectric generating stations or had catchments with boundaries extending into Northern Ireland, i.e. beyond the spatial extent of available landscape data.
4. Hydrometric stations with data quality scores for high and low flow that were deemed unacceptable (i.e. with DQ score of 0) were eliminated. These scores were based on the expert opinion of the EPA and on recent station reviews (Sweeney *et al.*, 2011).

As a result of limited data availability at the beginning of the project (see Chapter 3), we could not screen for abstraction pressures at this stage. This does not meet the spirit of the ELOHA framework, which recommends

setting a hydrologic foundation built using unimpacted reference sites. Our decision to proceed was based on a lack of firm data to assess abstraction pressures and by uncertainties in establishing reference condition credentials for each hydrometric station.

2.2.2 Flow metrics and characterisation

Flow metrics were derived from the daily flow records using the free IHA software developed by The Nature Conservancy (TNC) (https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/IndicatorsofHydrologicAlteration/Pages/IHA-Software-Download.aspx).

The IHA software generates over 130 flow metrics, 34 of which are considered core metrics of hydrologic regime (Table 2.1). The software has advantages in that it (1) automatically ignores years in which more than 10% of the data is missing (although this was

Table 2.1. Indicators of hydrological alteration flow metrics

Group	Metric	Units	Description
Magnitude	OCT	cms	October median daily flow
	NOV	cms	November median daily flow
	DEC	cms	December median daily flow
	JAN	cms	January median daily flow
	FEB	cms	February median daily flow
	MAR	cms	March median daily flow
	APR	cms	April median daily flow
	MAY	cms	May median daily flow
	JUN	cms	June median daily flow
	JUL	cms	July median daily flow
	AUG	cms	August median daily flow
	SEP	cms	September median daily flow
	BFI		Baseflow index (7-day minimum flow/mean flow)
Duration	MIN_1d	cms	1-day minimum
	MIN_3d	cms	3-day minimum
	MIN_7d	cms	7-day minimum
	MIN_30d	cms	30-day minimum
	MIN_90d	cms	90-day minimum
	MAX_1d	cms	1-day maximum
	MAX_3d	cms	3-day maximum
	MAX_7d	cms	7-day maximum
	MAX_30d	cms	30-day maximum
	MAX_90d	cms	90-day maximum
	Zero_days		Number of zero flow days in a year
Timing	PRED[a]	cms	Flow predictability
	MIN_jdy		Date of minimum flow
	MAX_jdy		Date of maximum flow
Frequency and duration of high and low pulses	LPULSE_n		Low pulse count
	LPULSE_dur		Low pulse duration
	HPULSE_n		High pulse count
	HPULSE_dur		High pulse duration
Rate of change	RISE_rate		Rise rate
	FALL_rate		Fall rate
	REVERS_n		Number of reversals

[a]Predictability of minimum instantaneous flow (month), which is composed of two independent, additive components: constancy (a measure of temporal invariance) and contingency (a measure of periodicity).

checked in a pre-screen); (2) interpolates across small data gaps of ≤ 10 days; (3) generates median as well as mean flow metrics (we used median metrics and non-parametric analyses in this analysis, because they are considered more appropriate to flow data that does not have many zero flow observations, which was the case with the data used here); and (4) generates flood measures, flow duration curves (FDCs) and time series graphs.

In addition to calculating estimates of the median from annual values, the software calculates the coefficient of dispersion (CD) for each metric (with the exceptions of predictability and number of zero days). The CD is a measure of interannual variability based on the distribution of metrics calculated for each water year in the period of record using Equation 2.1, where the percentiles used refer to the metric in question.

$$\text{CD} = (\text{75th percentile} - \text{25th percentile}) / \text{50th percentile} \qquad \text{(Equation 2.1)}$$

We selected the 34 IHA metrics in Table 2.1 for analysis, as they are commonly used in other studies and have been found to capture flow variability in studies in the UK (Black *et al.*, 2005; Worrall *et al.*, 2014). IHA metrics in units of cubic metres per second (cms) were divided by the median annual daily flow (MDAF) to remove the effect of flow magnitude, as this, to a large extent, reflects catchment area. To prevent incorrect interpretation of differences in the metric for Julian date of maximum flow (JDY_max), 365 was added to Julian dates from 1 January onward. This was necessary to retain a continuous variable representing the continuum from late autumn to spring, which is the period of maximum flow in Ireland. Finally, fall rate (Fall_rate) was multiplied by –1 to eliminate negative values in the metric dataset. It should be noted that the metric for the number of days of zero flow was not included in further analyses, because it was zero for most of the hydrometric stations in the study set and thus provided little useful information for analysis.

2.2.3 Flow exceedance values

In addition to generating flow metrics, we also made estimates of MDAF, MAF and flow exceedance values between Q95 (the flow rate exceeded 95% of the time) and Q5 (the flow rate exceeded 5% of the time). Flow duration curves were generated for each hydrometric station used in the analysis.

2.2.4 Landscape features

Landscape features representing natural features, such as catchment configuration, climate, groundwater hydrogeology, surface connectivity, and landform and anthropogenic alterations (e.g. channelisation, land drainage and land use), were compiled from available geospatial datasets for each hydrometric station (Table 2.2). The features that were selected are known or hypothesised to influence flow regime in Ireland and elsewhere. Geospatial data were sourced from the EPA, the Geological Survey of Ireland (GSI) and Met Éireann (Table 2.2; Appendix 1). Geoprocessing was done using ArcGIS 10.2 software, with features compiled at the catchment scale using shapefiles for the hydrometric stations that were provided by the EPA Hydrometric Section. Two additional spatial scales were investigated for a subset of features. First, abstraction, channelisation and the presence of upstream lakes were quantified with a 1 km buffer around each hydrometric station location, which was clipped to include only the area within the catchment. Second, a 500 m buffer around combined rivers (vectors converted to polygon features) and lake polygons was generated and used to quantify sand and gravel aquifers; while not found in large numbers in Ireland, they can be locally important to water flowpaths. Data for land use and soil types within the catchment were aggregated into groups as shown in Table 2.2 using schemes shown in Appendix 2. Features that were quantified as total counts, areas or lengths within a spatial unit were scaled by dividing them by the area of that unit (e.g. catchment area or buffer area).

2.3 Statistical Analyses

Our statistical analyses were informed by approaches that have been described in the literature (Olden *et al.*, 2012; Snelder and Booker, 2012; Peñas *et al.*, 2014). The goal of the analyses was to generate clusters representing hydrometric stations with similar flow regimes and to predict cluster membership using landscape features. This prediction step would also provide insights into the landscape controls on flow

Table 2.2. Landscape features used to characterise flow clusters

Group	Variable name	Units	Scale[a]	Predictors[b]	Description	Data source code[c]
Catchment	ORDER	na	CA	N	Strahler river order at station	a
	AREA	km^2	CA	S	Catchment area	b
	BFORM	na	CA	N	Basin form factor area/length²	b
Elevation and slope	ELEV_mn	m	CA	N	Mean elevation	c
	ELEV_cv	m	CA	N	CV of elevation (topographic roughness)	c
	BASREL	m	CA	N	Basin relief (caelev_rng/ca_length)	c
	SLP_mn	% m/m	CA	N	Slope mean	c
	SLP_sd	% m/m	CA	N	Slope standard deviation	c
Surface connections	CA_pnolks	%	CA	N	% CA not intercepted by lakes ≥ 10 ha	d
	LK10DEN	n/km^2	CA	N	Lakes density in catchment (≥ 10 ha)	d
	LK10ARp	ha/km^2	CA	N	Lake area/catch area (≥ 10 ha)	d
	LKDEN	m/km^2	CA	N	Lakes density in catchment (all 12K lakes)	d
	LKARp	ha/km^2	CA	N	Lake area/catch area (all 12K lakes)	d
	RIVDEN_12	m/km^2	CA	N	River density orders 1–2 in the catchment	e
	RIVDEN_p12	%	CA	N	Percentage of river length of order 1–2	e
	RIVDEN_47	m/km^2	CA	N	River density orders 4–7 in the catchment	e
	RIVDEN	m/km^2	CA	N	Rivers total density	e
Climate/ hydrology	TMP8110_mn	°C	CA	N	Average 1981–2010	f
	PPT6190_mn	mm	CA	N	Average 1961–1990	g
	EF_RAIN	mm	CA	N	Effective rainfall	h
	PE6190_mn	mm	CA	N	Average 1961–1990	i
	Recharge	mm	CA	(N)	Groundwater recharge	j
Soils classed by drainage	SOIL_WD	%	CA	N	Well-drained	k
	SOIL_IDWD	%	CA	N	Intermediate to well-drained	k
	SOIL_PDID	%	CA	N	Intermediate to poorly drained	k
	SOIL_PD	%	CA	N	Poorly drained	k
	SOIL_XRCK	%	CA	N	Exposed rock	k
	SOIL_PEAT	%	CA	N	Peat (not soil)	k
Sand/gravel aquifer	SG500_Lg	%	500 m	N	Lg (locally important) sand and gravel	l
	SG500_Rg	%	500 m	N	Rg (regionally important) sand and gravel	l
Karst features	KARST_dens	n/km^2	CA	N	Total number of karst features/CA	m
Groundwater Vulnerability Index	VULIND_E	%	CA	N	Extreme (1) vulnerability	n
	VULIND_X	%	CA	N	Extreme (2) vulnerability	n
	VULIND_H	%	CA	N	High vulnerability	n
	VULIND_L	%	CA	N	Low vulnerability	n
	VULIND_M	%	CA	N	Moderate vulnerability	n
Bedrock aquifer	BRAQ_Rk	%	CA	N	Regionally important, karstified bedrock	o
	BRAQ_Rkc	%	CA	N	Karstified, regionally important – conduit flow	o
	BRAQ_Rkd	%	CA	N	Karstified, regionally important – diffuse flow	o
	BRAQ_Rf	%	CA	N	Regionally important – fissured bedrock	o
	BRAQ_Lm	%	CA	N	Locally important – moderately productive	o

Table 2.2. continued

Group	Variable name	Units	Scale[a]	Predictors[b]	Description	Data source code[c]
Bedrock aquifer	BRAQ_LI	%	CA	N	Locally important – moderately productive local zones	o
	BRAQ_Lk	%	CA	N	Locally important karstified	o
	BRAQ_PI	%	CA	N	Poor aquifer – unproductive except for local zones	o
	BRAQ_Pu	%	CA	N	Poor aquifer – unproductive	o
Land use	CL12_fcon	%	CA	A	Conifer forest	p
	CL12_aghi	%	CA	A	Agriculture – high intensity	p
	CL12_past	%	CA	A	Agriculture – pasture over improved land	p
	CL12_pastpt	%	CA	A	Agriculture – pasture over unimproved land	p
Soil type	PWSO_made	%	CA	A	Used to approximate urbanised LULC	q
Modelled land drainage	DRAIN_PEAT	%	CA	A	Land drainage in peat	r
	DRAIN_OTH	%	CA	A	Land drainage, non-peat	r
	DRAIN_ALL	%	CA	A	Land drainage, all	r
Channelisation	CH_dens	m/km^2	CA	A	Channelisation density (OPW plus drainage districts)	s,t
	CH1kb_km	km	1 km	A	Channelisation density (OPW plus drainage districts)	s.t
Abstraction	ABS_SWRIV	n/km^2	CA	I	Surface water/river abstractions	u
	ABS_total	n/km^2	CA	I	All abstractions	u

[a]Scales are as follows: CA, catchment; 500 m, 500-m buffer around the hydrometric station site; 1 km, 1-km buffer around the hydrometric station site.

[b]The codes for predictors are as follows: S, screening for site selection; I, screened as potential confounding factors; N, "natural" predictors used in statistical analyses; A, anthropogenic predictors used in statistical analyses.

[c]See Appendix 1 for information on data source codes.

n, number.

regime across Ireland. The approach used here is considered inductive, as it uses flow data to generate flow types rather than landscape features (Olden *et al.*, 2012). The following sections describe the statistical methods used to define flow types and identify controlling landscape features.

2.3.1 Flow regime clusters

Due to covariance among the 33 flow metrics, we used principal components (PC) analysis to generate orthogonal composite axis scores for use in the cluster analysis. Flow metrics from the study stations were centred (mean subtracted) and standardised (divided by the standard deviation) so that each metric had a mean of 0 and standard deviation of 1. PC analysis was conducted using the prcomp software package in R (R Core Team, 2015). Axes that explained 85% of the variation in the data were retained for further analysis. Each PC axis reflects subsets of flow metrics that co-vary, with the axes ordered by the amount of between-station variation that is explained.

Using the PC axis scores for each hydrometric station as input, flow clusters were generated using the partitioning around medoids (PAM) method. This non-hierarchical method is similar to k-means but, instead of grouping objects by maximising the total error sum of within-groups in the k-means method, PAM clustering identifies *k* clusters such that the sum of dissimilarities of site-specific observations to their closest representative object (e.g. medoid) is minimised (Borcard *et al.*, 2011). This clustering method was used by Peñas *et al.* (2014) in a similar study. Medoid hydrometric stations from each cluster were used to demonstrate flow patterns and are the basis of data experiments described in Chapter 4.

The optimal number of clusters (*k*) was determined by running the PAM clustering algorithm iteratively over the range of 2 to 20 clusters and identifying the cluster

number that had the highest mean silhouette width. Silhouette width measures the difference between the mean within-cluster dissimilarity and the minimum dissimilarity between the given cluster and any other cluster, divided by the maximum dissimilarity either within or between clusters. A silhouette width near 1 indicates the observation is well classified; a value near 0 indicates observations that are on the boundary between clusters and a value near –1 indicates that an observation is misclassified. The mean of silhouette widths indicates the strength of the overall clustering, while low values for individual stations indicate potential cluster outliers.

After identifying the optimal cluster number, the stability of cluster membership was assessed by bootstrapping with 500 runs. The bootstrapping analysis output is the Jaccard similarity index for each cluster, which can then be used, along with cluster silhouette width, to assess cluster strength. Jaccard similarity indices of 0.75 or more are considered to indicate a valid stable cluster, while clusters with indices below 0.6 are not stable. Clusters were generated using the function PAM from the R package cluster and bootstrapping of cluster membership was done using the function clusterboot from the R package fpc.

The Random Forest (RF) approach was used to identify the most important flow metrics and how well they predicted cluster membership (R package randomForest). RF methods are based on tree models, which recursively identify the split value for a predictor that best explains cluster membership. At each "leaf" of the tree, the splitting process is run again, with reuse of predictors permitted. Each iteration also withholds a subset of sites for comparison between predicted and assigned cluster membership. RF generates a user-specified number of classification trees, withholding a designated proportion of randomly selected predictors (here, individual flow metrics) each time. The results from each classification tree are combined to generate an overall measure of importance (e.g. the Gini impurity index) for each input predictor; the most important predictors are those explaining the highest amount of between-cluster variation. The benefit of RF is that it does not have any normality assumptions for the predictors, generates out-of-bag (OOB) estimates of classification errors for each cluster and can identify the most probable cluster membership for any other site for which predictor data are available. Inspection of boxplots of the most important features identified in the RF analysis by cluster membership provided insights into the type of relationship between flow metric and cluster membership.

2.3.2 Landscape characterisation of flow regime classes

The final list of landscape features used to distinguish between flow regimes was reduced from the initial large dataset as follows. First, features with little information (e.g. a large number of zero or very low values) were discarded. Second, we deleted features that showed a high degree of correlation with each other. Third, we applied an initial RF analysis using landscape features as predictors and identified features with very low importance values. A set of 37 landscape features was used in the final RF analysis (Table 2.2). OOB classification error estimates and the most important landscape features were identified from the output. Boxplots of landscape predictors were used to describe cluster characteristics.

2.3.3 Potential confounding factors influencing cluster membership

To determine whether data source (e.g. OPW or EPA/local authorities), length of data record, hydrometric station quality ranking, location of an abstraction within 1 km of the station (based on the EPA GIS abstraction layer) or percentage of effective rainfall abstracted (see Chapter 3) were related to cluster membership or to cluster outliers, we plotted these features against station sill width, both by cluster and across all clusters. There was no obvious effect of these potentially confounding factors on silhouette width and thus the strength of cluster membership.

2.4 Results

2.4.1 Study stations

After restricting stations to those with at least 10 years of complete data and catchment areas less than 3000 km^2, 166 hydrometric stations with a median of 18 years of data (range 10–28 years) between 1984 and 2014 were used in these analyses (Appendix 3). Due to gaps in data records, each water year, with the exception of 1984 and 2014, was represented by

results from at least 80 stations, with up to a maximum of 121 having data in water year 2009 (Figure 2.1). Data records often had gaps or were more continuous in either the early or later part of the data record (Figure 2.2).

The study stations represented a wide range of elevation and annual precipitation (Table 2.3) and were well distributed across Ireland (see Figure 2.5). However, upland rivers (e.g. Strahler orders 1–3) were not well represented, with most rivers having Strahler order between 3 and 5. Of the 166 stations, 107 were unique members of a river waterbody; of the remaining 59, there were 15, 5, 1, and 2 river waterbodies with 2, 3, 4 and 5 hydrometric station respectively. We did not eliminate hydrometric stations within the same river system from our analyses.

2.4.2 Flow regime clusters

Using PC analysis, the 33 flow metrics were reduced to seven orthogonal (i.e. independent) PC axes explaining 85.7% of the variation between hydrometric stations in terms of flow metrics. These seven PC axis scores were used as the input into the PAM clustering algorithm. The optimal number of clusters was five, which had the highest average sill width of 0.15 when all cluster numbers between 2 and 20 were tested. In the five-cluster solution, the number of hydrometric stations within each cluster varied from 53 in Cluster 5 to 18 for Cluster 1 (Table 2.4).

From the five-cluster solution, Clusters 1 and 5, with the highest average sill width, were the strongest clusters (Table 2.4). Clusters with sill widths near 1 are considered well classified, those with near 0 have observations on the boundary between clusters and a value near –1 indicates that an observation may be incorrectly classified. Clusters 2–4 had average sill width near zero, indicating weak clusters that are likely to overlap in cluster membership.

Using bootstrapping, average Jaccard Index values were highest for Clusters 1 and 5 at 0.83 and 0.65, indicating stable to near stable cluster membership. Bootstrapped values for Clusters 2–4 were less than 0.6, at 0.59, 0.52, and 0.43, indicating that these clusters, particularly 3 and 4, were less stable. These bootstrapping results were in agreement with assessment of silhouette values.

2.4.3 Flow regime characterisation of clusters

In order to improve our understanding of the relationships between individual flow metrics and cluster membership and to define cluster-specific flow regimes, we examined the output from the RF analysis combined with boxplots for each metric. The RF analysis had an overall OOB estimate of error of 21.7%, indicating that nearly 80% of the hydrometric stations could be accurately classified to the proper cluster. This high classification rate was not unexpected, as composite flow metrics

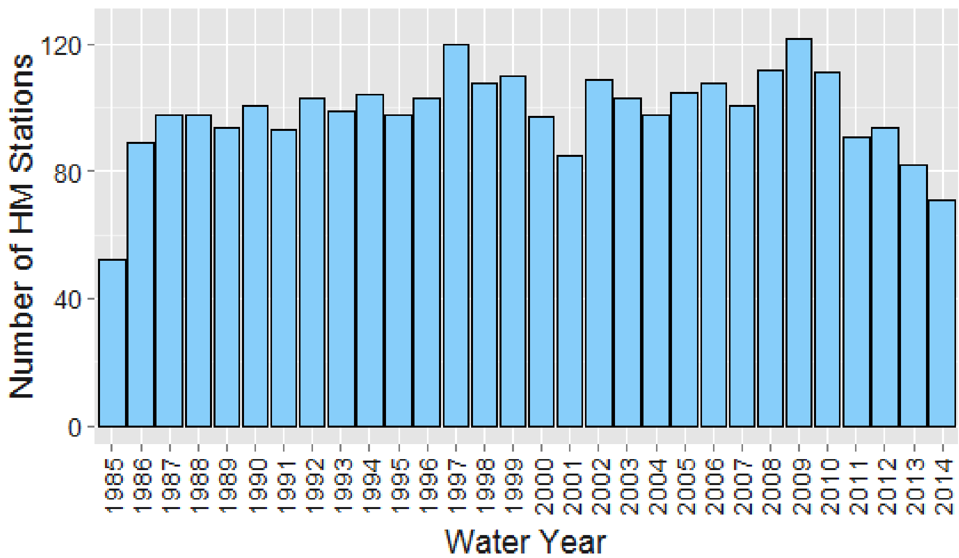


Figure 2.1. Number of hydrometric (HM) stations (of 166 total) with complete data for each water year between 1985 and 2014.

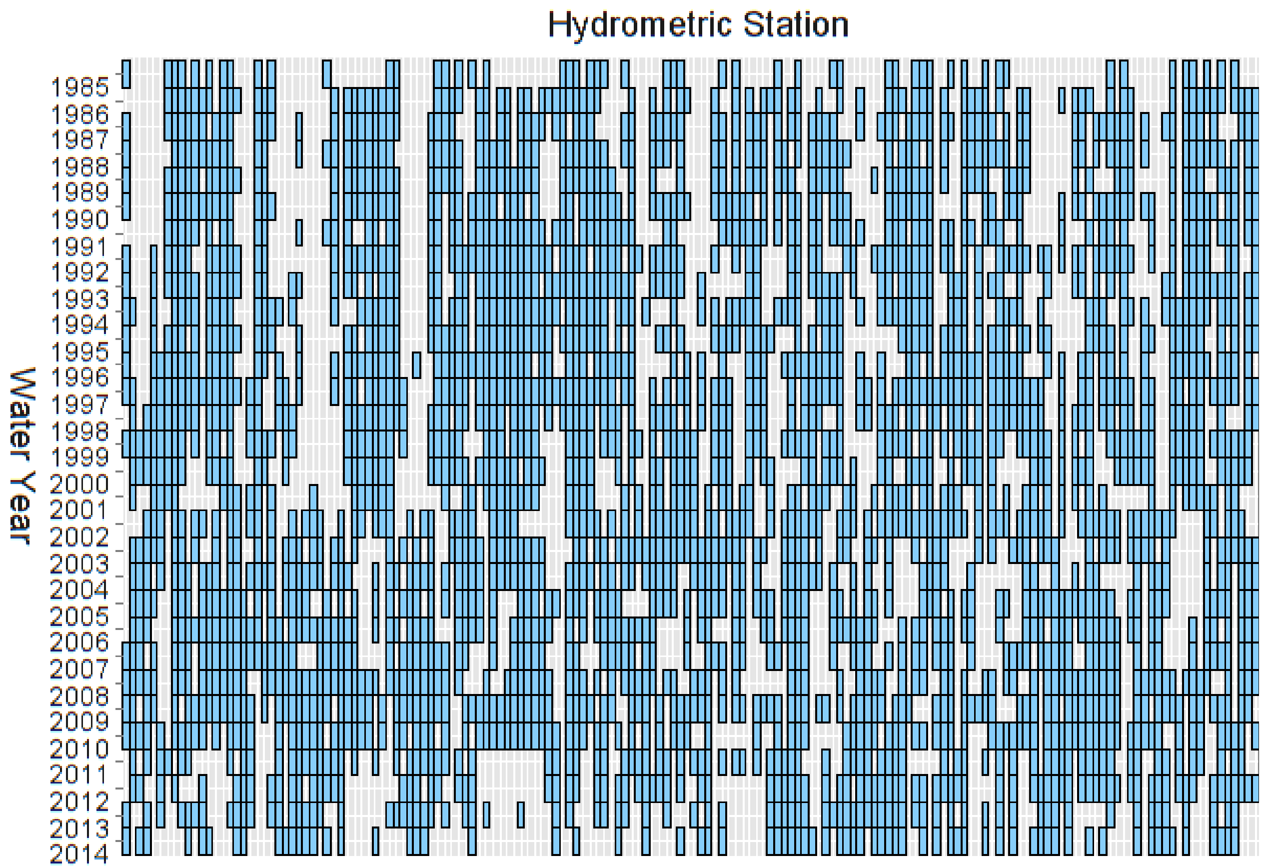


Figure 2.2. Heatmap showing the distribution of years with complete data for each of the 166 hydrometric stations studied. Blue squares indicate years for which data are available.

Table 2.3. Landscape features of the 166 study hydrometric stations

Feature	Units	Median	Mean	Min	Max
Catchment area	km^2	180	402	0.06	2778
Strahler river order	Not applicable	5	4.5	1	7
Years of data	n	18	17.8	10	28
Elevation	m	128	141	25	352
Precipitation (1961–1990)	mm/yr	1106	1214	696	2527

Table 2.4. Cluster diagnostics including cluster size (*n*), mean silhouette width and Jaccard Index

Cluster	*n*	Mean silhouette width	Jaccard Index
1	18	0.34	0.83
2	38	0.06	0.59
3	32	0.07	0.52
4	25	0.08	0.43
5	53	0.24	0.65

derived from PC analysis were used to generate the clusters. The results from the confusion matrix were more useful; this compares observed and predicted class membership for each cluster. Classification errors ranged from 5.6% to 40.0%; corresponding to the stability analyses described above, the lowest

classification errors (< 10%) were found for Clusters 1 and 5, and the highest for Clusters 2 and 4 (> 30%) (Table 2.5).

The importance values generated by the RF procedure reflect the ability of a given flow metric to differentiate the clusters. Importance values were highest for REVERS_n, APR, SEP, MIN_3d, and BFI, indicating that these metrics best distinguished the clusters (Figure 2.3). Using boxplots as a guide (Figure 2.4), the annual number of reversals was highest for Cluster 1 and lowest for Clusters 2 and 3; April flow was highest for Cluster 3; Clusters 1 and 2 had high flow in September; and Cluster 5 had the highest 3-day minimum flow. Baseflow index (BFI) increased across clusters in order of Clusters 1, 4, 2, 3, and 5. Because BFI reflects the relative contribution of groundwater,

Table 2.5. Confusion matrix and classification error from Random Forest analysis of flow metrics. Shaded cells are matches between predicted and observed cluster membership; the results show the number of hydrometric stations

		RF predicted cluster membership					Classification error (%)
	Cluster	C1	C2	C3	C4	C5	
Observed cluster membership	C1	17	0	0	1	0	5.6
	C2	1	25	0	4	8	34.2
	C3	0	2	25	1	4	21.9
	C4	1	5	2	15	2	40.0
	C5	0	2	2	1	48	9.4

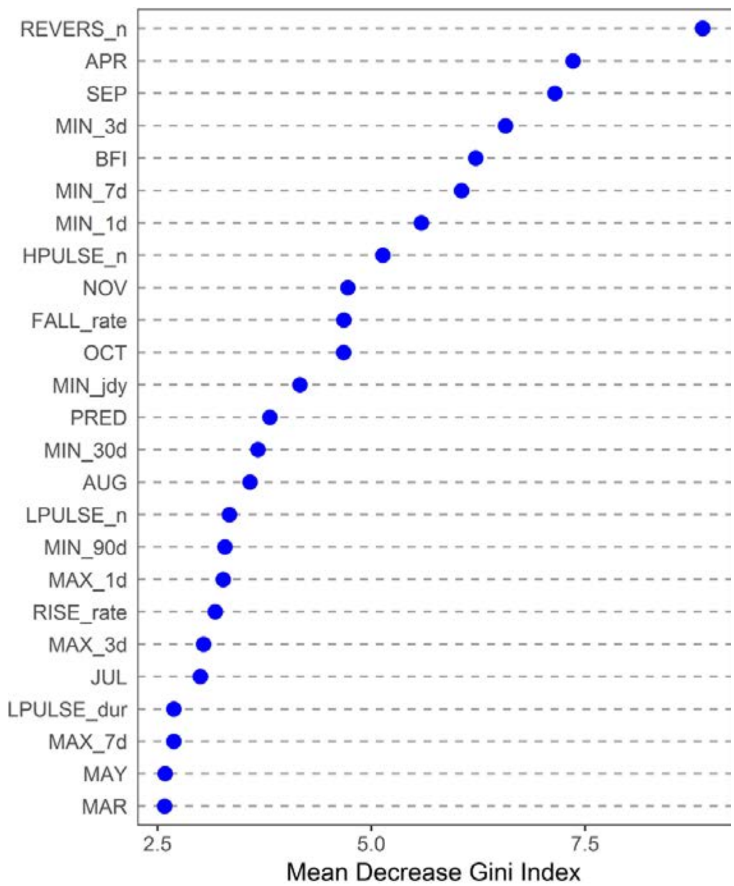


Figure 2.3. Predictor importance plot from Random Forest analysis of flow metrics predicting cluster membership. Abbreviations for flow metrics are shown in Table 2.1.

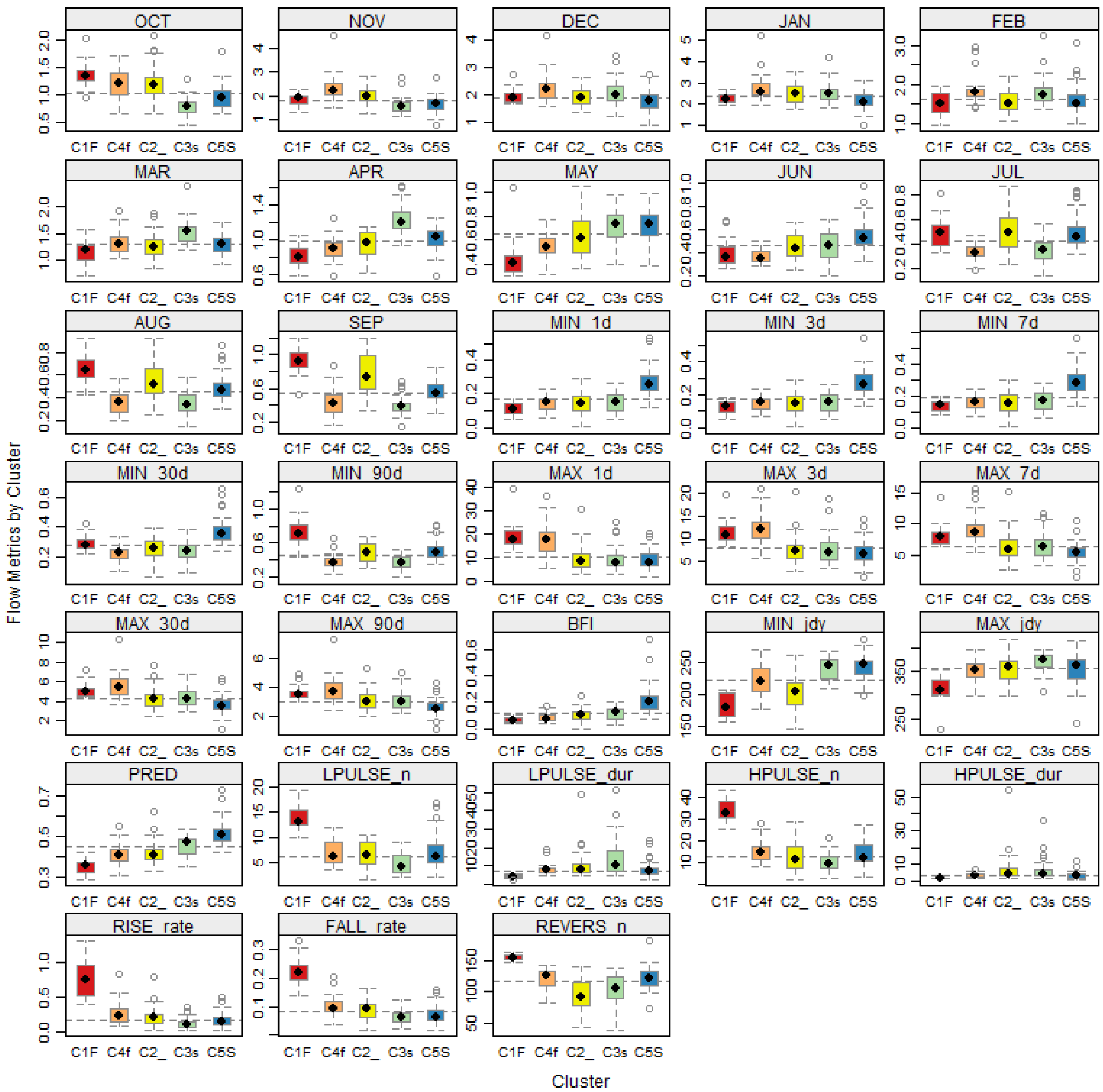


Figure 2.4. Boxplots of flow metrics from the 166 hydrometric stations grouped by cluster. The dashed line is the median value; magnitude metrics have been scaled to median annual daily flow. See Table 2.1 for the flow metric abbreviations and units.

we ordered the clusters by BFI in boxplots and in figures shown later in this report. An overall summary of flow regime characteristics of each cluster is given in Box 2.1. Note that metrics in units of cms have been scaled to median annual flow, therefore their values are presented as relative to median flow.

Another way to explore between-cluster differences in flow regime is by the examination of relationships between high- and low-flow exceedance values (Figure 2.5) and FDCs (Figure 2.6). The relationship between Q5 (the flow rate exceeded 5% of the time) and Q95 (the flow rate exceeded 95% of the time) for each hydrometric station followed an expected log–linear relationship (Figure 2.5). A more interesting result is the divergence of Cluster 5 values from the other clusters with respect to the relationship between Q5 and Q95; the values have a steeper slope and lower intercept compared with the cloud of points containing Clusters 1–4. This divergence is shown more clearly when the Q5 and Q95 values are scaled to mean annual daily flow (MAF) to remove the influence of flow rate (Figure 2.5). In this form of analysis, Clusters 1 and 5 are clearly distinguished as end members, with Cluster 4 points closer to Cluster 1 and Cluster 3 points closer to Cluster 5; Cluster 2

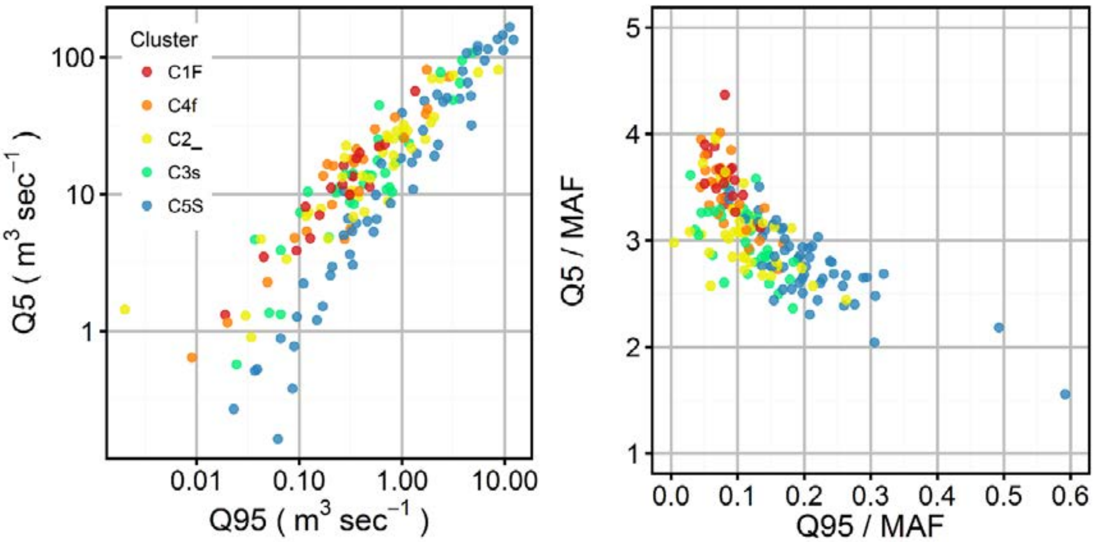


Figure 2.5. Q5 flow plotted against Q95 (a) on a log-10 scale and (b) with exceedance values scaled to mean annual daily flow. Cluster membership is indicated by dot colour.

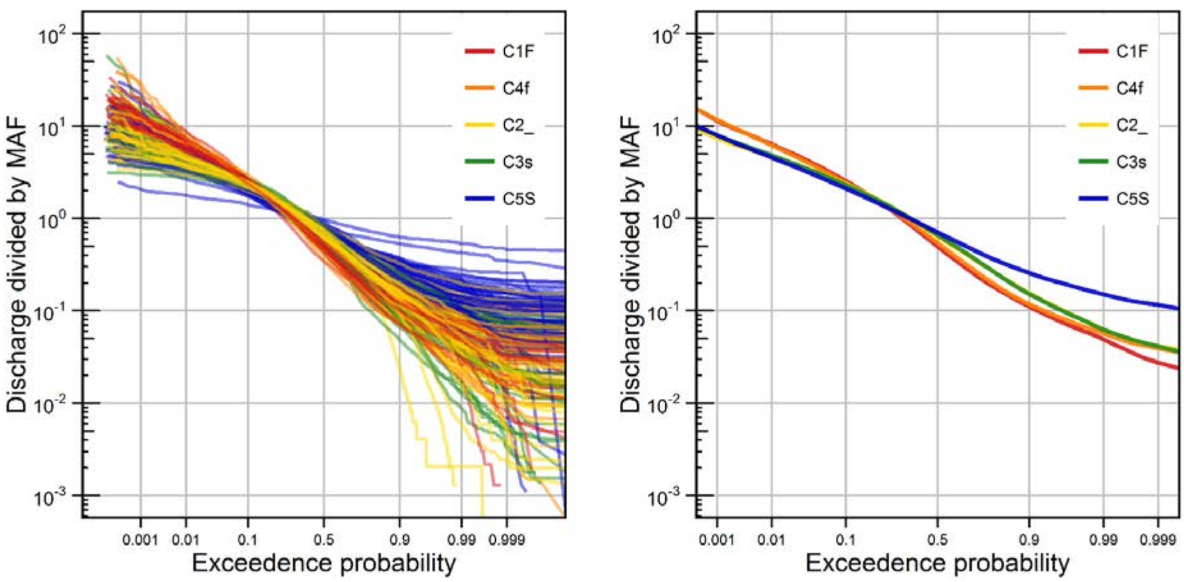


Figure 2.6. Flow duration curves showing daily flow scaled to mean annual daily flow plotted against exceedance probability; (a) individual flow duration curves for each station coloured by flow cluster and (b) averaged flow duration curves for each flow cluster.

members were not as compact and lay throughout the range of data from Cluster 1 and Cluster 5. Flashier flow conditions are indicated when the Q5 exceedance value is high relative to the Q95 value, while stable flow is suggested by lower divergence between the Q5 and Q95.

Similar patterns were shown for log-normal FDCs for each hydrometric station and averaged across members within a cluster (Figure 2.6). Flow duration curve steepness declined from Cluster 1, the low-BFI flashy cluster, to Cluster 5, the high BFI stable cluster, in a similar pattern as shown by the data in Figure 2.5.

To provide examples of differences in annual hydrographs in low-, medium- and high-flow years (Figure 2.7), we plotted daily flow data for cluster medoids, identified during the PAM clustering procedure as stations most typical of the cluster (see Table 4.1 for station information). These

Box 2.1. Flow regime characteristics of each cluster (see Figures 2.3 to 2.6)

Cluster 1 had higher values for rise and fall rates, higher frequencies of high and low pulses and higher numbers of reversals in flow compared with other clusters, indicating a flashier hydrology. Predictability and baseflow tended to be lower. Flow minima tended to be lower relative to the median flow, while maxima tended to be higher. Consequently, low-flow periods in June tended to be low, while high-flow periods in the autumn months were high. The divergence between Q5 and Q95 values was the highest and the FDC curves were the steepest of all clusters. This cluster is described as flashy (F).

Cluster 4 was more similar to Cluster 1 than to Cluster 5, with lower BFI and predictability, and higher maximum flows. Mid-to-late summer monthly flow was low. The relationships between Q5 and Q95 and between FDC curves were similar to those for Cluster 1. This cluster is described as moderately flashy (f).

Cluster 2 was similar to Cluster 1, in that summer flow (i.e July–September) tended to be high relative to MDAF and the number of reversals was low (similar to Cluster 3). This cluster was typed overall as moderate in the flashiness of flow. However, within-cluster variability in relationships between Q5 and Q95 was greatest for Cluster 2; therefore, there was uncertainty in defining a flow regime signature for this cluster.

Cluster 3 was considered most similar to Cluster 5 and was typed as moderately stable (s). It was distinguished from the other clusters by a tendency to a higher duration of both high- and low-flow periods. Like Cluster 4, mid-to-late summer monthly flow was low. Flow exceedance relationships and FDC curves were variable within this cluster and patterns were intermediate between Cluster 1 and Cluster 5.

Cluster 5 flow metrics were generally opposite to those of Cluster 1. Compared with other clusters, predictability and BFI were high, rise and fall rates and the number of reversals were low and minimum and maximum flows tended to be high and low, respectively. Q5 and Q95 were less divergent and the FDC curves were the flattest of all the clusters. This cluster is described as having stable flow (S).

graphs highlight the differences between the flashy hydrograph for Cluster 1, the more stable hydrograph with higher baseflow for Cluster 5 and the modulated flow shown by Cluster 2. Summer flow was often quite low for Clusters 3 and 4, and was at or below 30% of MAF, a level considered indicative of flows low enough to degrade fish habitats in North America and Canada (Caissie *et al.*, 2015).

2.4.4 Landscape characterisation of flow types

We applied the same set of exploratory tools that we applied for flow metrics in the previous section to identify relationships between landscape features and cluster membership. In this case, a strong relationship between flow cluster and landscape features would provide a means for predicting flow cluster membership for unmonitored stations for which the same landscape data were available.

Classification of flow clusters using landscape features produced an overall OOB estimate of an error rate of 36.8%. This error rate was higher than that estimated using flow metrics and indicated that the use of landscape features was successful in identifying cluster membership 63.2% of the time. As was seen for classification by flow metrics, the lowest classification errors (≈17%) were observed for Clusters 1 and 5, and the highest for Clusters 3 and 4 (greater than 50%) (Table 2.6).

Based on the RF analysis, the most important landscape features distinguishing clusters were the percentage of pasture over peat, the percentage of the catchment not intercepted by upstream lakes, precipitation, effective rainfall, the density of lakes larger than 10 ha and high-intensity agricultural land use (Figure 2.8). The patterns shown in boxplots (Figure 2.9) suggested that that there was a close relationship between clusters arranged in order of BFI and features reflecting the relative importance of surface or groundwater flowpaths (Box 2.2). This was particularly the case when distinguishing between end-members in flashy Cluster 1 (high-elevation and high-precipitation stations with thin or peaty soils) and

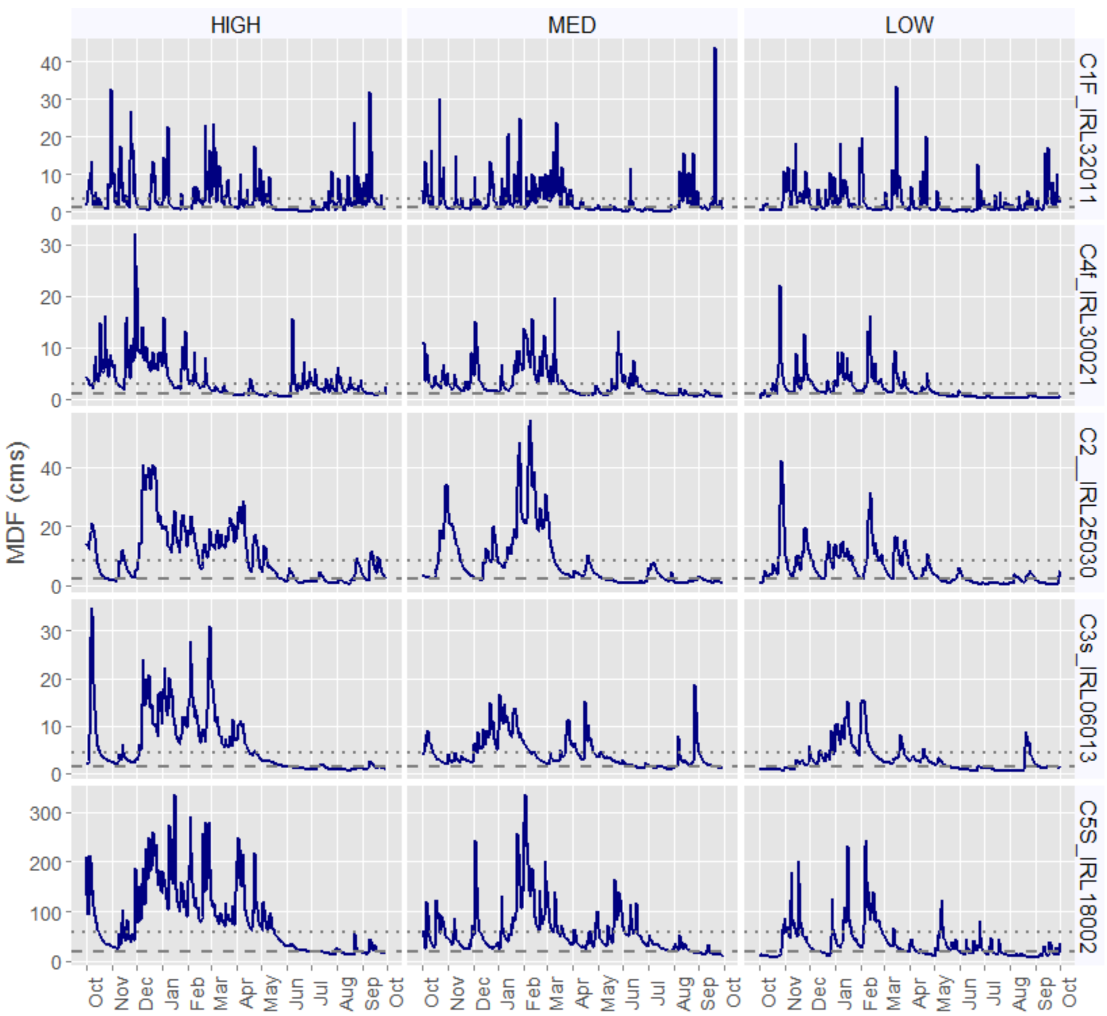


Figure 2.7. Annual hydrographs of daily flow in high, medium and low water years for the five-cluster medoid stations. The dotted line is the mean annual daily flow and the dashed line is 30% of the mean annual daily flow.

Table 2.6. Confusion matrix and classification error from Random Forest analysis of landscape features

		RF predicted cluster membership					Classification error
	Cluster	C1	C2	C3	C4	C5	
Observed cluster membership	C1	15	2	0	0	1	0.167
	C2	4	24	2	4	4	0.368
	C3	0	4	14	4	10	0.563
	C4	0	3	6	8	8	0.680
	C5	0	3	4	2	44	0.170

stable-flow members in Cluster 5 (lowland stations typically in well-drained soils).

Next in importance were features that reflected alteration of flowpaths as a result of the legacy of centuries of agricultural land use. This was most apparent for Clusters 3 and 4, which had substantial proportions of poorly and intermediate-poorly drained soils accompanied by the largest proportion of estimated human alterations by land drainage and channelisation.

Cluster 2 was distinguished from the other clusters by the influence of lakes ≥ 10 ha in surface area in the catchment, which are the likely cause of modulated flow regime; both the percentage of the catchment

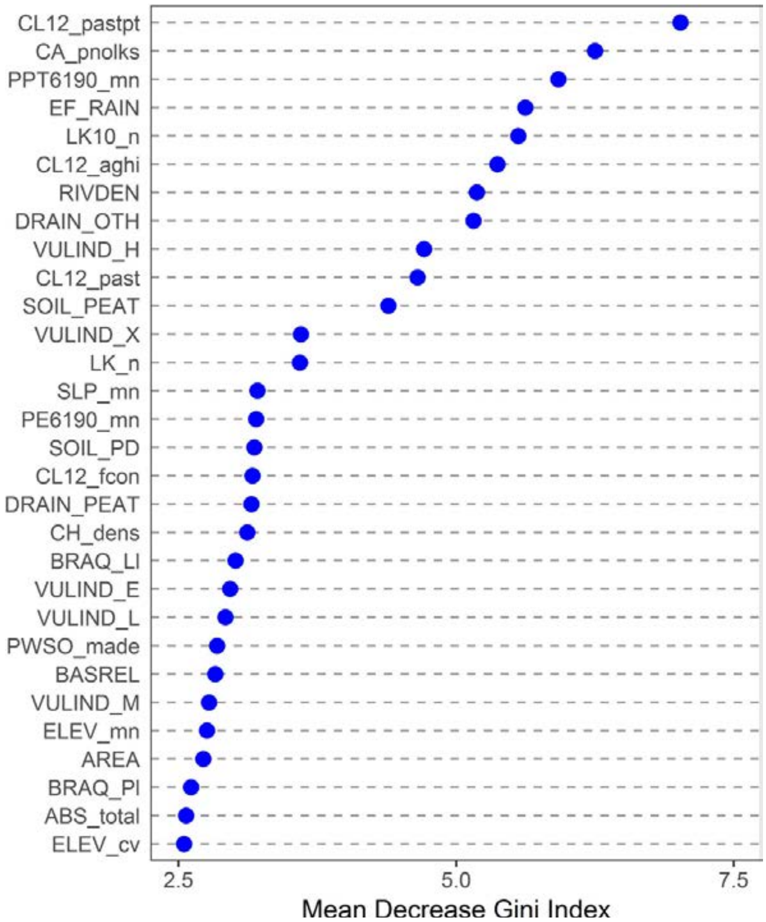


Figure 2.8. Predictor importance plot from Random Forest analysis of landscape features predicting cluster membership (see Table 2.3 for the landscape feature abbreviations).

intercepted by upstream lakes and the density of lakes ≥ 10 ha were high for this cluster. However, not all stations in this cluster were lake influenced. The subset of sites with little lake influence tended to have catchments dominated by moderately productive aquifers and more well-drained soils compared with the lake-influenced C2 subset, which included more karstic catchments. Both groups tended to have higher precipitation and be located at intermediate elevations.

Geographically, Clusters 1–5 were not distributed randomly across Ireland but showed spatial structure (Figure 2.10). Cluster 1 hydrometric stations tended to be in the north-west or near the coast. Those in Cluster 2 tended to be in the west, with the exception of one eastern station in the Wicklow Mountains. Clusters 3–5 stations tended to be located in the central, southern and south-eastern parts of the country. These spatial patterns in cluster membership overlapped with landscape features as shown in the maps in Figure 2.11.

2.5 Recommendations for Flow Regime Clusters

2.5.1 Flow regime clusters: a first step towards defining flow types in Ireland

The five flow clusters defined here are reasonable from the perspective that the flow characteristics align reasonably well with landscape features summarised in Table 2.7 and highlighted in the conceptual diagrams of water flow shown for each cluster in Figure 2.12. The dominant natural features influencing cluster membership, elevation/precipitation, soil drainage and dominance of surface and groundwater flowpaths, would be considered typical of features influencing flow regime in Ireland. A strikingly similar set of natural features was found to be the set that gave the best prediction of BFI in Ireland in a study by the OPW (2009). They found that the top predictors of BFI were, in order of weighting, well-drained soils, landcover from water bodies, FLATWET (a soil

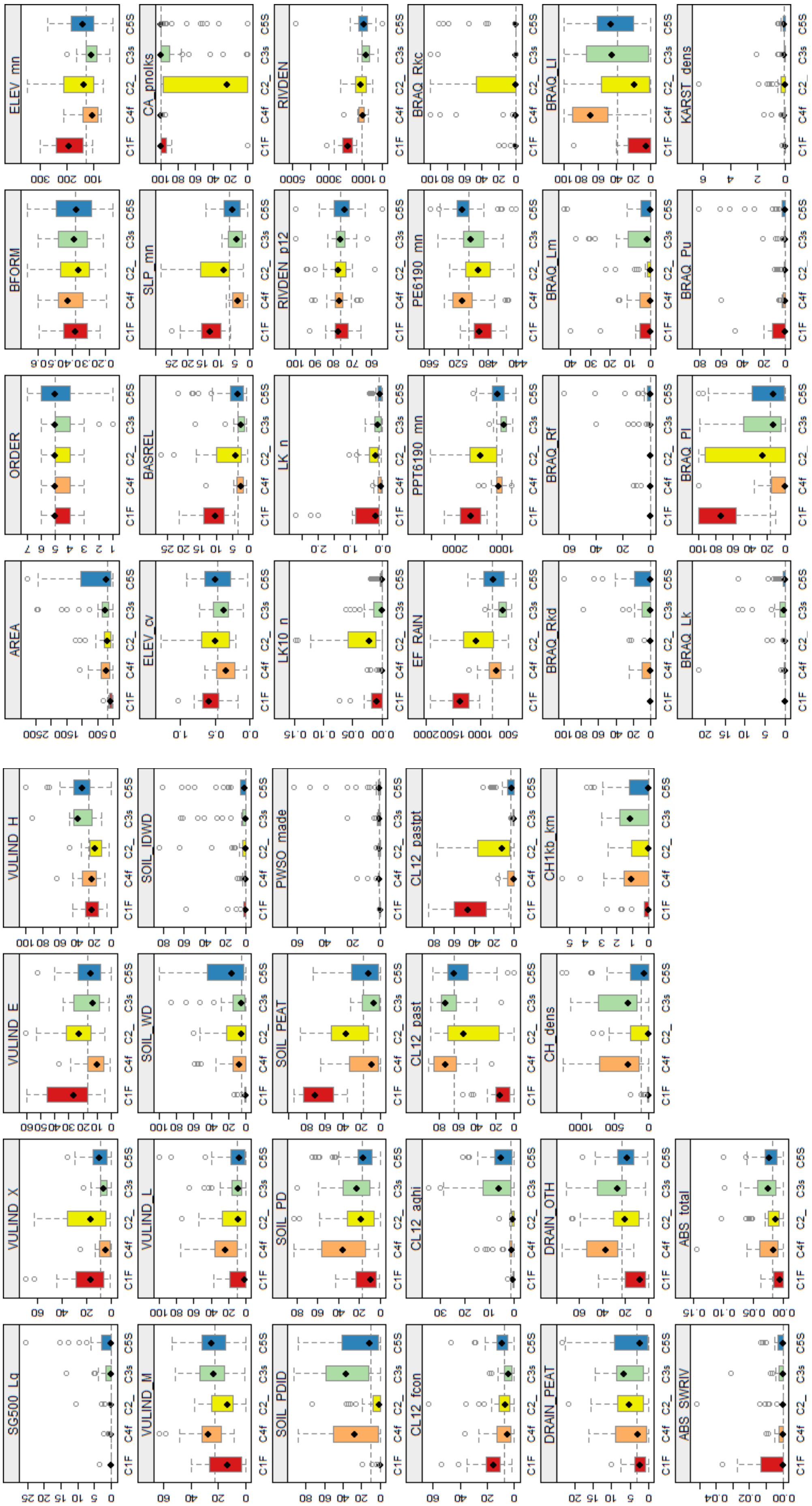


Figure 2.9. Boxplots of landscape features from the 166 hydrometric stations grouped by cluster. The dashed line is the median value (see Table 2.3 for the landscape feature abbreviations).

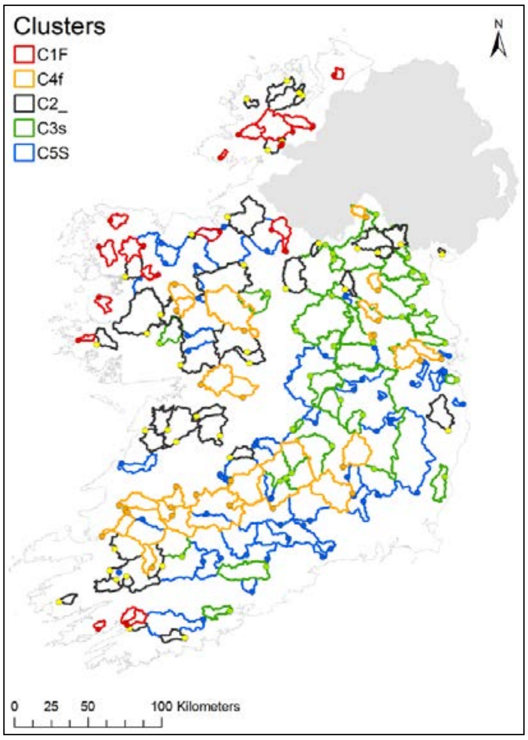


Figure 2.10. Catchments of 166 hydrometric monitoring stations colour coded by cluster membership. Outlines show catchment boundaries; dots are hydrometric station locations.

Table 2.7. Overview of hydrogeology, climate and pressures influencing the five flow clusters

Flow cluster	Baseflow index	Elevation/slope	Location	Soils drainage	GW Vul (subsoil impermeability)	Bedrock aquifer	Climate	Landuse	Potentially modified land drainage	Channelisation
C1F	Low	High	NW	Peat	Very high (X, E)	Poor Prod	High PPT	Past-peat & forest	Low	Low
C4f		Low		Poor	Low–Mod	Mod Prod	High PE	Past	High	High
C2		Mod	Not in SE	Peat and poor	High (E, X) to Mod	Poor and Karst	Mod PPT	Past & past-peat	Mod	Mod
C3s		Low	EA and SE	Poor to int	Mod to High	Local	Low PPT	Past & arable	High	High
C5S	High	Low–Mod		Well	High	Local reg; S&G	High PE	Past & arable	Mod	Mod

GW Vul, groundwater vulnerability; Mod, moderate; Mod Prod, moderately productive; Poor Prod, poorly productive; PPT, precipitation; S&G, sand and gravel.

wetness index we did not use), poor aquifer availability (e.g. unproductive bedrock), low subsoil permeability (e.g. groundwater vulnerability index), poorly drained and moderate permeability soils.

In addition to depicting the importance of landscape features influencing hydrologic flowpaths, these analyses demonstrated the influence of catchment alterations related to agricultural activities on flow regime. Catchments of rivers in the two least stable clusters, Clusters 3 and 4, tended to have relatively high estimated land drainage, which is likely to be a result of poorly drained lowland soils and channelisation. We hypothesise that these hydromorphological modifications have altered

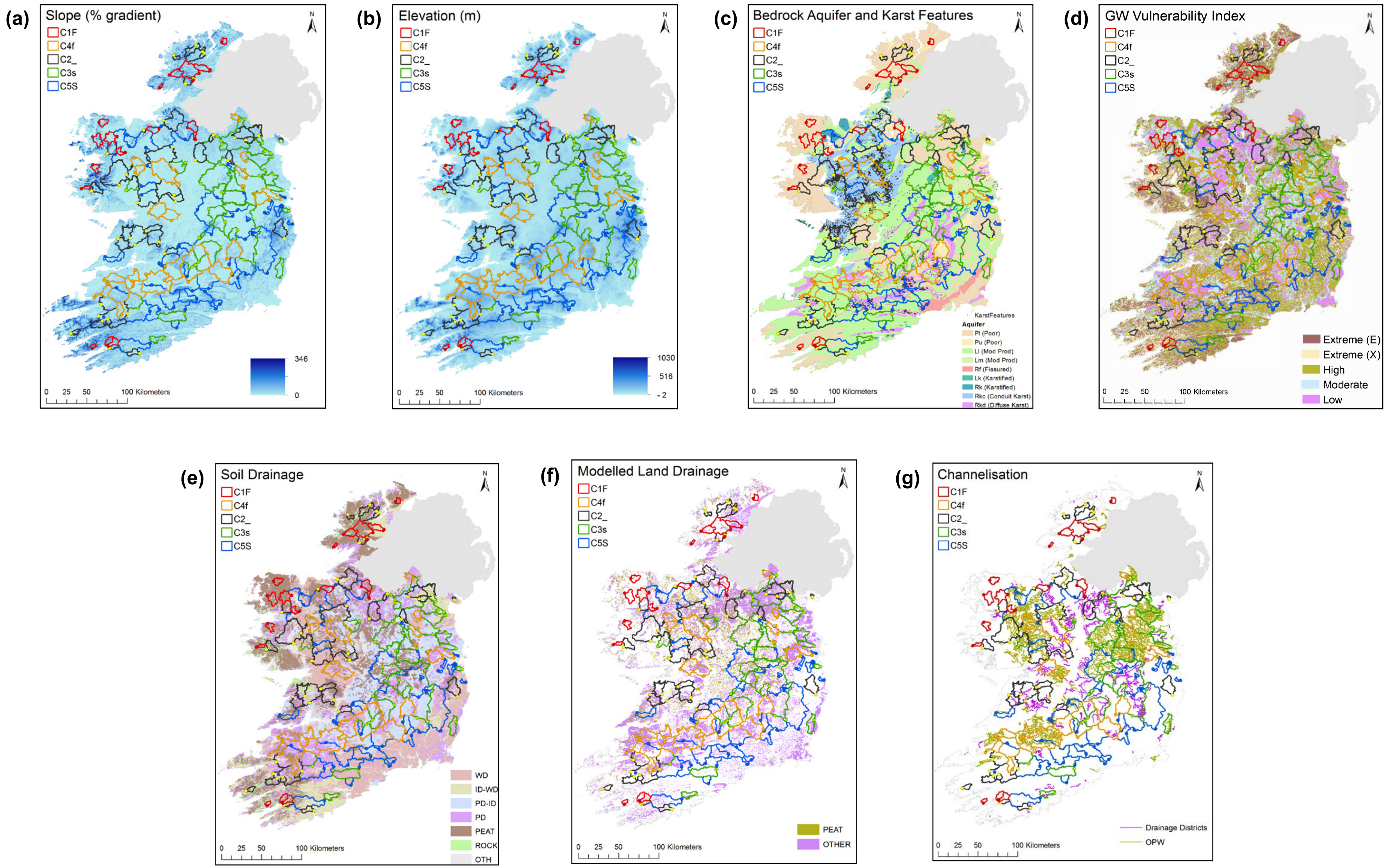


Figure 2.11. Maps of landscape features with catchment boundaries of hydrometric stations, colour coded by cluster membership for (a) slope [the blue shading indicates the gradient of the slope as a percentage of the change in elevation (m) over distance (m)]; (b) elevation [the blue shading indicates the elevation in metres (from –2 to 1030 m)]; (c) bedrock aquifer type and location of karst features (black dots); (d) groundwater vulnerability index; (e) soil type by drainage (WD, well-drained; ID, intermediate; PD, poorly drained, OTH, other); (f) land drainage modelled by the EPA using data from Mockler *et al.* (2014); and (g) channelisation of rivers from data maintained by the OPW and drainage districts.

Box 2.2. Landscape characteristics of each cluster (see Figures 2.8–2.11)

Cluster 1 (F): This flashy cluster had relatively high percentages of catchments characterised by peat soils and pasture over peat that were higher in elevation, slope and basin relief. Subsoils tended to be thin (as indicated by high proportions of Groundwater Vulnerability Indices E and H) and bedrock aquifers tended to be poor (Pl). These results are indicative of steep upland rivers with a geomorphology typical of flashy flow in the Irish context. These stations are located along the west coast of Ireland (Figure 2.10). *Flowpath: surface water dominated.*

Cluster 4 (f): Soils tended to be poorly drained, aquifer type was mainly moderately productive (LI), and groundwater vulnerability index values tended to be low and moderate categories. These stations were typically lowland sites with low catchment relief and slope. Precipitation and effective rainfall tended to be low and potential evapotranspiration PE high. Pasture was the dominant agricultural land use. The catchments of stations in this cluster had the highest values for the proportion of drained soils (DRAIN_OTH) and channelisation density was higher than for all other clusters, with the exception of Cluster 3. These stations are located within the interior of the country, as are Clusters 3 and 5. *Flowpath: surface water dominated.*

Cluster 2: The primary distinguishing characteristic for two-thirds of stations in this cluster was the low percentage of the catchment that was not intercepted by upstream lakes and the high number of larger lakes (> 10 ha) in the catchment; these two characteristics suggest that a strong influence on flow regime results from the interception of flow by upstream lakes. This cluster was notable for high late-summer flow and few flow reversals, which makes sense when considering the modulating influence of lakes on flow regime. Cluster 2 stations are located in all areas of Ireland, except for the south-east where large lakes are lacking. *Flowpath: lake dominated.*

Cluster 3 (s): Soils in this cluster were typically poorly (PD) to intermediate (ID) drained and there was very little distinction with respect to bedrock aquifer type. Groundwater Vulnerability Indices were dominated by medium and high categories. Like Cluster 4, these rivers also had lowland catchments with little relief. Precipitation and ER were low. Catchment land use was dominated by pasture with a high incidence of high-intensity agriculture; land drainage and channelisation density were higher than in other clusters. *Flowpath: groundwater dominated.*

Cluster 5 (S): Landscape features of note include relatively large catchment areas, a relatively high number of sand/gravel aquifers and, although this is not wholly distinctive, a subset of catchments with bedrock aquifers coded as diffuse-flow karst (Rkd). Soils were often more well-drained than for other clusters, elevations covered a wider range than for Cluster 3 and 4 and lakes in the catchment were at very low densities. Soil drainage and channelisation tended to be low. Precipitation and ER are low to average, but PE tended to be high. *Flowpath: groundwater dominated.*

"natural" flow regimes in heterogeneous ways, causing higher between-site variability and preventing detection of strong flow clusters.

The next step in the ELOHA framework (Figure 1.3) would be to estimate cluster membership for unsampled stations based on landscape characteristics and to use predictive methods, such as RF analysis. We had a few concerns regarding future implementation of this next step. First, the study hydrometric stations may not be representative of all river locations of interest, as they were biased towards larger catchments relative to all the ungauged river stations in Ireland (Figure 2.13) and most were of order 3–5, with headwater rivers under represented (see Table 2.1). Any confidence in extrapolation would have to be made to stations with characteristics represented by the range of stations used to develop the clusters. The procedure we utilised in this study is a "classify then predict" approach that is considered more statistically robust than deriving flow clusters from landscape features; however, this "predict then

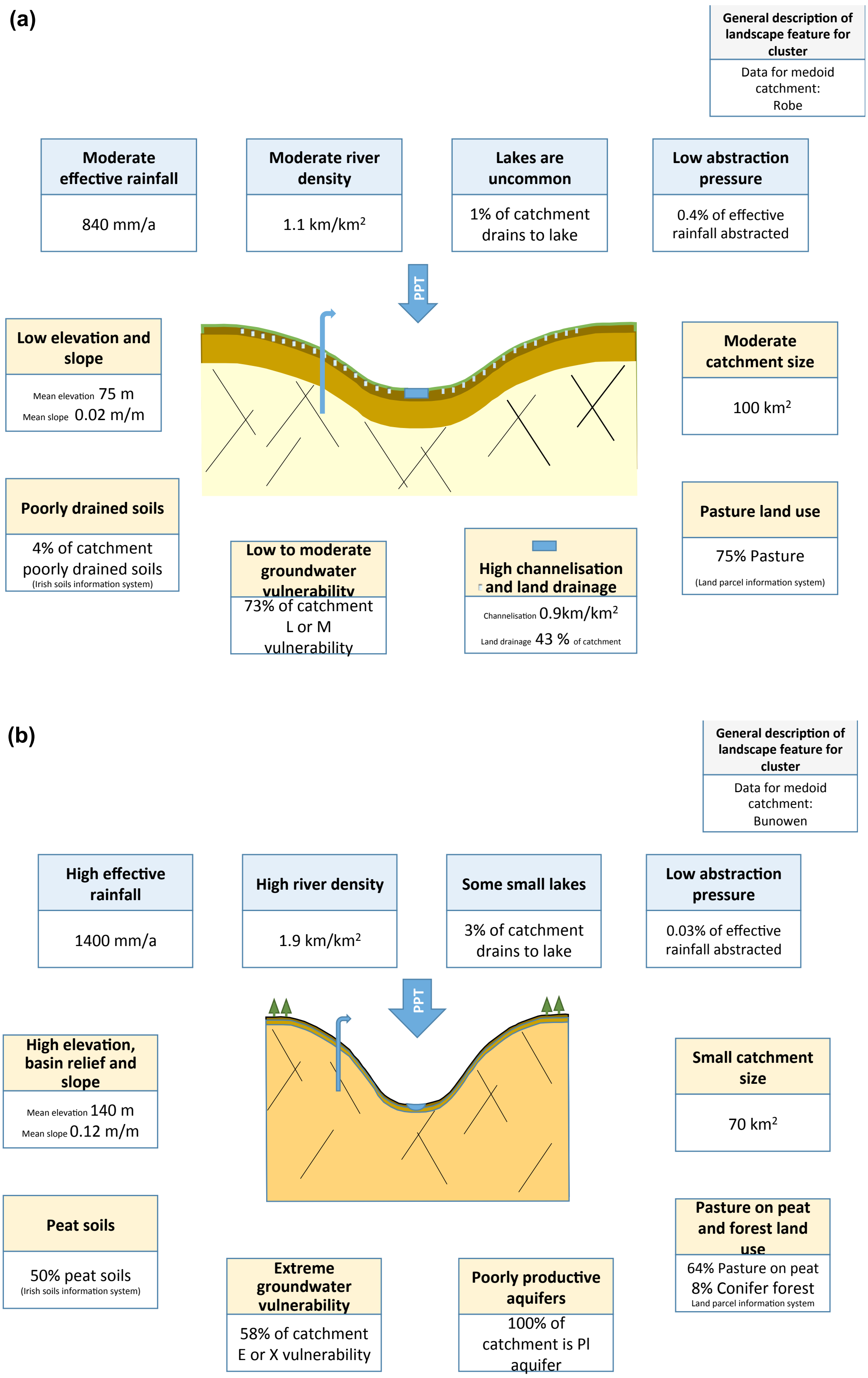


Figure 2.12. Representation of hydrogeology using data for medoids from (a) flashy Cluster 1 and (b) moderately flashy Cluster 4. Ll, bedrock that is moderately productive only in local zones; Pl, bedrock aquifer that is generally unproductive except for local zones; Rkd, regionally important karstified aquifer dominated by conduit flow.

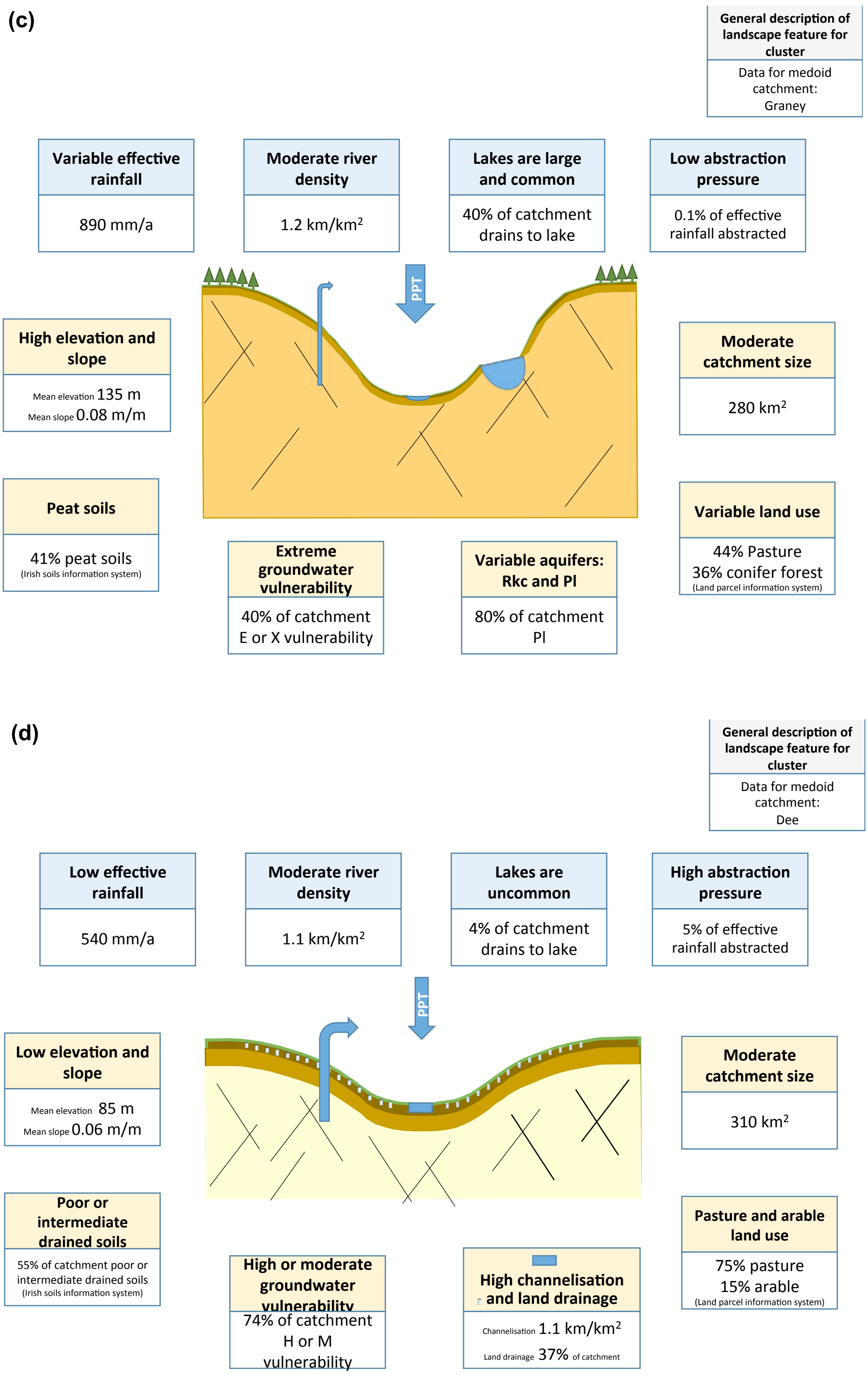


Figure 2.12. continued. Representation of hydrogeology using data for medoids from (c) intermediate lake-influenced Cluster 2; (d) moderately stable cluster 3. "Pasture on peat" is the land parcel information system's pasture over unimproved land; channelisation is defined by the OPW as arterial drainage and local area drainage district schemes of rivers; in (b) land drainage was calculated from the Predicted Land Drainage map (EPA and Mockler *et al.* 2014); and in (c) large lakes are defined as >10 ha. Ll, bedrock that is moderately productive only in local zones; Pl, bedrock aquifer that is generally unproductive except for local zones; Rkd, regionally important karstified aquifer dominated by conduit flow.

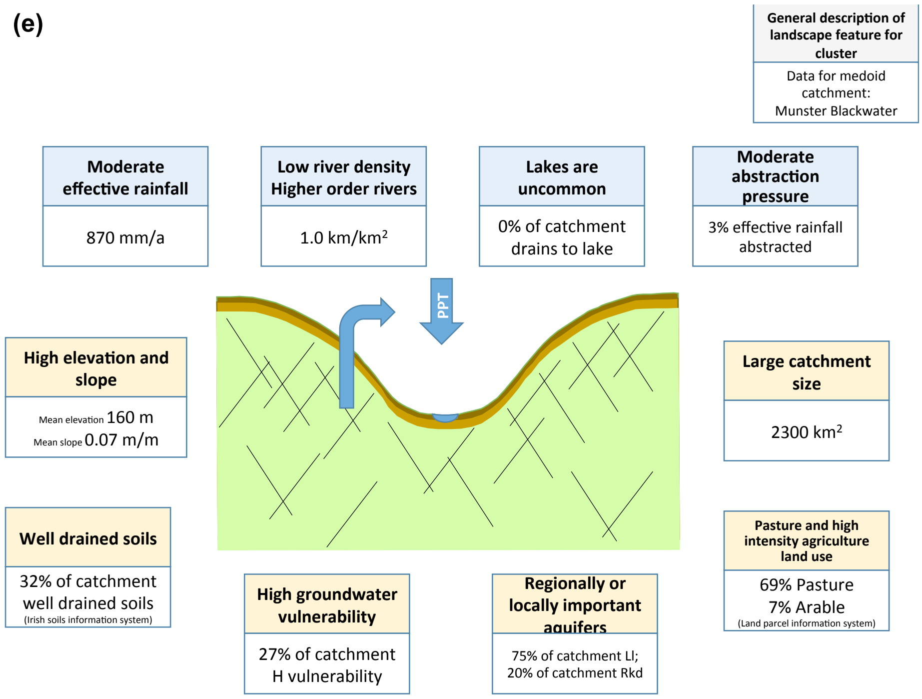


Figure 2.12. continued. Representation of hydrogeology using data for medoids from (e) stable Cluster 5. LI, bedrock that is moderately productive only in local zones; PI, bedrock aquifer that is generally unproductive except for local zones; Rkd, regionally important karstified aquifer dominated by conduit flow.

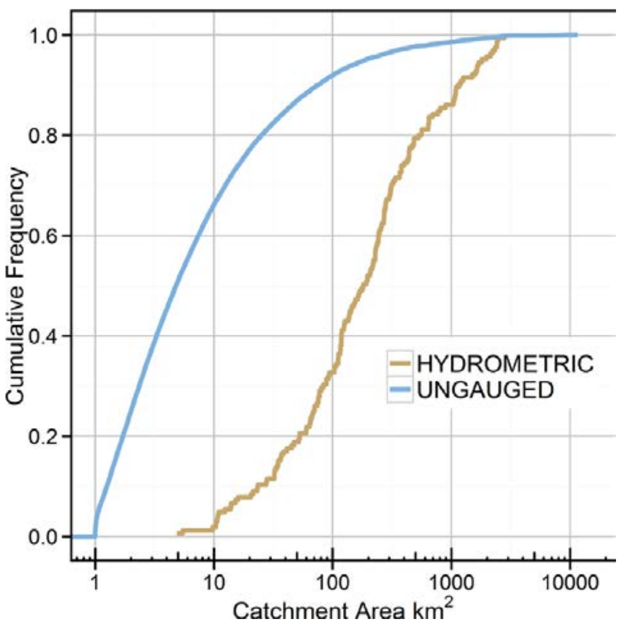


Figure 2.13. Cumulative frequency diagram showing the distribution of catchment areas in the hydrometric stations used in this report (brown line) compared with that of ungauged river catchments (blue line) (based on 2015 EPA data on the catchment areas of ungauged river stations in Ireland used for the OPW's Flood Studies Update project).

classify" approach, where relationships between individual flow metrics and landscape features are defined and used to generate flow metrics for unmonitored locations, followed by a classification applied to the entire population of rivers, can provide a way to assess flow classes that are rare or underrepresented (Snelder and Booker, 2012; Peñas *et al.*, 2014).

Second, the hydrologic foundation steps in ELOHA should rely on data from reference sites that are not subject to abstraction pressures. However, a complete database on abstraction intensity within each catchment was not available when we began this work; it was only at the end of the project that we obtained estimates of abstraction as a proportion of effective rainfall (Chapter 3). Further, large parts of Ireland are agriculturally influenced (Figure 2.11), making identification of catchments that are without significant pressures, but have sufficient flow data, impractical. Therefore, the flow classes described here include river sites that are not likely to reflect background flow conditions but, in contrast, are likely to reflect current realities in flow status for Irish rivers for which abstraction pressures have historically been on the low side.

We conclude that the best application of the cluster results is to understand interacting controls on flow regime – mainly to do with flowpath-related features (surface–water versus groundwater influence; soil drainage) that must be considered in the context of agricultural activities in catchments (in particular, field drainage and channelisation). We recommend that development of future flow classes in Ireland for use in applying abstraction-licensing frameworks should consider the following features as of particular interest in distinguishing different flow types:

1. Upland flashy systems had the most distinctive flow signature and, combined with their location in sensitive landscapes and landscapes that are likely to be protected, need to be considered as a separate class.
2. Lake-influenced rivers have flow regimes that are affected by water storage and release from upstream lakes; this modulates the direct relationships between flow and precipitation.
3. Lowland rivers in well-drained soils, which may be less influenced by channelisation and drainage, had the second-most distinctive flow signature with a high BFI. However, intensive agriculture is likely to interact strongly with flow regime, particularly with respect to other stressors influencing rivers, such as nutrient enrichment and silt flux, and multiple stressors are likely to be influential.
4. In intensively farmed agricultural areas with poorly drained soils, we have evidence that artificial field drainage and channelisation may be influencing flow regime. There are flow metrics that provide an indication of separation between what appear to be surface-water- and groundwater-dominated rivers, but predictability is poor.

2.5.2 *Application of the UK flow type classification to Irish rivers*

To determine whether the clusters we developed aligned with the flow classification used in the UK to set environmental flow standards (SNIFFER, 2006), we applied their classification tree (Figure 2.14) to the study hydrometric stations. The factors used to classify sites are precipitation (SAAR represents long-term annual precipitation), catchment area and BFI calculated from HOST soil type. The results reported in OPW (2009) could be used in the future to develop

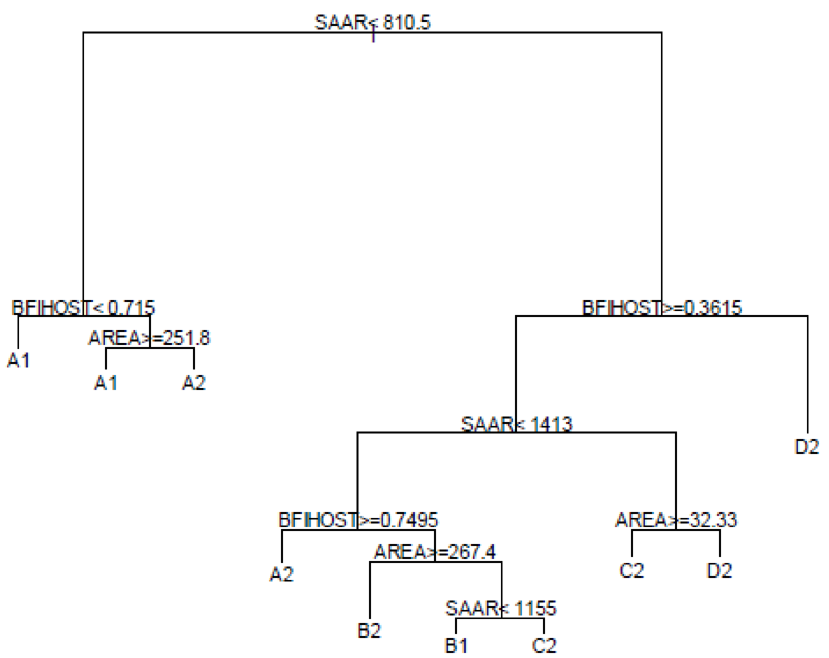


Figure 2.14. Decision tree to identify flow classes for river typology used in the UK to set environmental flow standards. SAAR is long-term average rainfall (mm); BFIHOST is baseflow index calculated from HOST soil type; AREA is catchment area (figure and definitions from SNIFFER, 2006).

a similar index to the HOST soil classifications used in the UK; for this example, we substituted BFI estimates derived from the flow data.

This exercise classified 159 of the 166 hydrometric stations as D2, which are high-gradient, high-altitude, low-order bedrock/boulder types. Five were classed as A2 (low altitude, eutrophic, silty clay). The remaining two were classified as Type B, described as hard sandstone/calcareous shale mesotrophic stations.

It is likely that the high precipitation in Ireland compared with that in the UK means that this type of system is not sensitive to conditions in Ireland, where higher precipitation has the result that the majority of the study rivers, with the exception of those in Cluster 5, fall in the low BFI range, based on the ratio between Q95 and Qmean. Forty per cent of all stations were in the flashy range (ratio < 0.1), including the majority of Cluster 1 stations (Figure 2.15). High and very high BFI values categories (ratios in excess of 0.2 and 0.4, respectively) were generally restricted to Cluster 5 stations. The "flashier" Irish rivers are likely to require a different set of criteria to capture flow types from those built into the UK system. Further development of a flow classification scheme for Ireland could utilise the BFI predictive model that was developed by the OPW to extend resolution into the flashier flow range in the UK scheme with the aim of developing a more widely applicable classification for Irish rivers. In this classification process, BFI was one of the main flow metrics that distinguished between flow clusters (Figures 2.3 and 2.4) that differ in multiple flow metrics used to assess potential ecosystem effects of altered flow regime.

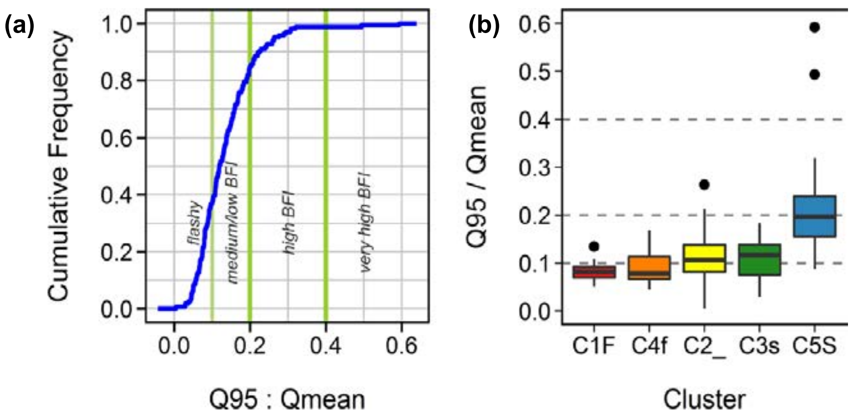


Figure 2.15. Application of UK flashiness criteria based on the ratio between Q95 and mean daily flow (Qmean) for (a) cumulative frequency distribution for the 166 hydrometric stations and (b) boxplots by cluster

3 Abstraction Pressures in Ireland

3.1 Objective

The second objective was to provide an assessment of current abstraction pressures on Irish rivers. This objective corresponds to the first part of Step 3 of the ELOHA process, assessing the degree of flow alteration. At the time of this work, a comprehensive database of abstraction pressures currently influencing rivers in Ireland was not available. The goals of Chapter 3 were to compile and summarise abstraction pressures in Ireland and provide an initial assessment of the impact of the abstractions on river flow.

3.2 Historical Perspective

Ireland generally has low abstraction pressures (Figure 3.1) and is classified as having "little of no water scarcity" by the UN World Water Assessment Programme (UN, 2012). The European Environment Agency calculated Ireland's Water Exploitation Index (defined as the annual water abstraction as a percentage of long-term available water) as one of the lowest in Europe, at less than 10% (EEA, 2012; Figure 3.2). This low abstraction pressure is a result of Ireland's high effective rainfall and relatively low population and industrial density.

The existing abstraction controls in Ireland [e.g. via Environmental Impact Assessment (EIA) and planning laws] do not fully satisfy requirements of the WFD (Dublin City Council *et al.*, 2009). Article 11.3e (Programme of Measures) of the WFD requires the following minimum requirements to be complied with:

> Controls over the abstraction of fresh surface water and groundwater, and impoundment of fresh surface water, including a register or registers of water abstractions and a requirement of prior authorisation for abstraction and impoundment. These controls shall be periodically reviewed and, where necessary, updated. Member States can exempt from these controls, abstractions or impoundments that have no significant impact on water status.

Abstraction risk to Irish water bodies was quantified during the first cycle of the WFD in the Article 5 Risk Assessments (CDM, 2008, 2009; EPA/RBDCA, 2005). The revised risk assessment found that approximately 5% of river water bodies were "at risk" or "probably at risk" of failing to comply with the abstraction criteria of the WFD's objective to obtain good status by 2015 unless measures are taken in the meantime (CDM, 2008; Table 3.1). River water bodies were characterised as "at risk" of not achieving good status as a result of abstraction pressures, based on the ratio

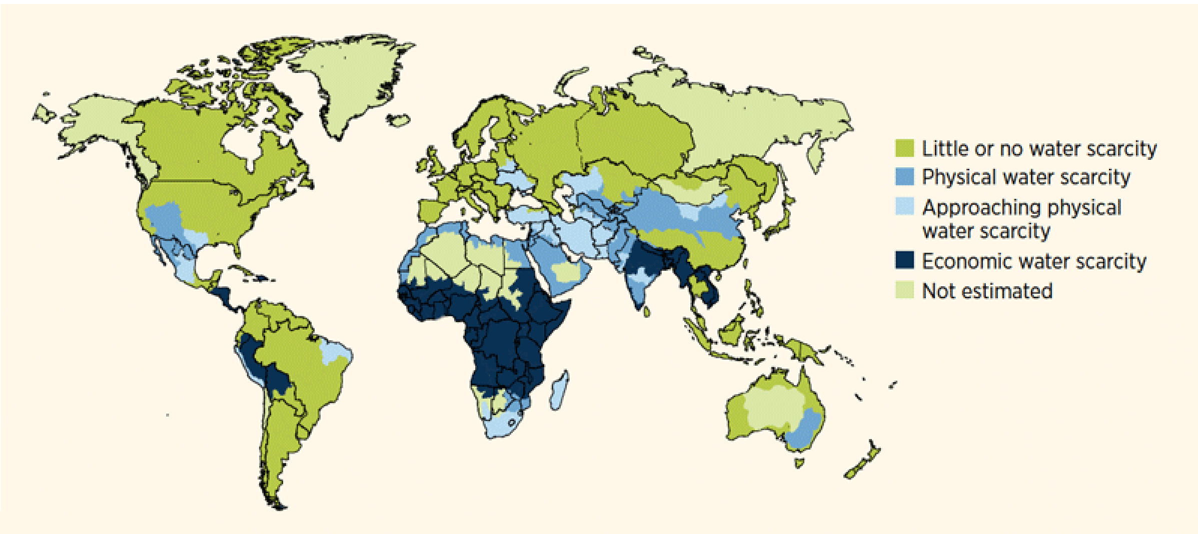


Figure 3.1. Global physical and economic water scarcity (UN, 2012).

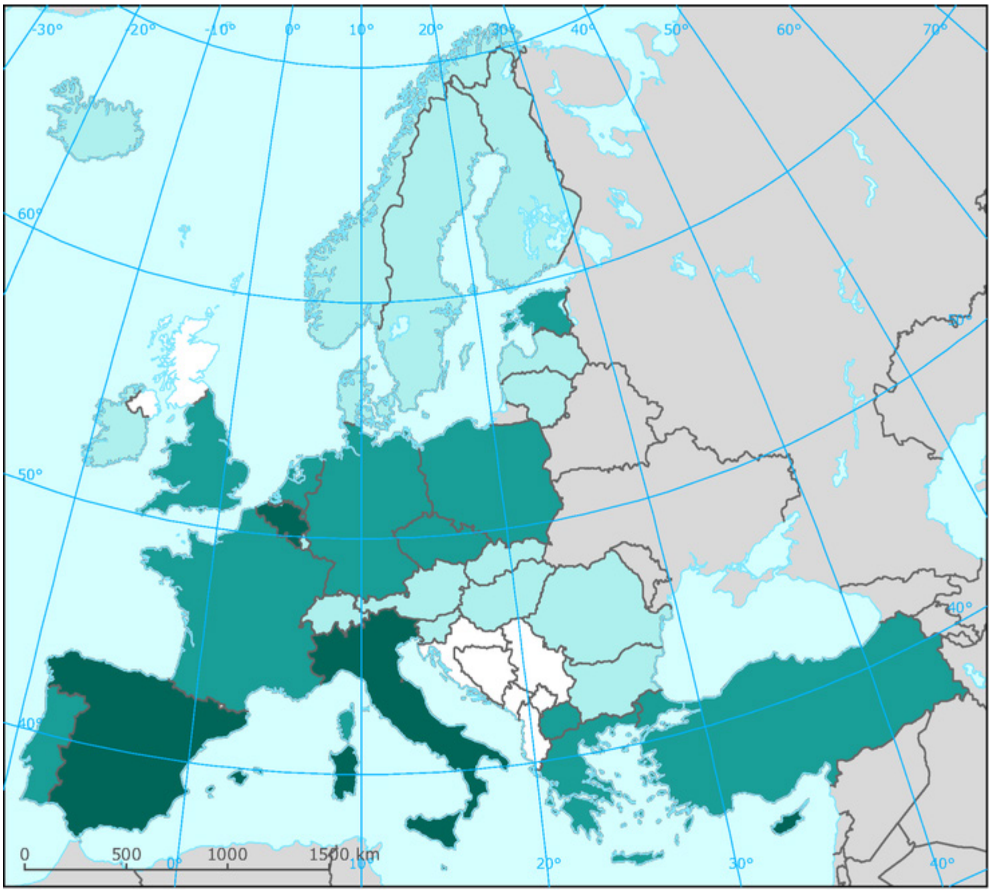


Figure 3.2. Water Exploitation Index using 2009 or latest available data (from EEA, 2012).

Table 3.1. The number of river water bodies “at risk” or “probably at risk” of failing to comply with the abstraction criteria of the Water Framework Directive’s objectives, from 2005 and 2008 risk assessments

Risk category	Risk class	Number of river water bodies in each risk category	
		Initial risk assessment[a]	Revised risk assessment[b]
2b	Not at risk	4201	4168
2a	Probably not at risk	64	60
1b	Probably at risk	107	141
1a	At risk	95	97

[a]**EPA/RBDCA, 2005.**

[b]**CDM, 2008.**

of net surface water abstraction to low flow (defined as Q95). The thresholds used to define risk are shown in Table 3.2. Risk assessments for the other water body types found that 16% of lakes and 6% of groundwater bodies were “at risk” or “probably at risk” of not achieving good status due to abstraction pressures (CDM, 2009). At a EU level, excessive abstraction significantly affects 10% of surface water bodies and 20% of groundwater bodies (EC, 2015b).

3.3 Abstraction Databases Used to Estimate Abstraction Pressure

Abstraction data for this project were compiled from a number of disparate sources (Table 3.3) and compiled into a national ArcGIS geodatabase. Abstraction data were sourced from personnel within the Department of the Environment, the ESB, Irish Water and the National Federation of Group Water Schemes and

Table 3.2. Risk categories and thresholds for revised river risk assessment

Risk Category	Risk class	Threshold value of net abstraction[a] to low-flow ratio
2b	Not at risk	<5%
2a	Probably not at risk	5–10%
1b	Probably at risk	10–40%
1a	At risk	>40%

[a]Net abstraction was calculated using only surface water abstractions.

Table 3.3. Features and limitation of each data sources used to compile a national abstraction geodatabase

Layer name (data source)	Features	Limitations
Draft National Abstraction inventory (Department of the Environment)	Good national summary	Many abstractions unknown, often no XY data
Catchments team south-east pilot project (EPA)	Regional register including different sources	Many abstractions unknown, often no XY data
IPPC register (EPA)	Includes industrial abstractors	No abstraction information, proxy data in licence documents, time consuming to compile
Power generators (ESB/IPPC register)	Includes abstractions for power generation	Abstraction (proxy) data is limited to licence details, limited XY data
GIS abstractions (EPA)	National coverage	No abstraction information, unknown source
CDM national abstraction register (EPA/CDM, 2009)	National register including different sources	Many abstractions unknown, now out of date
Public water supplies (Irish Water)	Most up to date Public Water Supply dataset	Many abstractions unknown
Group Water Schemes (National federation of group water schemes)	Most up to date Group Water Scheme dataset	Many abstractions unknown, limited dataset

a number of sections within the EPA (Hydrometric and Groundwater Section, Catchment Science & Management Unit, Office of Climate, Licensing, Research and Resource Use). Table 3.3 outlines the features and limitations of the databases used.

The limitations of each of the contributing databases (Table 3.3) apply equally to the final geodatabase. Many details of known abstractions are missing or inaccurate (e.g. location, abstraction volume, status of abstraction, etc.). Further, many more abstractions are unknown. However, the abstractions geodatabase was required to provide an estimate of the current abstraction pressures in Ireland. With these limitations in mind, results from these analyses should be used with caution. An accurate national abstraction database will be essential for future work assessing the impacts of abstractions on Irish rivers.

A number of projects are ongoing to address the paucity of abstraction data in Ireland, which will be of use to future research. These projects include the EPA Catchment Science & Management Unit's National Abstraction and Discharge project; the Department of the Environment's Abstraction Working Group and Irish Water's Abstraction Review.

When compiling the abstraction geodatabase for this project, the following assumptions or calculations were made:

1. Data on how abstraction volumes vary with time were not available from any of the data sources. Therefore all abstractions are assumed to be operating on a steady state basis.
2. Where data for intensive agricultural abstractions (e.g. pigs and poultry) were not available, estimates were made using animal numbers from individual IPPC licences and water consumption rates outlined in the draft Best Available Techniques reference document for the Intensive Rearing of Poultry and Pigs (JRC, 2015).
3. Abstraction points without location details were omitted from the geodatabase.

4. Duplicate abstraction points that overlapped with another point with the same location and name were removed.
5. Where two abstraction points with the same name and location overlapped with different abstraction values, the most recent data point was retained in the database.
6. The geodatabase is unlikely to capture all domestic, non-intensive agricultural or irrigation (e.g. golf courses) abstractions.
7. The GSI's Groundwater Wells database (GSI, 2007) was not included in the abstraction geodatabase but would be a valuable inclusion to future work.

The final database comprises over 4,600 abstraction points, which collectively abstract in excess of 5,382,000 m^3 of water per day (Figure 3.3). Over 1000 of these locations (23%) have no abstraction volume data. Figure 3.4 shows the location and volume abstracted by selected large abstractions (with abstraction volumes in excess of 10,000 m^3/d). These abstractions include public water supplies, industry supplies and energy generation locations.

The geodatabase shows that there are many more, smaller groundwater abstractions than surface water ones. Fifty-seven per cent of abstraction points are from groundwater sources, while groundwater only represents 17% of the volume of water abstracted. The source of water for 25% of the abstraction points is unknown (Figure 3.5 and Table 3.4).

Sixty-three per cent of the abstractions (by number of abstraction points) are used for drinking water supplies, including public water supplies, group water schemes and domestic supplies; 5% are used for industry, including mining, quarrying, food and drink production and electronics; 3% are used for intensive agricultural (i.e. pigs and poultry) and 0.2% for energy generation. Over 1330 abstraction points, 29% of those in the geodatabase, have an unknown use (see Figure 3.6 and Table 3.5).

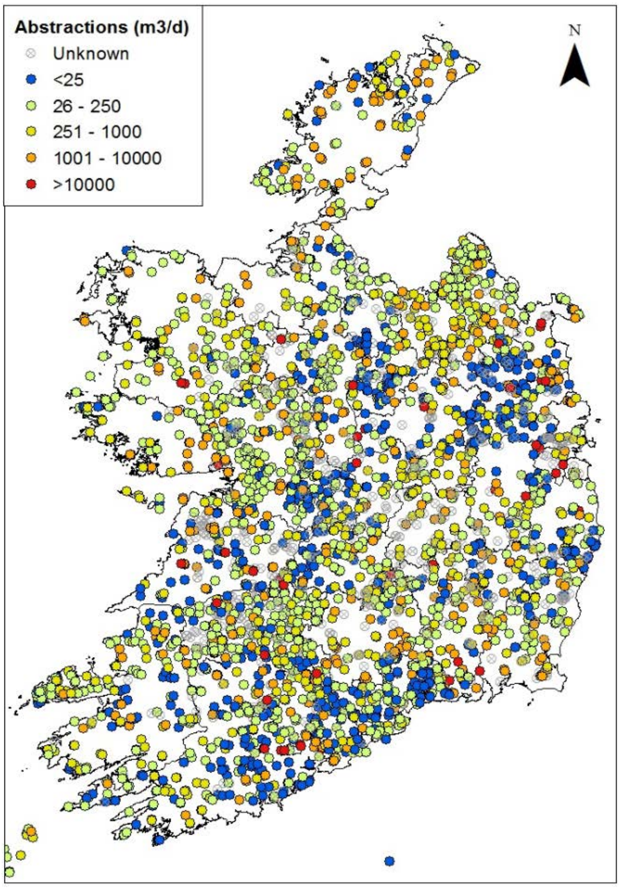


Figure 3.3. National abstraction geodatabase showing abstractions points categorised by abstraction volume.

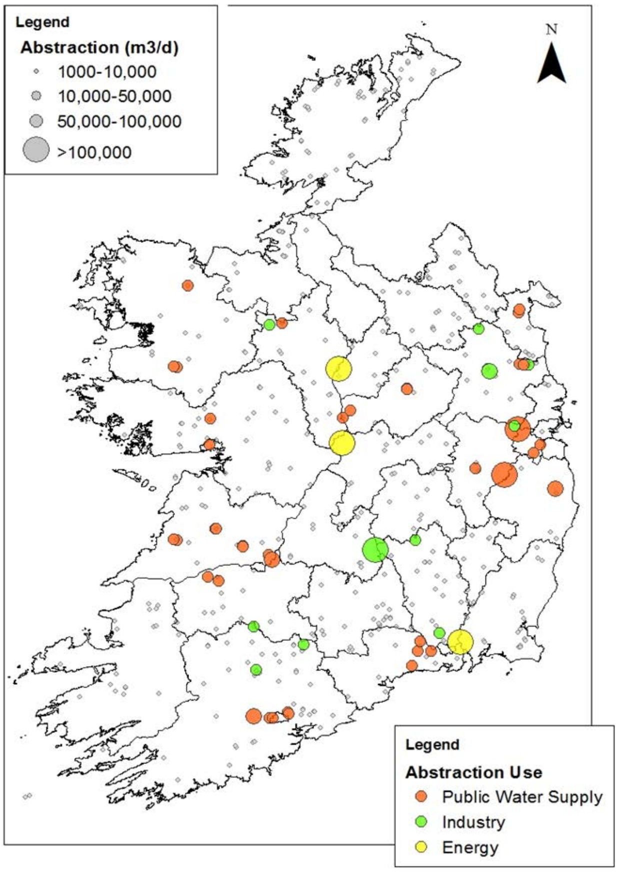


Figure 3.4. Location and volume abstracted by selected large abstractions (abstraction volumes in excess of 10,000 m^3/day.

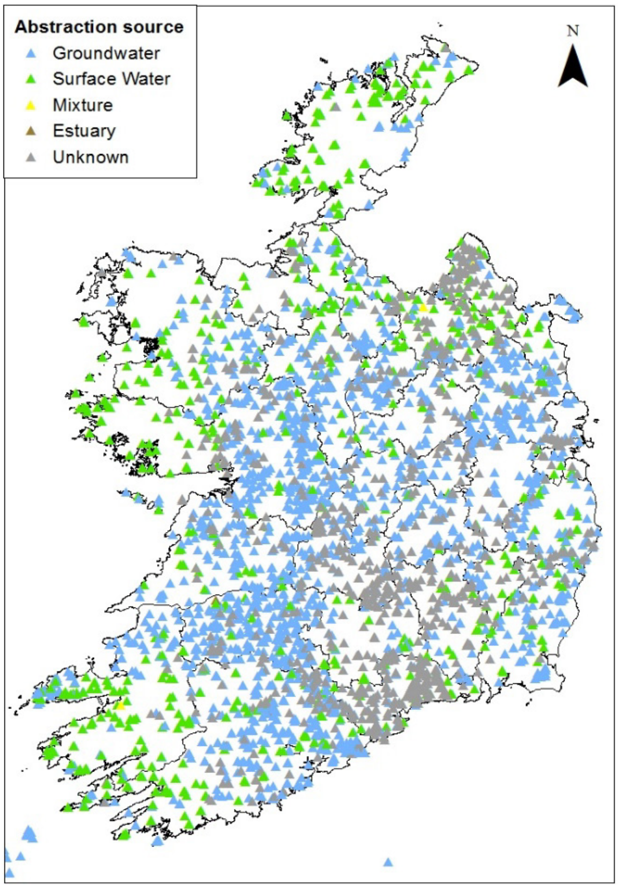


Figure 3.5. National abstraction geodatabase showing abstraction points categorised by water source.

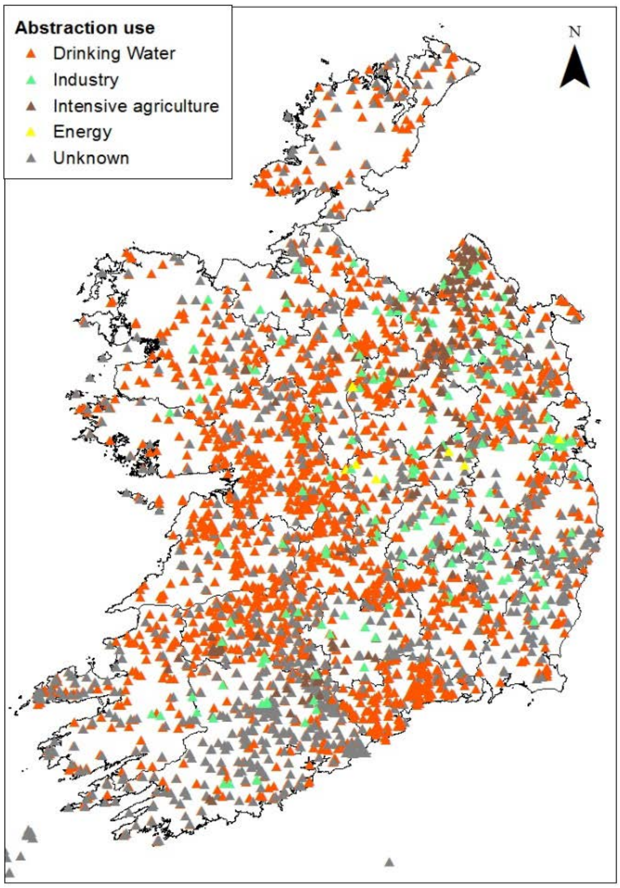


Figure 3.6. National abstraction geodatabase showing abstraction points categorised by water use.

Table 3.4. Division of groundwater and surface water abstraction points in geodatabase

Water source	Percentage of abstraction points (by number of abstraction points)	Percentage of water abstracted (by volume of water abstracted)
Groundwater	57	17
Surface water	19	49
Mixture	0.1	0.2
Unknown	25	34

Table 3.5. Uses of abstracted water from geodatabase

Use	Percentage of abstraction points (by number of abstraction points)	Percentage of water abstracted (by volume of water abstracted)[a]
Drinking water	63	52
Industry	5	12
Intensive agriculture	3	–
Energy generation	0.2	35
Unknown	29	–

[a]Per cent of water abstracted by volume of water abstracted is for selected large abstractions only.

3.4 Method to Estimate Current Abstraction Pressures

The national abstraction geodatabase was used to provide an estimate of the current abstraction pressures in Ireland. Specifically, it was used to calculate the proportion of water abstracted from the catchments to the 166 selected hydrometric stations included in the flow regime analysis (outlined in section 2.4.1 and shown in Figure 2.6). Twenty-five catchments had no abstractions within their boundaries.

A number of metrics were used to estimate the water available for abstraction in each catchment. These included the following:

1. effective rainfall (defined here as the proportion of rainfall that is potentially available to move through the terrestrial part of the water cycle (i.e rainfall that is not evaporated or transpired); effective rainfall was calculated for each catchment using data from the GSI's groundwater recharge map (GSI, 2008);
2. monthly low-flow values; and
3. flow duration exceedance percentiles (e.g. Q5 to Q95).

For these calculations, a number of assumptions were made. First, all abstractions are considered to be consumptive (i.e discharges were not considered). The effects of water abstraction on rivers act at a variety of spatial scales, from local to regional. For example, in most settings, domestic water supplies discharging to septic tanks have only local impacts and would not be considered consumptive. An exception to this would be where soils are poorly drained and/or groundwater vulnerability is low and where water is abstracted from groundwater but discharged to surface water. Water abstraction for run-of-river hydroelectric schemes may only have a local impact, as intake water is released further downstream, although these local impacts may restrict river continuity. Public water supplies, combined with urban waste water discharges, have impacts at the catchment scale. Intensive agriculture, such as pigs and poultry, has local catchment impacts and is semi-consumptive. Industrial uses (e.g. for food and beverage products) and irrigation are typically consumptive and have regional to national impacts. In addition, the project did not have the resources to collate a national discharge database in addition to the abstraction geodatabase. This assumption means that the proportion of catchments calculated by this project to be impacted by abstraction is likely to be an over-estimate. Documenting the cumulative effects of these different modes of abstraction within Irish catchments is a high priority to understand the effects on flow regime and ecological responses.

Second, it was assumed that groundwater abstractions are removing water that would have otherwise have been discharged into surface water. Groundwater abstractions are treated in the same way as surface water abstractions and the total abstraction is defined as the sum of surface water and groundwater abstractions. In a setting with poorly drained soils and/or low groundwater vulnerability, surface water and groundwater may not be connected at a local scale. Therefore, the validity of this assumption in all settings should be assessed during future work.

Third, abstractions are assumed to come only from the catchments into which they are classified. That is, it is assumed that there is no connection between catchments. This may not be the case if the spatial extents of groundwater and surface water catchments are not the same, which may be the case, for example, for karstified aquifers. This assumption also means that errors or inaccuracies in the location of abstraction points may be important.

3.5 Abstraction Pressures on Study Catchments

3.5.1 Effective rainfall

The proportion of effective rainfall abstracted from the catchments ranged from 0% to 32%. However, the majority of catchments have low abstraction pressures. Less than 5% of the effective rainfall is abstracted from 90% of the catchments. The distribution of the results is shown in Table 3.6 and Figure 3.7. The catchments where more than 10% of the effective rainfall was abstracted contain either large public water supplies or industrial abstractions.

3.5.2 Monthly low flows

Table 3.7 shows how the proportion of the monthly low flow that was abstracted varies over time. The largest impact was seen in the summer months (in June and July, in 90% of the catchments, up to 20% of the

Table 3.6. Distribution of percentage of effective rainfall abstracted in the 166 catchments

Percentile	Percentage of effective rainfall abstracted (%)
5th	0
10th	0
25th	0
50th	1
75th	2
90th	5
95th	7
99th	20

Table 3.7. The percentage of monthly low flows abstracted from each of the surveyed river catchments at each percentile

	Percentage of monthly low flows abstracted (%)											
Percentile	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
5th	0	0	0	0	0	0	0	0	0	0	0	0
10th	0	0	0	0	0	0	0	0	0	0	0	0
25th	0	0	0	0	0	0	0	0	0	0	0	0
50th	2	1	2	1	2	2	2	3	4	4	4	3
75th	5	4	3	3	3	4	5	7	8	9	8	7
90th	11	7	7	6	8	8	10	13	20	20	18	14
95th	16	11	10	9	11	12	14	21	27	32	30	26
99th	43	32	29	26	31	33	38	48	63	78	69	60

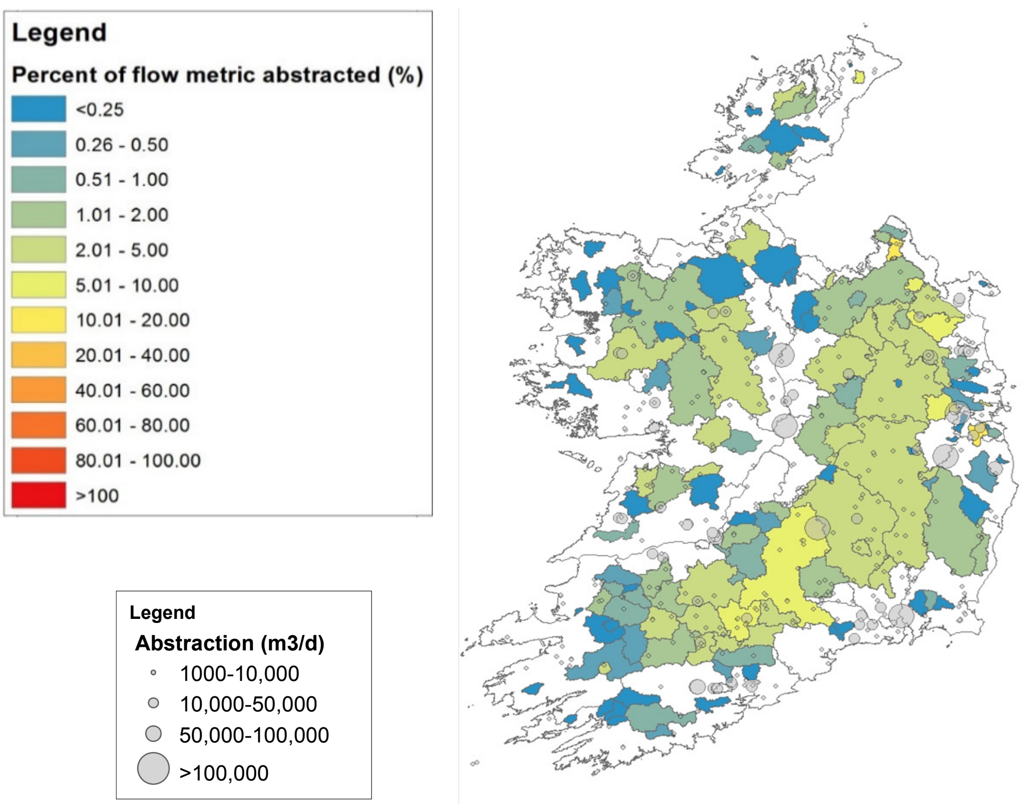


Figure 3.7. The proportion of effective rainfall abstracted from catchments with selected large abstractions.

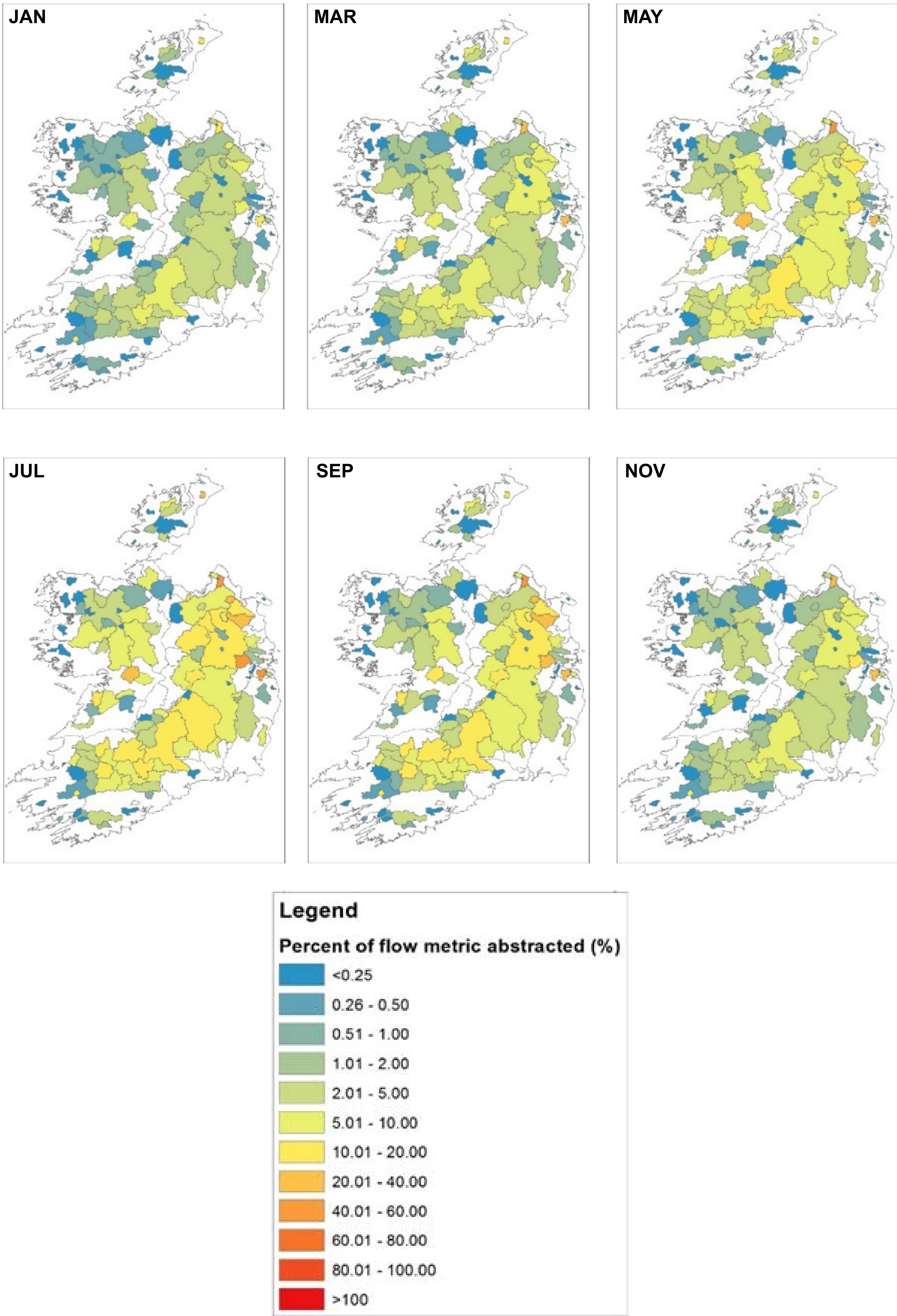


Figure 3.8. The proportion of monthly low flow abstracted in January, March, May, July, September and November.

monthly low flow was abstracted). The lowest impact was observed in January, when 6% of the monthly low flow was abstracted in 90% of the catchments. Figure 3.8 shows the pattern of how the percentage of flow abstracted varies with time. Figure 3.9 shows the percentage of monthly low flows abstracted from the five medoid catchments. These catchments show a similar temporal pattern to the other catchments, with the highest percentage abstracted being in July and the lowest in January.

Information on how abstraction volumes vary with time was not available from any of the data sources (section 3.4.1). Therefore, the variation in the proportion of water abstracted represents only the variation in river flows. Some abstractions will increase in the summer (e.g. irrigation supplies) and will place additional pressure on summer low flows. Future work should seek to repeat this exercise when data on how abstraction volumes vary with time are available.

3.5.3 Flow duration exceedance percentiles

Table 3.8 and Figure 3.10 shows how the proportion of the flow duration exceedance percentiles that was abstracted varies. Less than 45% of the Q95 was abstracted in 90% of the catchments surveyed. Table 3.9 shows an evaluation of abstraction pressures in the surveyed river catchments using the 2008 risk assessment threshold for failing to comply with the abstraction criteria of the WFD's objectives (CDM, 2008; Table 3.2). Seventy-nine catchments (49%

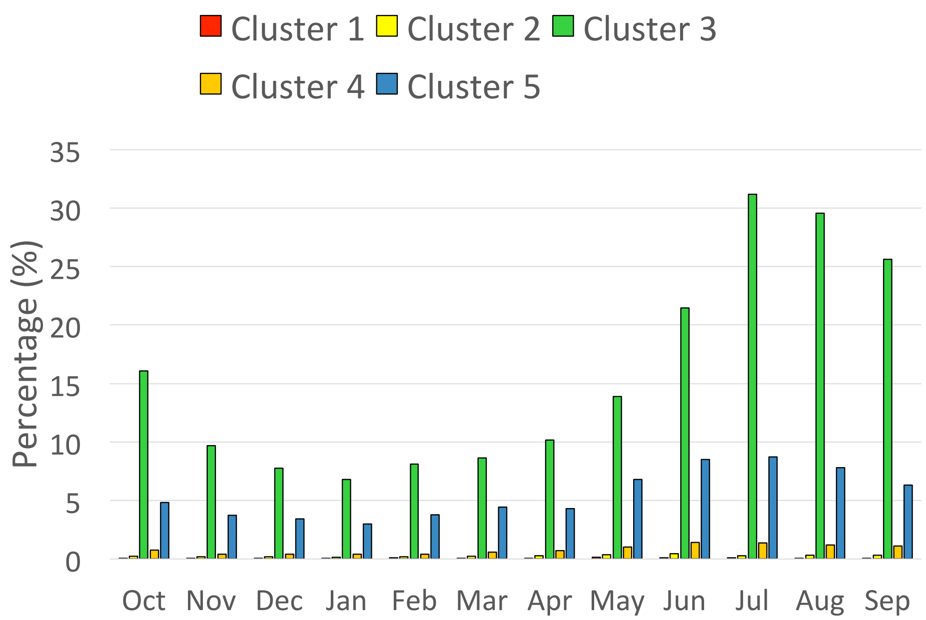


Figure 3.9. The percentage of monthly flow abstracted from the five medoid catchments.

Table 3.8. The percentage of the flow abstracted at selected flow duration exceedance percentiles from each of the surveyed river catchments

	Percentage of flow duration exceedance percentiles abstracted (%)						
Percentile	Q95	Q90	Q70	Q60	Q50	Q33	Q5
5th	0	0	0	0	0	0	0
10th	0	0	0	0	0	0	0
25th	1	1	0	0	0	0	0
50th	10	7	3	2	2	1	0
75th	22	16	7	5	4	3	1
90th	45	30	12	9	7	5	2
95th	69	54	20	14	11	7	2
99th	205	128	49	38	29	19	7

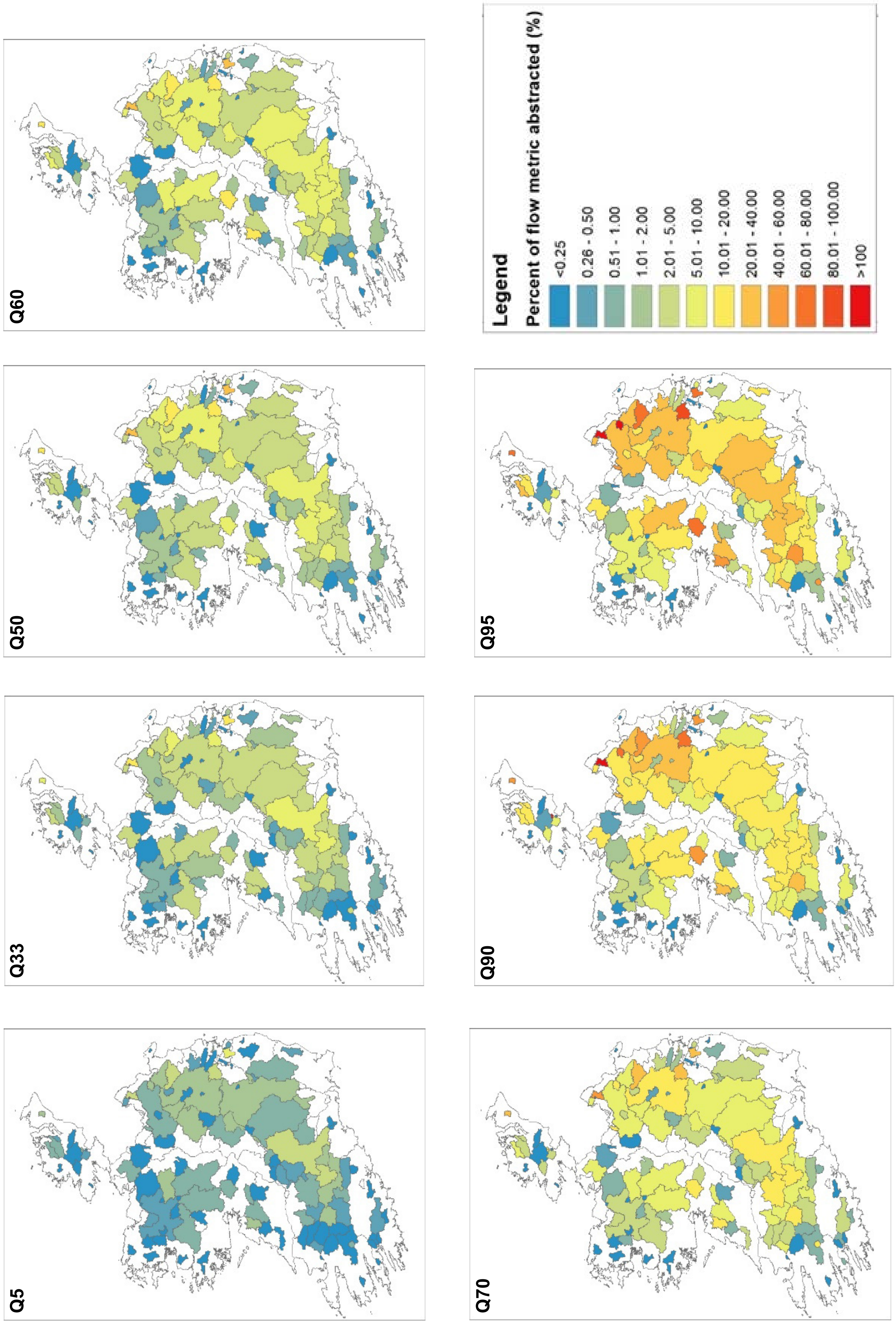


Figure 3.10. The percentage of flow abstracted at selected flow duration exceedance percentiles from each of the surveyed river catchments.

Table 3.9. Evaluation of abstraction pressure the surveyed river catchments investigated in this study using the 2008 risk assessment thresholds

Risk level	Risk class	% of Q95 flow abstracted	Number of catchments	% of catchments
At risk	1a	>40%	19	12
Probably at risk	1b	10–40%	60	37
Probably not at risk	2a	5–10%	23	14
Not at risk	2b	<5%	62	38

of catchments assessed) would be classified as "at risk" or "probably at risk" using these thresholds. This is much higher than the 5% of river water bodies found to be "at risk" or "probably at risk" by the 2008 risk assessment (CDM, 2008). Of course, these assessments are not directly comparable, as the assessment units vary. The 2008 risk assessment used river water bodies, whereas this assessment uses catchments to hydrometric stations. The much higher estimate calculated by this assessment is likely to be due to different assumptions made by the two assessments: (1) this study considered all abstractions, groundwater and surface water, as consumptive, and (2) the 2008 risk assessment considered only surface water abstractions when assigning the risk categories.

4 Experimental Approach to Estimating the Effects of Abstraction on Flow Regime

4.1 Objectives

Our third objective was to determine how flow regimes of sites that were representative of each cluster would change in response to abstraction, as these were results that would inform the development of abstraction standards to protect environmental flows. This objective parallels Step 3.2 in the ELOHA process (Figure 1.3) that compares flow regimes derived from pre- and post-abstraction records. As described in Chapter 3, at the start of the study a comprehensive abstraction database for Ireland was not available for this type of analysis. Instead, we applied a set of abstraction scenarios, reflecting potential abstraction rates, existing UK standards and current abstraction rates, to the daily flow records from hydrometric stations representative of each flow cluster and compared metrics from the raw and abstracted data series.

The specific goals were to determine:

1. how alternative flow abstraction schemes alter environmental flow metrics and other measures of flow regime; and
2. whether or not sites representing each flow cluster differ in their sensitivity to abstraction.

These data experiments provided insights into how rivers in each flow class might respond to a range of abstraction pressures, which aspects of flow regime are most sensitive to abstraction and how sensitivity differs by flow class. This information can be used to inform future studies and risk assessments.

4.2 Methods

4.2.1 Study stations

Abstraction experiments were carried out for the five stations designated as "medoid" sites for each of the flow clusters defined by the PAM cluster analysis (see section 2.3.1); locations are shown in Figure 4.1. Based on the abstraction database compiled in Chapter 3, these stations are currently not influenced by abstraction. These five stations include four with relatively similar catchment areas, while the catchment area of the Cluster 5 medoid station is substantially larger (Table 4.1).

4.2.2 Abstraction experiments

Daily flow records (sections 2.21 and 2.22) for the five medoid stations were manipulated in 14 abstraction experiments to simulate abstraction to allow us to compare IHA flow metrics from unabstracted (original raw data) and abstracted time series. The raw daily flow records represent baseline or "pre" experimental abstraction conditions; none of the flow from five medoid river stations is currently abstracted, based on the database compiled in Chapter 3. Four sets of abstraction scenarios were applied to the daily flow records and comparisons were then made between the IHA flow metrics (see Table 2.1), hydrographs from high- and low-flow years and FDCs for these "pre" and abstracted flow series. Four sets of abstraction scenarios were applied, three based on instantaneous flow values and a fourth using the same abstraction amount (Table 4.2), defined as follows:

1. UK1–4: proposed proportional standards to maintain GES for UK rivers as described in Acreman and Ferguson (2010).
2. HO1–5: a hands-off (HO) limit was set at the Q90, below which no abstraction was allowed. Above this, a set percentage of instantaneous flow, from 10% to 50%, was abstracted. This scenario was chosen to reflect how different proportions of abstraction that retained low flows would affect flow regime. Such scenarios are typical of flow standards designed solely to maintain adequate low flows.
3. HEP: abstraction follows a typical setup for run-of-river hydroelectric power (HEP) schemes. Abstraction does not start until Q70 is reached. Above Q70, all flow is abstracted up to Q29 (a likely maximum for efficient HEP operation). A HO flow of Q80 is always retained when flow

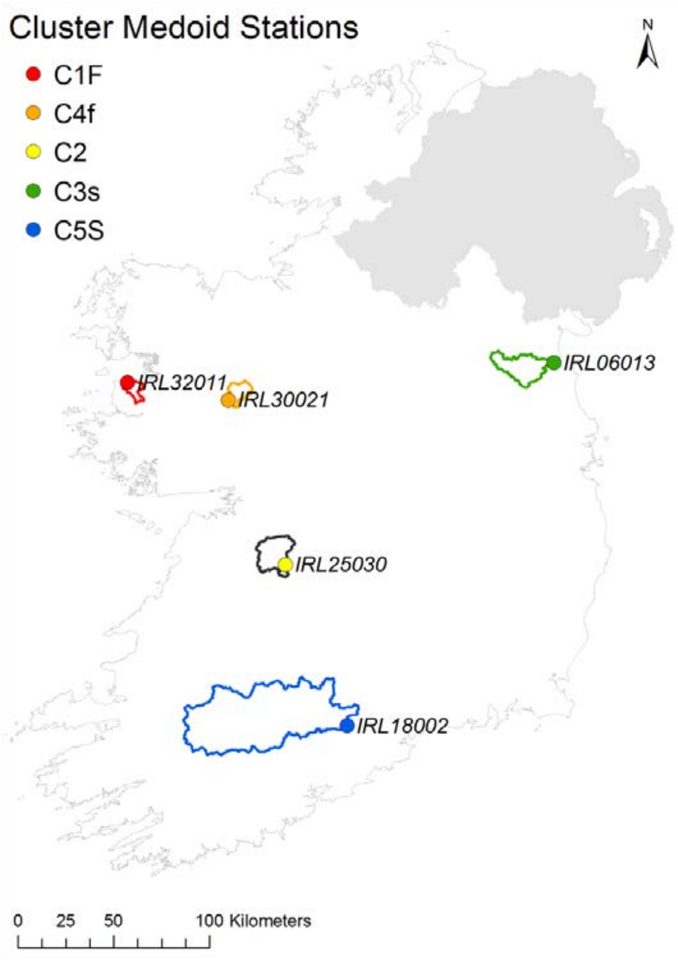


Figure 4.1. Location of cluster medoid hydrometric stations and corresponding catchment boundaries.

Table 4.1. Summary characteristics of the cluster medoid stations used in the experiments

Hydrometric station	Cluster	Station name	Water body	County	RBD	Easting	Northing	Data source	Yrs	CA area (km²)	Ord
IRL06013	C3s	Charleville	Dee	Louth	NB	304411	290763	OPW	26	309	5
IRL18002	C5S	Ballyduff	Blackwater (Munster)	Waterford	SW	196410	099140	OPW	27	2334	6
IRL25030	C2	Scarriff	Graney	Clare	SH	164180	184277	OPW	23	280	5
IRL30021	C4f	Christina's Bridge	Robe	Mayo	WE	134442	270996	EPA	18	104	4
IRL32011	C1F	Louisburg Weir	Bunowen	Mayo	WE	081604	280258	EPA	16	70	5

CA, catchment area; Ord, Strahler order; RBD, river basin district; Yrs, years of complete hydrometric data.

exceeds Q80 and the abstraction on a given day is determined by the instantaneous flow.

4. ABS25–95: application of a fixed daily abstraction amount reflecting the 25th, 50th, 75th and 95th percentiles of abstraction values, as described in Chapter 3; the quartiles were chosen to represent the range of annual abstraction rates (no daily rates were available) currently influencing Irish rivers. In these scenarios, no HO flow was maintained.

These scenarios provide a range of potential abstraction schemes, including set volumes and daily instantaneous abstractions, as well as those that do and do not maintain low flow. The sections below provide further details on each of these abstraction scenarios.

Table 4.2. Abstraction percentages applied to daily flow records from test medoid stations based on instantaneous flow exceedance value. Numbers are percentage of flow abstracted within different flow exceedance categories, based on instantaneous flow

Abstraction scenario	Season	Flow exceedance levels							
		> Q60	> Q70	> Q80	< Q80	> Q90	< Q90	> Q95	< Q95
UK1	Apr–Oct	30	25	20	20	20	20	20	15
UK1	Nov–Mar	35	30	25	25	25	25	25	20
UK2	Apr–Oct	25	20	15	15	15	15	15	10
UK2	Nov–Mar	30	25	20	20	20	20	20	15
UK3	Apr–Oct	20	15	10	10	10	10	10	7.5
UK3	Nov–Mar	25	20	15	15	15	15	15	10
UK4	June–Sep	25	20	15	15	15	15	15	10
UK4	Oct–May	20	15	10	7.5	7.5	7.5	7.5	7.5
HO1	NA	10	10	10	10	10	0	0	0
HO2	NA	20	20	20	20	20	0	0	0
HO3	NA	30	30	30	30	30	0	0	0
HO4	NA	40	40	40	40	40	0	0	0
HO5	NA	50	50	50	50	50	0	0	0

UK schemes (UK1–UK4)

The UK schemes proposed for setting standards to maintain GES (Table 4.2) consisted of four alternatives that depend on river typology and corresponding sensitivity (Acreman and Ferguson, 2010). Abstraction rates vary by season (e.g. summer and winter), instantaneous daily flow and the corresponding flow exceedance class of that daily flow (e.g. within flow intervals defined by Q95, Q70, and Q60). For example, for UK1 during the summer, if the flow on a given day is above the Q90 and less than Q70, 20% of daily flow can be abstracted; in winter a higher abstraction rate of 25% is allowed. UK4, which was designed to protect salmonid spawning and nursery areas, and is likely to be the scheme that is the most applicable to the Irish situation, specifies different monthly intervals for the two seasons compared with UK1-UK3, which have has the lowest allowable abstraction percentage. All the UK schemes allow proportional abstraction across all flow exceedance levels (i.e there is no HO flow).

Flow exceeding "hands-off" (HO1–HO5)

Protection of HO flow to maintain low flow has long been considered important for the maintenance of ecological integrity. We applied six abstraction rates from 10% to 50% (in intervals of 10%) to daily instantaneous flow exceeding the HO level of Q90 (Table 4.2) in order to assess how protection of only low flow affects the range of environmental flow metrics. Daily flow was not permitted to be abstracted when flow rates were less than Q90; abstraction above Q90 was allowed, but flow rates could not fall below Q90. The numbers following the letters HO in each experiment code indicate the percentage of flow abstracted (e.g. HO1 refers to 10%, HO5 refers to 50%). Abstraction above 50% was found to have extreme impacts on flow metrics and was likely to be at the extreme end of the range.

Run-of-river hydroelectric power HEP abstraction scheme (HEP)

Run-of-river HEP (hydroelectric power) schemes, that divert river flow into a turbine system then return water downstream, are becoming more common in Northern Ireland (D. Quinn, NIEA, personal communication, May 2015). There are three aspects of HEP schemes, as applied in Northern Ireland, that were accounted for in these simulations: first, no flow was abstracted until flow exceeded the start-up flow value of Q70 (e.g. there was no abstraction if daily flow was < Q70); second, HEP schemes have a peak efficiency or maximum abstraction that we set at Q29 (the flow at Q29 was subtracted from daily flows exceeding Q29); and third, all flow above Q80 was abstracted between flow rates of Q29 and Q80.

Irish annual abstraction rates (ABS25–ABS95)

The compilation of annual abstraction estimates in section 3.4 provided a range of abstraction quantities that we used in the fourth set of abstraction scenarios. In order to assess effects that were representative of the range of current abstraction amounts within the database described in Chapter 3, we selected the 25th, 50th, 75th and 95th percentiles of annual abstraction. These annual quantities were converted into a constant daily value in cms that was subtracted from each daily flow value over the entire data record. Hands-off flow protection was not maintained. The abstracted daily flow amount was less than 2% of MAF for station IRL18002, which had the highest MAF, but ranged from 19% to 53% of the highest abstraction rate (ABS95) for the other four stations (Table 4.3).

4.2.3 Assessment of alteration in EFlow regime for each abstraction scheme

These abstraction scenarios generated 14 abstracted flow time series for each hydrometric station. In order to display the influence of a subset of the experimental abstraction schemes on daily flow for the Cluster 1 (flashy) and Cluster 5 (stable) stations, we generated FDCs, which show flow rate (on a log scale) plotted against exceedance probability (i.e. Q percentiles along a log-normal scale) for both the "pre" (i.e original raw flow data) and abstracted flow series. The FDCs were supplemented by time series plots that compare the "pre" and experimental abstraction time series during low-, medium- and high-flow years for each medoid station.

To apply the IHA software capability to compare pre- and post-abstraction time series, each of the experimental time series was appended to the original flow series ("pre"), for which the observation date was set to 40 years earlier; this was done to facilitate the generation of statistics by the IHA software (The Nature Conservancy, 2009). The simulated flow series were imported into the IHA software as described in section 2.2.2. The software generated a spreadsheet of IHA flow metrics for both the "pre" and abstracted time periods, including the medians from annual estimates of the 33 IHA metrics and the CD, as well as an estimate of significance (described below). As for the flow regime metrics described in Chapter 2, the water year, i.e. October through September, was used to represent annual estimates and medians used for metric comparison.

The significance of the effect of the abstraction scheme on each metric was estimated using the IHA software by randomly shuffling all the input data and calculating pre- and post-estimates of median and CD (section 2.2.2); this bootstrapping was repeated 1000 times. The actual medians and CD estimates were then compared with this bootstrapped population of estimates. The proportion of counts for which the actual medians and CD values were less than or greater than the population provides an estimate of significance, analogous to the *p*-value in parametric statistics.

4.3 Results and Discussion

4.3.1 Effects of abstraction experiments on flow

Flow duration curves for two hydrometric stations representing flashy (Cluster 1) and stable (Cluster 5) flow indicate that, while low levels of abstraction

Table 4.3. Medoid mean annual flow (MAF) and percentage of MAF abstracted for each abstraction scenario; ABS25–ABS95 refer to scenarios with abstraction rates representing percentiles of values in Irish rivers (Chapter 3); absolute abstracted values are shown in parentheses

Cluster	Medoid	MAF (cms)	% of MAF abstracted			
			ABS25 (0.0032) (cms)	ABS50 (0.0409) (cms)	ABS75 (0.224) (cms)	ABS95 (1.59) (cms)
C1F	IRL32011	3.24	0.10	1.26	6.92	49.13
C4f	IRL30021	3.01	0.11	1.36	7.44	52.84
C2	IRL25030	8.18	0.04	0.50	2.74	19.44
C3s	IRL06013	4.26	0.08	0.96	5.26	37.34
C5S	IRL18002	58.63	0.01	0.07	0.38	2.71

(e.g. ABS25 and HO1) did not appreciably influence flow, noticeable shifts were apparent for more severe abstractions (Figure 4.2). The Irish abstraction quantities representing the 75th and 95th percentiles (ABS75 and ABS85), which did not maintain HO flow, led to zero flow at all stations except IRL18002 (Cluster 5), which had substantially higher MAF compared with the other stations (Table 4.1). HEP schemes led to substantial decreases in flow between the HO value of Q80 to the Q29, assumed as the maximum flow that a HEP system can abstract. The HO abstraction schemes protected low flows but, at the higher levels tested, HO4 and HO5, high flows decreased. FDC curves for the UK scenarios all suggested relatively small decreases across all flow exceedance values. FDC curves for the abstracted flow series obtained through ABS25, ABS50, UK1 to UK3, and HO1 to HO4 did not show appreciable deviation in FDC curves from the “pre” condition.

To demonstrate the seasonality as well as differences in low-, medium- and high-flow years, annual hydrographs for the “pre” and the experimentally altered data were plotted for the same set of experiments discussed above, with flow truncated to emphasise changes at low flows (Figure 4.3). These results were consistent with effects described above.

4.3.2 EFlow metric alteration

Flow abstraction schemes had significant effects on IHA metrics for all stations. Results are displayed in heatmap plots in Figure 4.3 with the IHA flow metrics along the y-axis and “pre” (i.e unabstracted) and abstraction scheme along the x-axis.

Summaries of the results for individual stations by experiment (e.g. total significant changes across the five stations) and by station (e.g. total significant changes across 14 experiments) are shown in Figures 4.4 and 4.5, respectively. The group of metrics with the most change (except for the ABS series) were those having to do with maximum flow calculated across a variety of time steps; minimum flow was not generally affected, which was likely to be because low flow was often protected. Although low flow is considered most often for maintaining ecological function, high flows are increasingly being considered for their important roles in silt flux and in connecting river channels with riparian and floodplain habitats.

Other metrics that showed substantial changes were BFI, low pulse number, rise and fall rates and reversals. Abstraction, by dampening high flows, also reduced the flashiness of systems, which could be detrimental to organisms that rely on flow changes for persistence and advantageous for organisms who thrive in more predictable flow situations (Arthington, 2012).

When we applied an absolute daily abstraction rate without protecting HO flows, a somewhat different pattern emerged. Instead of affecting maximum flows, there was a greater effect on minimum flows, commonly during the summer months when flow is low. These effects occurred only at the abstraction amounts representing the 75th and 95th percentiles of abstraction rates in Ireland. At the highest abstraction rate, ABS95, four of five stations had zero flow days where previously there were none in the period of 10 or more years for which we analysed the record. The effects of these abstraction experiments were less severe on the C5 station, in part because it had higher flow than the other stations (Table 4.3) and, would thus be expected to respond less to the abstraction experiments. The C5 medoid station showed no significant changes in metrics to the ABS experiments even at the highest level of ABS95, which was less than 3% of that station’s MAF. HEP schemes influenced many flow metrics, although, with protection of low flow with HO limits, had less of an effect on summer flow compared with the ABS scenarios.

In addition to tallies by abstraction scheme, we also examined tallies by medoid station (Figure 4.5). Across the five stations, similar numbers of significant effects of abstraction were noted for maximum flow and BFI. Only the flashy station from Cluster 1 had substantially more significant effects on rise rate. However, for other metrics, such as those relating to monthly flow and number of reversals, significant effects were lowest for the station from the most flashy cluster (Cluster 1) and greatest for the station from the cluster with the highest BFI and most stable flow (Cluster 5).

The stronger effect of abstraction on flow metrics for the stable flow station may be interpreted by considering the lower interannual variability inherent in flow at this and other Cluster 5 sites. Because of this, abstraction could lead to conditions not observed previously in the long-term record and thus lead to significant changes in metrics when comparing “pre”

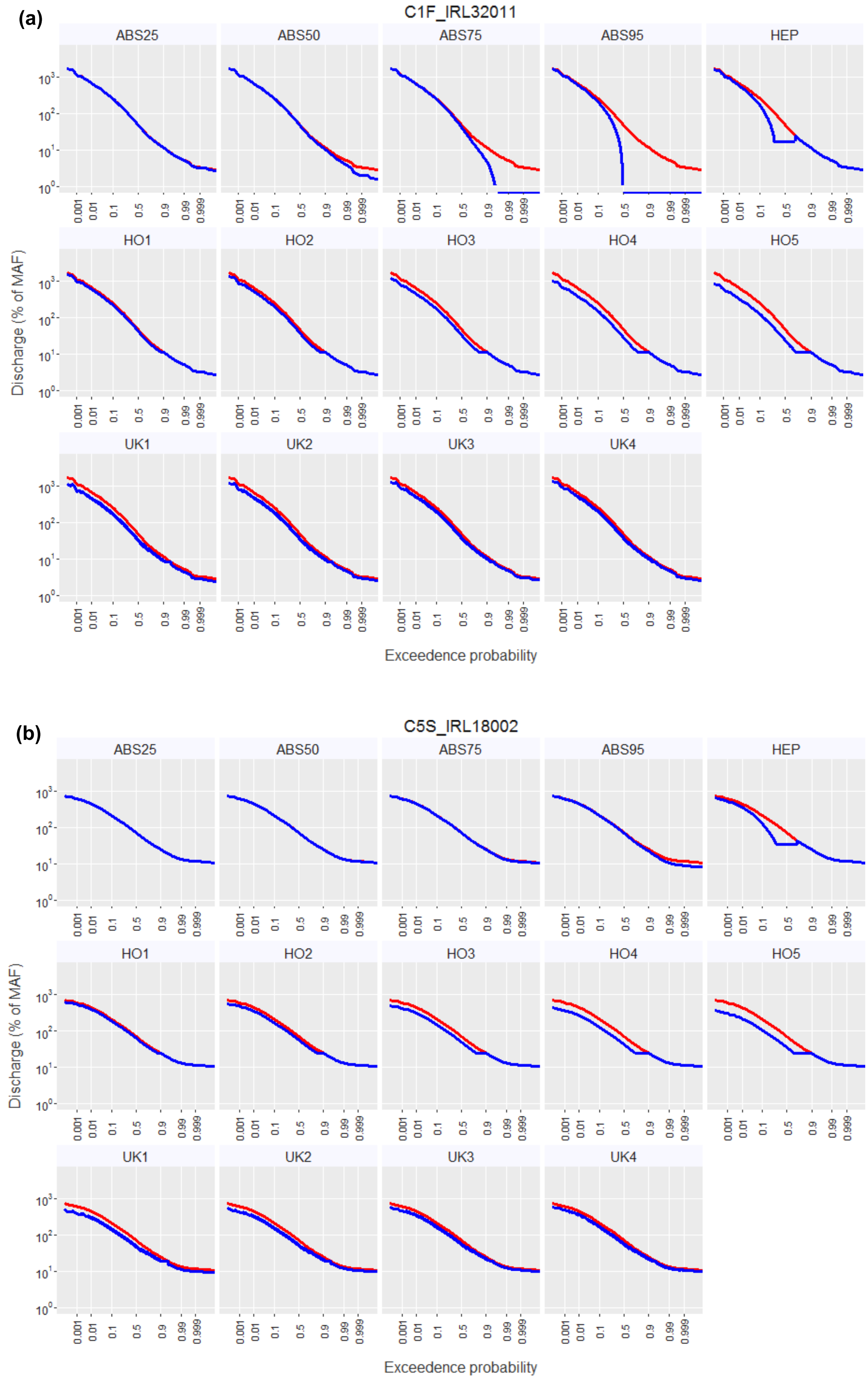
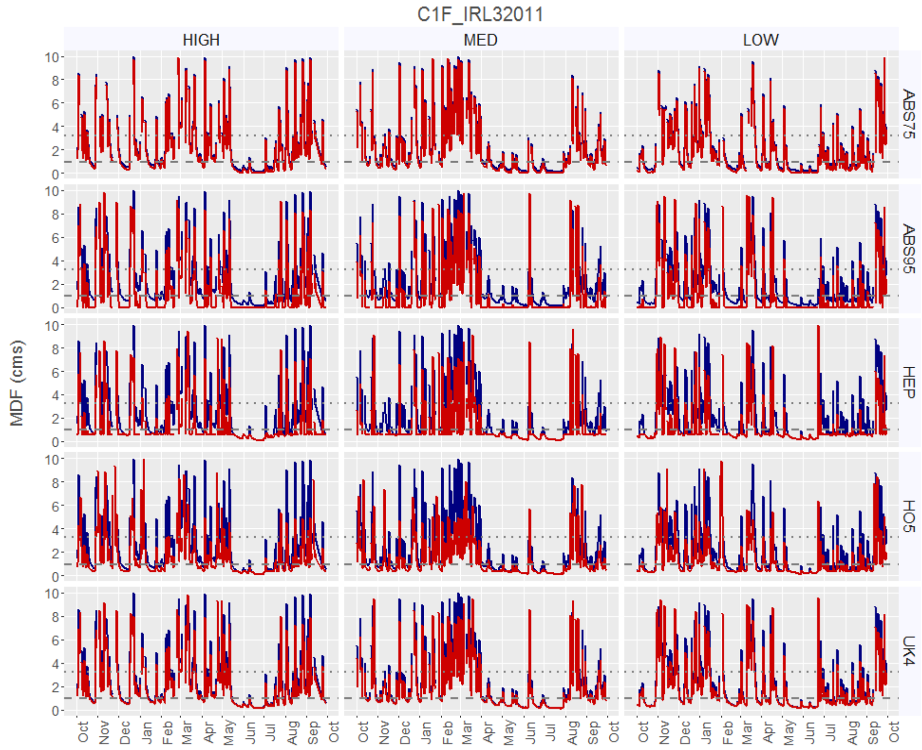


Figure 4.2. Flow duration curves for each abstraction scenario applied to (a) the Cluster 1 (flashy) medoid station and (b) the Cluster 5 (stable) medoid station. The red line is the original raw data and the blue line represents the flow following abstraction.

(a)



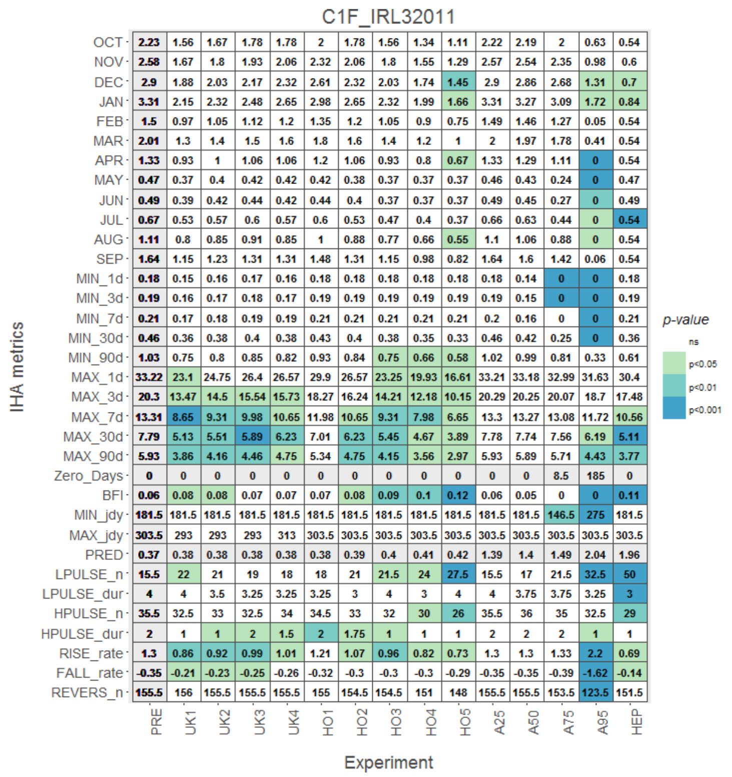
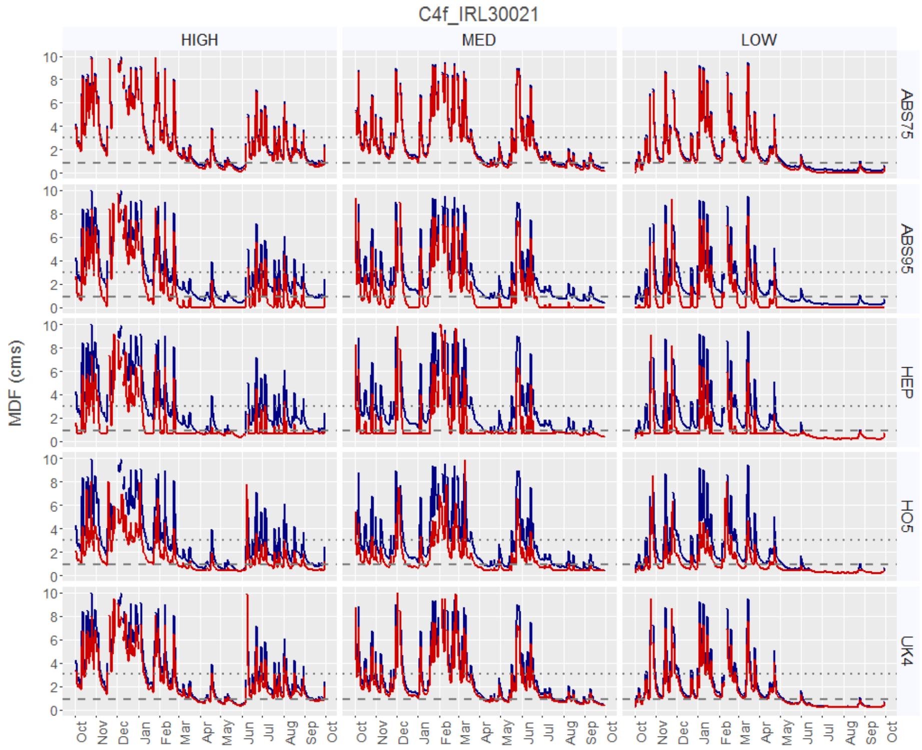


Figure 4.3. Hydrographs (high flows truncated to focus on low flow) for high-, medium- and low-flow years with heatmaps showing significant changes in flow metrics derived from the original data and the experimentally abstracted data for medoid stations representing (a) Cluster 1, (b) Cluster 4, (c) Cluster 2, (d) Cluster 3 and (e) Cluster 5. The top panel in each case shows the original data in red and the abstracted data in blue; the dotted line is the MAF and the dashed line is 40% of the MAF. In the heatmaps shown in the bottom panels, the numbers represent differences in each metric derived from the original and abstracted flow series and the shading indicates the significance level of each difference from zero. No statistical tests were run for ZERO_DAYS (number of zero flow days in a year) and PRED (flow predictability).

(b)



C4f_IRL30021

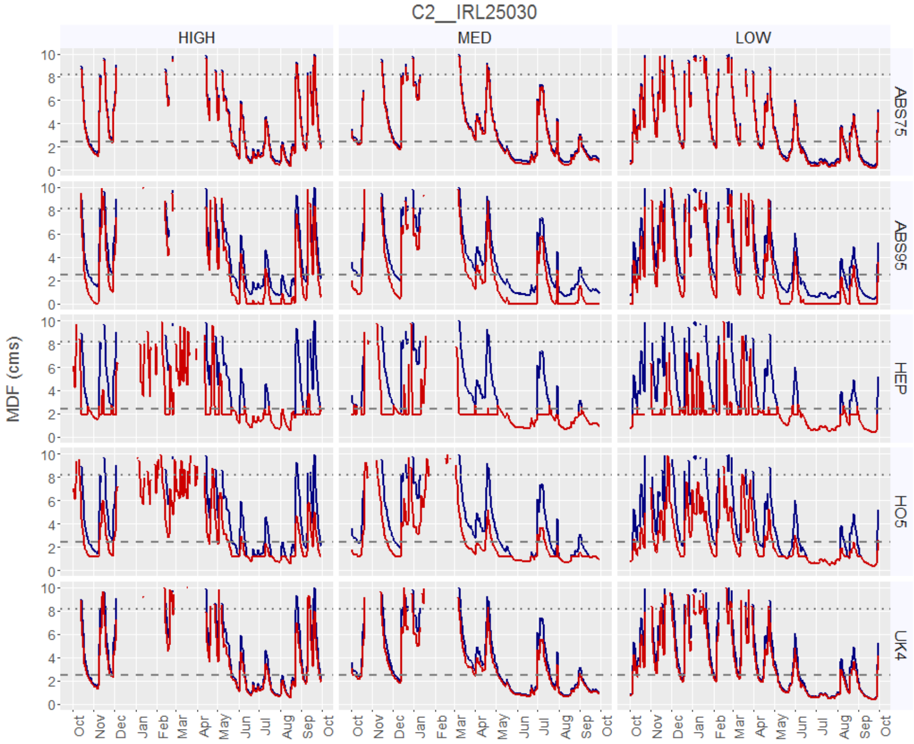
IHA metrics	PRE	UK1	UK2	UK3	UK4	HO1	HO2	HO3	HO4	HO5	A25	A50	A75	A95	HEP
OCT	1.3	0.93	0.99	1.06	1.06	1.17	1.04	0.91	0.78	0.65	1.3	1.26	1.08	0	0.65
NOV	4.13	2.69	2.89	3.1	3.31	3.72	3.31	2.89	2.48	2.07	4.13	4.09	3.91	2.54	1.45
DEC	4.88	3.17	3.42	3.66	3.9	4.39	3.9	3.42	2.93	2.44	4.88	4.84	4.66	3.29	2.2
JAN	4.45	2.89	3.11	3.34	3.56	4	3.56	3.11	2.67	2.22	4.45	4.41	4.22	2.86	1.77
FEB	3.18	2.07	2.23	2.38	2.54	2.86	2.54	2.23	1.91	1.59	3.17	3.14	2.95	1.59	0.65
MAR	1.83	1.19	1.28	1.38	1.47	1.65	1.47	1.28	1.1	0.92	1.83	1.79	1.61	0.24	0.65
APR	1.6	1.12	1.2	1.28	1.28	1.45	1.28	1.12	0.96	0.8	1.6	1.56	1.38	0.05	0.65
MAY	0.96	0.74	0.79	0.84	0.84	0.87	0.77	0.67	0.58	0.48	0.96	0.92	0.74	0	0.65
JUN	0.64	0.52	0.55	0.58	0.55	0.58	0.52	0.45	0.41	0.41	0.64	0.6	0.42	0	0.64
JUL	0.53	0.42	0.45	0.48	0.45	0.48	0.43	0.41	0.41	0.41	0.53	0.49	0.3	0	0.53
AUG	0.61	0.49	0.52	0.55	0.52	0.55	0.49	0.43	0.41	0.41	0.61	0.57	0.39	0	0.61
SEP	0.61	0.49	0.52	0.55	0.55	0.55	0.49	0.43	0.41	0.41	0.61	0.57	0.39	0	0.61
MIN_1d	0.27	0.23	0.25	0.25	0.25	0.27	0.27	0.27	0.27	0.27	0.27	0.23	0.05	0	0.27
MIN_3d	0.28	0.24	0.25	0.26	0.25	0.28	0.28	0.28	0.28	0.28	0.27	0.24	0.05	0	0.28
MIN_7d	0.29	0.25	0.26	0.27	0.26	0.29	0.29	0.29	0.29	0.29	0.29	0.25	0.07	0	0.29
MIN_30d	0.39	0.31	0.33	0.35	0.34	0.37	0.36	0.36	0.35	0.35	0.38	0.34	0.16	0	0.38
MIN_90d	0.61	0.47	0.5	0.53	0.51	0.57	0.52	0.49	0.46	0.43	0.6	0.57	0.38	0.01	0.5
MAX_1d	21.56	14.75	15.81	16.86	17.25	19.4	17.25	15.09	12.94	10.78	21.56	21.52	21.33	19.97	18.88
MAX_3d	17.05	11.62	12.45	13.28	13.64	15.34	13.64	11.93	10.23	8.52	17.04	17	16.82	15.45	14.37
MAX_7d	13.44	8.74	9.41	10.08	10.75	12.1	10.75	9.41	8.07	6.72	13.44	13.4	13.22	11.85	10.76
MAX_30d	8.76	5.69	6.13	6.57	7.01	7.88	7.01	6.13	5.26	4.38	8.76	8.72	8.54	7.17	6.08
MAX_90d	6.29	4.13	4.44	4.76	5.04	5.66	5.04	4.41	3.78	3.15	6.29	6.25	6.07	4.7	3.77
Zero_Days	0	0	0	0	0	0	0	0	0	0	0	0	0	172.5	0
BFI	0.1	0.12	0.12	0.12	0.12	0.11	0.13	0.14	0.17	0.2	0.1	0.09	0.03	0	0.18
MIN_jdy	221	221	221	221	215.5	221	221	221	221	221	221	221	215.5	275	221
MAX_jdy	341.5	341.5	341.5	341.5	341.5	341.5	341.5	341.5	341.5	341.5	341.5	341.5	341.5	341.5	341.5
PRED	0.44	0.46	0.45	0.45	0.45	0.45	0.46	0.47	0.48	0.52	1.16	1.17	1.25	1.8	1.58
LPULSE_n	6	7	7.5	7	6	6	7.5	7	7.5	9.5	6	6	8	12	22
LPULSE_dur	8	7.25	8.75	8.25	10.25	9.25	10	12	10.5	8	8.25	8.75	8.25	7.75	6.25
HPULSE_n	14.5	14	14.5	14	14	13.5	14	14	13.5	11	14.5	14	15	14	13.5
HPULSE_dur	3	2	2.25	2.5	2.5	3	2.5	2.25	2	2.25	3	3	3	2.25	2
RISE_rate	0.38	0.23	0.26	0.28	0.27	0.34	0.31	0.28	0.25	0.24	0.38	0.38	0.38	1.14	0.29
FALL_rate	-0.13	-0.09	-0.1	-0.1	-0.1	-0.12	-0.11	-0.11	-0.1	-0.1	-0.13	-0.13	-0.13	-0.5	-0.12
REVERS_n	111	117	115	114	116.5	110	108.5	107.5	104.5	100.5	111	111	108.5	77.5	98

Experiment

p-value: ns; p<0.05; p<0.01; p<0.001

Figure 4.3. Continued.

(c)



C2__IRL25030

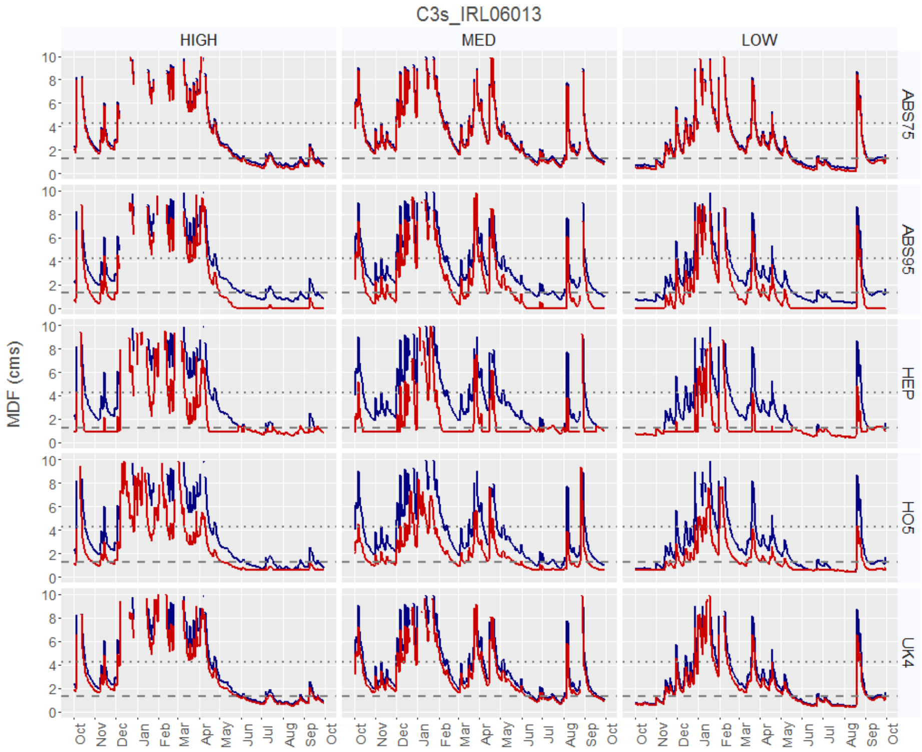
IHA metrics	PRE	UK1	UK2	UK3	UK4	HO1	HO2	HO3	HO4	HO5	A25	A50	A75	A95	HEP
OCT	6.14	4.29	4.6	4.91	4.91	5.52	4.91	4.29	3.68	3.07	6.13	6.09	5.91	4.54	1.93
NOV	8.94	5.81	6.26	6.7	7.15	8.05	7.15	6.26	5.36	4.47	8.94	8.9	8.71	7.35	1.93
DEC	11.17	7.26	7.82	8.38	8.94	10.05	8.94	7.82	6.7	5.59	11.17	11.13	10.95	9.58	3.24
JAN	14	9.1	9.8	10.5	11.2	12.6	11.2	9.8	8.4	7	14	13.96	13.78	12.41	6.07
FEB	8.65	5.62	6.06	6.49	6.92	7.79	6.92	6.06	5.19	4.33	8.65	8.61	8.43	7.06	2.08
MAR	5.69	3.7	3.98	4.27	4.55	5.12	4.55	3.98	3.41	2.85	5.69	5.65	5.46	4.1	2.05
APR	4.43	3.1	3.33	3.55	3.55	3.99	3.55	3.1	2.66	2.22	4.43	4.39	4.21	2.84	1.93
MAY	3.08	2.31	2.46	2.62	2.62	2.77	2.46	2.15	1.85	1.54	3.07	3.04	2.85	1.49	1.93
JUN	1.96	1.57	1.67	1.76	1.67	1.76	1.57	1.37	1.18	1.17	1.96	1.92	1.74	0.37	1.86
JUL	2.08	1.66	1.76	1.87	1.76	1.87	1.66	1.45	1.25	1.17	2.07	2.03	1.85	0.48	1.93
AUG	3.08	2.31	2.47	2.62	2.47	2.77	2.47	2.16	1.85	1.54	3.08	3.04	2.86	1.49	1.93
SEP	2.58	2.06	2.19	2.32	2.32	2.32	2.06	1.81	1.55	1.29	2.58	2.54	2.36	0.99	1.93
MIN_1d	0.67	0.57	0.61	0.62	0.61	0.67	0.67	0.67	0.67	0.67	0.67	0.63	0.45	0	0.67
MIN_3d	0.69	0.58	0.62	0.64	0.62	0.69	0.69	0.69	0.69	0.69	0.68	0.65	0.46	0	0.69
MIN_7d	0.75	0.63	0.67	0.69	0.68	0.75	0.75	0.75	0.75	0.75	0.75	0.71	0.53	0	0.75
MIN_30d	1.12	0.91	0.97	1.02	1.02	1.07	1.03	0.99	0.96	0.95	1.12	1.08	0.9	0.06	1.12
MIN_90d	2.21	1.67	1.78	1.89	1.8	2.02	1.84	1.67	1.51	1.38	2.21	2.17	1.98	0.86	1.5
MAX_1d	42.25	29.3	31.39	33.48	33.8	38.03	33.8	29.58	25.35	21.13	42.25	42.21	42.03	40.66	34.32
MAX_3d	39.49	26.93	28.86	30.78	31.59	35.54	31.59	27.64	23.69	19.74	39.49	39.45	39.26	37.9	31.56
MAX_7d	34.61	23.07	24.85	26.62	27.69	31.15	27.69	24.23	20.76	17.3	34.61	34.57	34.38	33.02	26.68
MAX_30d	22.34	14.87	16.01	17.15	17.87	20.11	17.87	15.64	13.41	11.17	22.34	22.3	22.12	20.75	14.47
MAX_90d	14.77	9.63	10.37	11.1	11.82	13.29	11.82	10.34	8.86	7.38	14.77	14.73	14.55	13.18	8.14
Zero_Days	0	0	0	0	0	0	0	0	0	0	0	0	0	57	0
BFI	0.09	0.11	0.11	0.11	0.1	0.1	0.11	0.13	0.15	0.17	0.09	0.08	0.06	0	0.16
MIN_jdy	216	216	216	216	216	216	216	216	216	216	216	216	216	162	222
MAX_jdy	362	358	358	358	364	362	362	362	362	362	362	362	362	362	362
PRED	0.39	0.4	0.4	0.4	0.4	0.39	0.4	0.42	0.43	0.46	1.02	1.02	1.05	1.23	1.38
LPULSE_n	7	8	8	8	7	7	8	8	9	10	7	7	7	8	20
LPULSE_dur	9.25	11	10.75	9	10	10.25	10.5	11	9	10.5	9.75	9.5	9.75	11.5	9.5
HPULSE_n	9	8	7	8	8	9	8	7	7	5	9	9	9	9	7
HPULSE_dur	6	5	6	6	6	6	6	6	4	4	6	6	6	6	4
RISE_rate	0.88	0.54	0.6	0.65	0.66	0.79	0.7	0.61	0.57	0.48	0.88	0.88	0.88	1.17	0.73
FALL_rate	-0.42	-0.27	-0.29	-0.33	-0.32	-0.38	-0.35	-0.32	-0.3	-0.28	-0.42	-0.42	-0.42	-0.58	-0.24
REVERS_n	84	88	88	87	88	82	81	80	78	77	84	84	84	72	72

Experiment

p-value: ns; p<0.05; p<0.01; p<0.001

Figure 4.3. Continued.

(d)



C3s_IRL06013

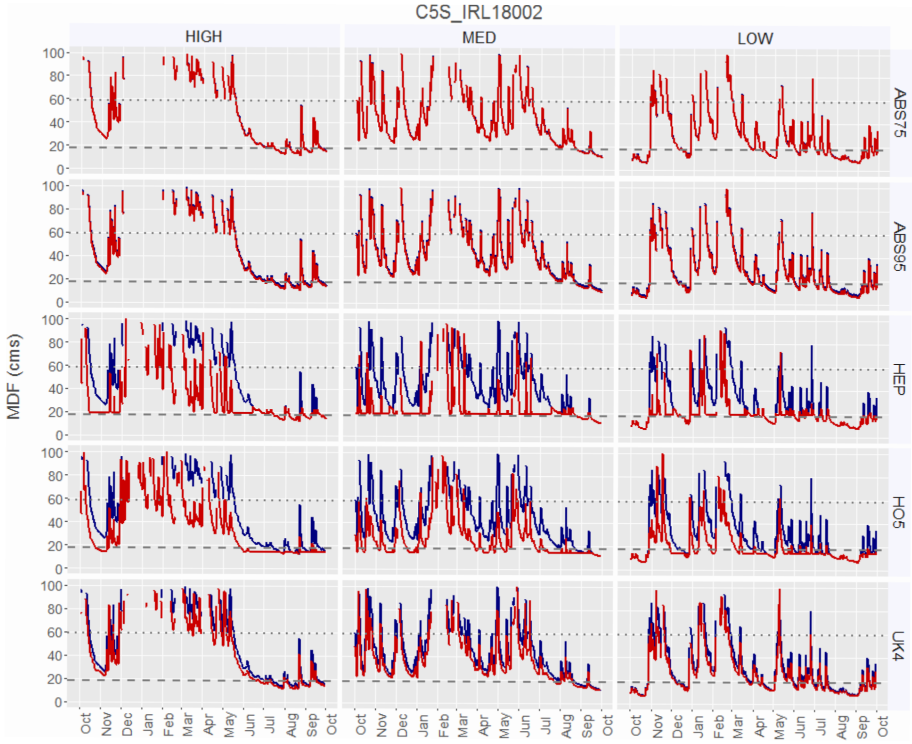
IHA metrics	PRE	UK1	UK2	UK3	UK4	HO1	HO2	HO3	HO4	HO5	A25	A50	A75	A95	HEP
OCT	1.98	1.45	1.55	1.65	1.65	1.78	1.58	1.38	1.19	0.99	1.98	1.94	1.75	0.39	0.95
NOV	4.38	2.85	3.06	3.28	3.5	3.94	3.5	3.06	2.63	2.19	4.38	4.34	4.15	2.79	0.95
DEC	6.36	4.14	4.46	4.77	5.09	5.73	5.09	4.46	3.82	3.18	6.36	6.32	6.14	4.77	2.48
JAN	7.52	4.89	5.26	5.64	6.02	6.77	6.02	5.26	4.51	3.76	7.52	7.48	7.3	5.93	3.63
FEB	4.98	3.24	3.49	3.74	3.99	4.49	3.99	3.49	2.99	2.49	4.98	4.94	4.76	3.39	1.09
MAR	4.66	3.03	3.26	3.49	3.73	4.19	3.73	3.26	2.79	2.33	4.65	4.62	4.43	3.06	0.95
APR	3.2	2.24	2.4	2.56	2.56	2.88	2.56	2.24	1.92	1.6	3.2	3.16	2.98	1.61	0.95
MAY	2.08	1.48	1.58	1.68	1.68	1.88	1.67	1.46	1.25	1.04	2.08	2.04	1.86	0.49	0.95
JUN	1.34	1.06	1.13	1.2	1.13	1.21	1.07	0.94	0.81	0.67	1.34	1.3	1.12	0	0.95
JUL	0.83	0.67	0.71	0.75	0.71	0.75	0.67	0.63	0.63	0.63	0.83	0.79	0.61	0	0.83
AUG	0.83	0.67	0.71	0.75	0.71	0.75	0.67	0.63	0.63	0.63	0.83	0.79	0.61	0	0.83
SEP	1.05	0.84	0.89	0.94	0.94	0.94	0.84	0.73	0.63	0.63	1.05	1.01	0.82	0	0.95
MIN_1d	0.43	0.36	0.39	0.4	0.39	0.43	0.43	0.43	0.43	0.43	0.43	0.39	0.21	0	0.43
MIN_3d	0.44	0.37	0.39	0.41	0.39	0.44	0.44	0.44	0.44	0.44	0.44	0.4	0.21	0	0.44
MIN_7d	0.45	0.38	0.4	0.41	0.41	0.45	0.45	0.45	0.45	0.45	0.45	0.41	0.22	0	0.45
MIN_30d	0.66	0.53	0.56	0.59	0.58	0.63	0.61	0.6	0.59	0.59	0.66	0.62	0.43	0	0.6
MIN_90d	0.95	0.75	0.8	0.84	0.8	0.86	0.79	0.73	0.68	0.65	0.95	0.91	0.72	0.03	0.86
MAX_1d	25.52	16.88	18.16	19.41	20.41	22.97	20.41	17.86	15.31	12.76	25.51	25.48	25.29	23.93	21.63
MAX_3d	23.35	15.46	16.61	17.76	18.68	21.01	18.68	16.34	14.01	11.67	23.34	23.31	23.12	21.76	19.46
MAX_7d	18.45	12.13	13.06	13.99	14.76	16.6	14.76	12.91	11.07	9.22	18.44	18.4	18.22	16.85	14.56
MAX_30d	12.86	8.36	9	9.64	10.29	11.57	10.29	9	7.71	6.43	12.85	12.82	12.63	11.27	8.97
MAX_90d	8.8	5.72	6.16	6.6	7.04	7.92	7.04	6.16	5.28	4.4	8.8	8.76	8.58	7.21	5.28
Zero_Days	0	0	0	0	0	0	0	0	0	0	0	0	0	118	0
BFI	0.12	0.14	0.14	0.14	0.13	0.13	0.15	0.17	0.2	0.23	0.12	0.11	0.07	0	0.22
MIN_jdy	246.5	248.5	248.5	246.5	237	246.5	246.5	246.5	246.5	248.5	246.5	246.5	246.5	275	246.5
MAX_jdy	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
PRED	0.45	0.46	0.46	0.46	0.46	0.45	0.46	0.47	0.48	0.53	1.06	1.07	1.12	1.5	1.48
LPULSE_n	3	4	4	3.5	4	3	3	4	4	6	3	3	3	6.5	14.5
LPULSE_dur	15	19	11.75	15.5	12.75	15.5	17.5	21	14	9.75	15	15	17.5	10.25	9.75
HPULSE_n	9	9	9.5	9	9	9	9	9	9	8	9	9	9	9	9
HPULSE_dur	5.5	3	3	4	4	4.75	4.25	3	3	3	5.5	5.5	5	4.25	3
RISE_rate	0.3	0.17	0.19	0.2	0.21	0.28	0.25	0.25	0.24	0.21	0.3	0.3	0.3	0.81	0.4
FALL_rate	-0.15	-0.1	-0.11	-0.11	-0.12	-0.14	-0.13	-0.13	-0.12	-0.12	-0.15	-0.15	-0.15	-0.29	-0.15
REVERS_n	96.5	104	102.5	102	103	96	94	90.5	88.5	83.5	96.5	96.5	96	69	77.5

Experiment

p-value: ns; p<0.05; p<0.01; p<0.001

Figure 4.3. Continued.

(e)



C5S_IRL18002

IHA metrics	PRE	UK1	UK2	UK3	UK4	HO1	HO2	HO3	HO4	HO5	A25	A50	A75	A95	HEP
OCT	44.71	31.3	33.53	35.77	35.77	40.24	35.77	31.3	26.82	22.35	44.7	44.67	44.48	43.12	19.52
NOV	71.06	46.19	49.74	53.29	56.85	63.95	56.85	49.74	42.64	35.53	71.06	71.02	70.83	69.47	21.93
DEC	76.43	49.68	53.5	57.32	61.14	68.79	61.14	53.5	45.86	38.21	76.43	76.39	76.2	74.84	26.38
JAN	89.78	58.36	62.85	67.34	71.83	80.81	71.83	62.85	53.87	44.89	89.78	89.74	89.56	88.19	39.74
FEB	67.48	43.86	47.24	50.61	53.99	60.73	53.99	47.24	40.49	33.74	67.48	67.44	67.26	65.89	19.52
MAR	51.67	33.58	36.17	38.75	41.33	46.5	41.33	36.17	31	25.83	51.66	51.62	51.44	50.07	19.52
APR	45.84	32.09	34.38	36.67	36.67	41.26	36.67	32.09	27.5	22.92	45.84	45.8	45.62	44.25	19.52
MAY	27.21	20.41	21.77	23.13	23.13	24.49	21.77	19.05	16.33	14.44	27.21	27.17	26.99	25.62	19.52
JUN	21.45	17.16	18.23	19.3	18.23	19.3	17.16	15.01	14.44	14.44	21.44	21.41	21.22	19.86	19.52
JUL	18.66	14.93	15.86	16.8	15.86	16.8	14.93	14.44	14.44	14.44	18.66	18.62	18.44	17.07	18.66
AUG	19	15.2	16.15	17.1	16.15	17.1	15.2	14.44	14.44	14.44	19	18.96	18.78	17.41	19
SEP	20.9	16.72	17.77	18.81	18.81	18.81	16.72	14.69	14.44	14.44	20.9	20.86	20.68	19.31	19.52
MIN_1d	10.66	9.01	9.57	9.86	9.68	10.66	10.66	10.66	10.66	10.66	10.66	10.62	10.44	9.07	10.66
MIN_3d	10.9	9.11	9.66	9.98	9.81	10.9	10.9	10.9	10.9	10.9	10.89	10.85	10.67	9.3	10.9
MIN_7d	11.67	9.41	10	10.58	10	11.67	11.67	11.67	11.67	11.67	11.67	11.63	11.45	10.08	11.67
MIN_30d	15.1	11.97	12.72	13.48	13.26	14.51	14.02	13.65	13.49	13.45	15.1	15.06	14.87	13.51	14.63
MIN_90d	19.16	15.09	16.05	17.01	16.27	17.61	16.33	15.49	15.02	14.75	19.15	19.11	18.93	17.56	17.48
MAX_1d	332	216.8	233.5	250.2	265.6	298.8	265.6	232.4	199.2	166	332	331.9	331.7	330.4	281.9
MAX_3d	279.1	181.4	195.4	209.3	223.3	251.2	223.3	195.4	167.5	139.6	279.1	279.1	278.9	277.5	229.1
MAX_7d	228.1	150.8	162.4	174	182.5	205.3	182.5	159.7	136.9	114.1	228.1	228.1	227.9	226.5	178.1
MAX_30d	149.6	97.94	105.2	112.5	119.7	134.6	119.7	104.7	89.74	74.79	149.6	149.5	149.3	148	99.52
MAX_90d	101.9	67.1	72.19	77.29	81.5	91.69	81.5	71.31	61.13	50.94	101.9	101.8	101.7	100.3	59.74
Zero_Days	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BFI	0.2	0.24	0.24	0.23	0.22	0.22	0.24	0.27	0.31	0.37	0.2	0.2	0.19	0.17	0.36
MIN_jdy	252	252	252	252	244	252	252	254	254	257	252	252	252	252	252
MAX_jdy	360	360	360	360	360	360	360	360	360	360	360	360	360	360	360
PRED	0.49	0.5	0.5	0.5	0.51	0.5	0.51	0.53	0.54	0.56	0.9	0.9	0.9	0.92	1.14
LPULSE_n	6	10	8	9	9	7	8	9	12	12	6	6	6	7	24
LPULSE_dur	10.25	7	8	6	6	8	7.5	8	6	8	10.25	10.25	10.25	8	6
HPULSE_n	14	13	14	14	14	14	14	14	11	9	14	14	14	14	12
HPULSE_dur	2.5	2	2	2	2	2	2	2	2	1.5	2.5	2.5	2.5	3	2
RISE_rate	7.63	4.24	4.59	5	5.07	6.89	7.1	6.76	6.34	5.93	7.63	7.63	7.63	7.63	5.72
FALL_rate	-2.71	-1.9	-2.04	-2.17	-2.24	-2.48	-2.43	-2.23	-2.2	-2.27	-2.71	-2.71	-2.71	-2.71	-1.78
REVERS_n	118	127	127	127	129	116	116	111	105	101	118	118	118	118	104

Experiment

p-value: ns; p<0.05; p<0.01; p<0.001

Figure 4.3. Continued.

Flow Metric	UK1	UK2	UK3	UK4	HO1	HO2	HO3	HO4	HO5	ABS25	ABS50	ABS75	ABS95	HEP
	Flow Experiment													
OCT									1				1	2
NOV	2	1	1				1	2	3					2
DEC	2							1	3				1	2
JAN	2	1	1				1	1	4				1	4
FEB	2	1	1				1	2	2				1	2
MAR	2	2	1					1	2				1	1
APR	1						1	2	4				1	3
MAY	1	1					1	1	2				3	4
JUN	2						1	1	1				4	2
JUL								1	1				3	1
AUG													3	1
SEP									1				2	1
BFI	2	2				2	5	5	5			3	4	5
MIN_1d												3	4	
MIN_3d												2	4	
MIN_7d												2	4	
MIN_30d													4	
MIN_90d							2	4	4				2	1
MAX_1d	5	4	4	4		4	5	5	5					2
MAX_3d	5	5	5	5		5	5	5	5					2
MAX_7d	5	5	5	5		5	5	5	5					4
MAX_30d	5	5	5	4		3	5	5	5				2	5
MAX_90d	5	5	5	5		5	5	5	5				2	5
ZeroDays												1	4	
MIN_jdy												1	2	
MAX_jdy														
PRED	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*	*na*
LPULSE_n	3	2	1	2		1	3	5	5			1	4	4
LPULSE_dur							1	1	1					2
HPULSE_n		1						2	3					2
HPULSE_dur	2	3	2	1	1	1	3	3	4			1	1	1
RISE_rate	4	3	2	2		1	2	2	4				4	1
FALL_rate	5	5	3	1					3				4	3
REVERS_n	2	2	2	2				2	2				4	3

Figure 4.4. (above) The number of cluster medoid stations (out of 5) with significant changes in IHA flow metrics for each abstraction experiment.

Flow Metric	CL1F IRL32011	CL4f IRL30021	CL2 IRL25030	CL3s IRL06013	CL5S IRL18002
OCT		1	1	1	1
NOV		3	1	3	7
DEC	3		1	4	4
JAN	3	2	4	1	7
FEB		4		3	7
MAR		1	2	5	5
APR	2	3	1	3	5
MAY	1	3	2	4	5
JUN	1	1	1	6	5
JUL	2	1		1	2
AUG	2	1	1	1	
SEP		1	1	2	1
BFI	8	6	6	6	7
MIN_1d	2	1	2	2	
MIN_3d	2	1	1	2	
MIN_7d	1	2	1	2	
MIN_30d	1	1		1	
MIN_90d	2	2	2	1	2
MAX_1d	4	8	9	7	9
MAX_3d	7	8	9	8	9
MAX_7d	9	6	9	9	9
MAX_30d	10	10	9	9	8
MAX_90d	10	10	7	9	9
ZeroDays	1	1	1	1	
MIN_jdy	2			1	
MAX_jdy					
PRED	*na*	*na*	*na*	*na*	*na*
LPULSE_n	6	6	4	7	9
LPULSE_dur	1	1			1
HPULSE_n	3	1	4		2
HPULSE_dur	7	1	3	5	5
RISE_rate	10	1	6	2	5
FALL_rate	5	4	7	5	3
REVERS_n	1	3	3	8	7

Figure 4.5. (right) The number of flow experiments (out of 14) with significant changes in IHA flow metrics for each cluster medoid station.

time series with the abstracted series. In contrast, flow data from the flashy station from Cluster 1 experienced much more interannual variability and was thus likely to require more severe abstraction before flow changes were sufficient to generate a significant change in flow metrics.

4.4 Conclusions

Coincident with the scientific consensus (Arthington, 2012), our results suggest that, when assessing the effect of abstraction on sensitive ecosystems, a holistic view of flow should be considered. This is because several aspects of flow regime beyond the low flows typically considered of concern, are likely to be sensitive to abstraction. It may be useful to consider whether the 30% of MAF suggested by Caissie *et al.* (2015) for Canadian rivers as a flow value below which river habitats become particularly sensitive to alteration is applicable in the Irish context. All levels of abstraction increased the percentage of days when flow was below 30% of MAF, with the exception of the minor effects of high quantities of abstraction on the high-flow C5 medoid station (Figure 4.6). The results presented here can be used to inform protective abstraction standards and provide insights into the components of the ecological flow regime that might be most influential on sensitive aquatic communities, habitats and functions.

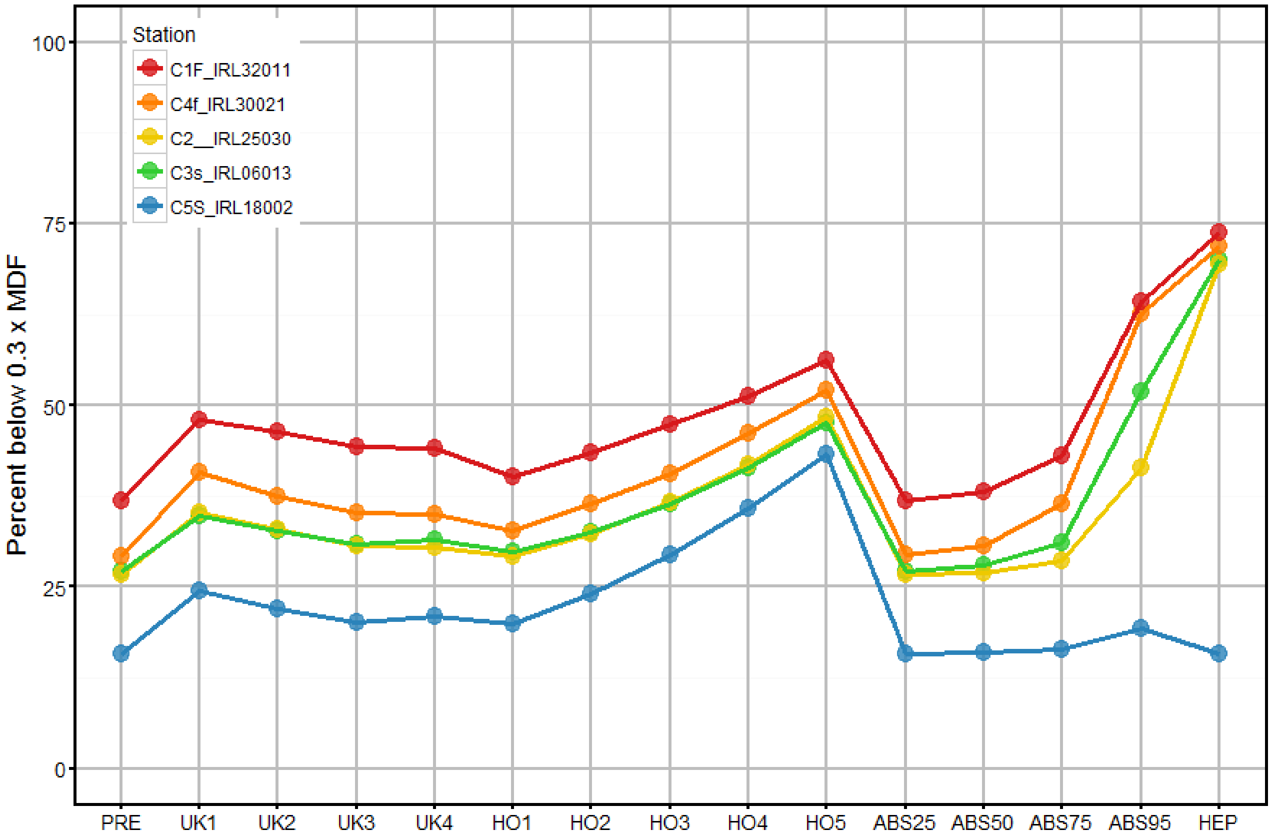


Figure 4.6. Percentage of daily flow observations that were less than 30% of the mean annual daily flow for each experiment, plotted by cluster medoid.

5 Information and Research Needs for Integrating Environmental Flow Concepts into Abstraction Policy

In this section, we combine insights from this research with feedback from speakers and experts attending the EFlow workshop held in November 2015 (Appendix 4) to identify data needs and priorities for future EFlow research supporting abstraction policy in Ireland.

5.1 Data Needs for National Assessment and Abstraction Characterisation

5.1.1 National abstraction and discharge database

Progress on evaluating the current status of abstraction for Irish rivers (which does not account for discharge; Chapter 3) and for screening stations (Chapter 2) was severely hampered by the lack of an integrated national database of abstraction and discharge. This is a key priority for many research and management activities (as indicated by feedback from the workshop participants). In Ireland, three projects are underway to compile abstraction data (section 3.4.1) and it will be important to co-ordinate these efforts to develop a single integrated database.

The effects of water abstraction on rivers act at a variety of temporal (seasonal to annual) and spatial (local to regional) scales, which need to be considered along with water consumption. Abstraction has a wide range of effects on both rivers and lakes. In most settings, domestic water supplies discharging to septic tanks have only local impacts and would not be considered consumptive. Water abstraction for run-of-river hydroelectric schemes may have only a local impact, as intake water is released further downstream (although these local impacts may restrict river continuity). Public water supplies, combined with urban waste water discharges, have impacts at the catchment scale. Intensive agriculture, such as pigs and poultry, have local to catchment impacts and are semi-consumptive. Industrial uses (e.g. for food and beverage products) and irrigation are typically consumptive and have regional to national impacts. Documenting the cumulative effects of these different modes of abstraction within Irish catchments is a high priority for understanding the effects on flow regime and ecological responses.

We recommend that the following components and considerations should be included in a national abstraction database:

1. Documentation of both abstraction and discharge points, including accurate location information and documentation of changes in location over time. It would also be useful to consider effluent discharge, as this may contribute towards the assimilative capacity of rivers.
2. Temporal resolution, preferably at daily timescales, but at a minimum monthly resolution, in abstraction and discharge data to enable understanding of seasonal effects on river flow. Some abstractions, such as those for irrigation for agriculture or for golf courses, are most consumptive in the summer.
3. Consumptive characteristics of abstraction types.
4. Integration between surface and groundwater abstractions to determine the potential influence of groundwater abstraction on surface water flow. Currently, we estimate that, for 34% of abstractions, there is no information on whether abstractions are from surface- or ground-water sources (Table 3.4). Such basic information is critical for a national database.
5. Spatial scaling to enable estimates of cumulative effects on downstream stations. Although they are not likely to be licensed, there are more than 150,000 unregulated agricultural groundwater abstractions, which are small but potentially important cumulatively.
6. Biological data are needed to enable exploration of the impacts of abstraction and discharge changes on the ecology of rivers and lakes. Given that there has been little investigation of the relationships between abstraction and biological metrics of flow alteration pressure in Ireland, we

strongly recommend that ecological monitoring sites be integrated with flow stations to facilitate environmental flow research. We also recommend that raw data on the densities of species should be recorded from every sampling event; densities, even if recorded on a log scale, would enable direct translation of research in the UK and other countries (Dunbar *et al.*, 2010a,b) to the Irish context (see section 5.1.2).

5.1.2 The hydrometric monitoring network and supporting data

Hydrometric data are the foundation of efforts to integrate an EFlow approach into management. Therefore, the first priority for national assessment is the maintenance of a robust, representative and long-term hydrometric network. Three points are highlighted below.

Maintenance of a long-term and representative network of hydrometric and ecological stations

The catchment areas of the hydrometric stations used to generate flow regime clusters suggested a bias towards larger catchments compared with all river segments in Ireland, indicating that these results do not adequately represent upland rivers (e.g. those with low Strahler order) with small catchments (see Figure 2.15). Hydrometric station selection was restricted by data requirements for long-term records. Therefore, it is possible that newer upland hydrometric stations were excluded from these analyses. We recommend that the commitment to maintain long-term hydrologic records is continued and targeted to resolve biases, as it is these records that provide the basis for understanding the effects of abstraction, as well as other drivers of hydrologic regime, such as climate change, in the future. We also recommend that upcoming hydrometric station reviews consider including more upland stations, as well as maintaining existing stations, to fill in any spatial gaps and overcome biases. Finally, it would be useful, for future research examining long-term trends, to consider using the results of the cluster analysis in this paper to identify river locations with relatively low pressures that could serve as hydrologic reference stations.

Assess co-ordination between ecological and hydrologic monitoring

Currently, to our knowledge, there has been no assessment of how many long-term hydrometric stations are in sufficient proximity to ecological and nutrient monitoring stations. Although there may be some practical difficulties, such basic information is, nevertheless, a necessary first step towards developing ecology–flow relationships, which are critical for the progress of environmental flow research.

Availability of accurate supporting data for hydrometric stations

Access to supporting information for hydrometric stations would be beneficial for future research activities. We found that the boundaries of some hydrometric station catchments were not harmonised with other river or lake catchments; the harmonisation of catchment boundaries would be very helpful to future research, particularly in the light of new catchment-based management priorities. In addition, topographical boundaries reflecting surface water flowpaths may not applicable to rivers that are dominated by groundwater, particularly those in karst regions (Coxon and Drew, 2000); in such settings, an understanding of groundwater catchments would be necessary. Other points brought up in the workshop were the need to enhance and maintain hydrometric records and associated data, such as rating curves, and the need for appropriate profiles of gauging stations and hourly climate data. Finally, from our experience of compiling landscape data at the catchment scale, we had to exclude some hydrometric stations with adequate long-term data, but with cross-border catchments, where spatial cover by landscape features ended at the border.

5.2 Research Needs

The research needs for expanding the knowledge base on environmental flow in Ireland are important for upcoming abstraction legislation, as well as for meeting a variety of short-term and long-term EPA information targets for WFD-related activities, such as River Basin Management Plans and Programmes of Measures. Key research needs are described in more detail below.

5.2.1 Developing ecology–flow relationships for assessing abstraction pressures

We recommend that the next research effort on environmental flows in Ireland should focus on the development of flow–ecology relationships for Ireland. Such relationships are critical for setting abstraction limits to protect aquatic communities and ecosystem function.

As discussed above in section 5.1.2, although the EPA has an ecological monitoring programme that stretches over several decades, there are concerns regarding use of these data to develop ecology–flow relationships. Questions that need to be answered are (1) the extent to which existing ecology monitoring sites and hydrometric stations are located in sufficient proximity to each other to enable the inclusion of the resulting data in datasets to develop these relationships (note that co-location is not always possible due to conflicts in siting criteria for flow and ecological monitoring); and (2) whether the EPA relative abundance data on macroinvertebrates have adequate resolution in abundance and taxonomy to be translated into Irish versions of the LIFE (Lotic Invertebrate Index for Flow Evaluation) and DRIED-UP indices in use in other regions (Dunbar *et al.*, 2010a,b). Due to the long-term nature of the data and number of stations, it would be useful to at least explore the utility of these data for environmental flow assessment prior to the development of a more targeted monitoring scheme. The challenges of developing ecology–flow relationships, even for well-studied organisms, such as macroinvertebrates, can not be understated; it is particularly difficult to isolate the effects of flow alteration from co-occurring and interacting pressures related to channel morphology and eutrophication. Macroinvertebrates have long been used as biological indicators and do have advantages for developing flow metrics over other taxa, such as fish, which have additional sources of natural variability related to age structure (with related differences in sensitivity to pressures), population dynamics and management actions, such as stocking, that need to be accounted for (M. Acreman, personal communication, April 2016).

A robust classification typology is essential to the practical integration of ecology–flow relationships into a national assessment of sensitivity to abstraction. These research results provide a typology based on landscape features that are related to flow regime, which can provide a foundation for investigating ecology–flow relationships. Due to the climatic and landscape characteristics of Ireland, we suggest caution when applying typologies developed elsewhere, such as the UK schemes described in section 2.5.2 that classified most of the study rivers as highly sensitive, as these may obscure more subtle differences in hydrology that are important when assessing sensitivity across the country.

5.2.2 Assessment of flow as a component of multiple ecological pressures influencing Irish rivers

Flow is a master driver of river ecology, as it controls habitat structure, and nutrient and sediment transport, and connects rivers with riparian floodplains and wetlands, all of which are key influences on river communities. These interrelationships make it difficult to determine the specific effects of altered flow on ecological status. Therefore, there is a need to improve our understanding of how flow alteration, resulting from pressures such as abstraction, affect the complex interactions with morphology, sediment dynamics and nutrients. The understanding of the cumulative impacts of these multiple pressures is a key knowledge gap for Ireland and for the wider scientific community. The workshop participants identified the following pressures as having potential interactions with flow regime alteration:

- upland forestry;
- windfarm development and associated infrastructure development that can influence drainage, particularly in small catchments;
- hydropower and other barriers to continuity;
- hydromorphology (including channelisation, riparian management, bank erosion);
- sedimentation and silt flux, in particular increased deposition resulting from decreased flow;
- nutrients, especially transport, in-stream cycling and the dilution potential of diffuse emissions and discharge from waste water treatment systems and septic tanks; and
- land management, including drainage and other agricultural practices that alter the delivery of water and silt/nutrients from land to rivers.

5.2.3 What is "natural" in the Irish context?

Many aspects of this research led us to debate what is "natural" in the Irish context. The steps to establish a hydrologic foundation under the ELOHA approach that we followed in Chapter 2 require the use of hydrometric data from representative rivers that have only limited pressures. However, large parts of Ireland are in agricultural use and have centuries of alterations, such as field drainage and channelisation (Figure 5.1), that are now established features of the landscape. These legacies of past land use are often unquantified and are unlikely to be remediated. The approach used in this study was to consider such agricultural uses as "ambient background". Indeed, we found that such widespread agricultural activities were features of rivers in clusters with low membership stability, suggesting that their effects on flow are somewhat site-specific. When trying to characterise landscape settings, it is important to understand what is meant by "natural" and what level of "natural-ness" we are likely to be able to model. While it may be possible to account for abstraction and (possibly) channelisation, we are not going to be able to account for land use changes over the past hundreds to thousands of years.

We recommend that with an improved abstraction database, research should be conducted to identify the current levels of abstraction that are causing deviation from the "natural" state or that need to be accounted for when quantifying background flow regime characteristics. For example, to account for the impact of abstraction in each catchment, we need to define the natural state we want to model. In this situation, can catchments where less than 10%, 5% or 1% of effective rainfall is abstracted be considered "natural"?

In addition to abstraction pressures, there is a need for improved assessment of morphological changes to river channels and associated riparian zones. New data, such as efforts by the OPW to quantify channelisation, as well as river surveys done for hydromorphology, will contribute to resolving these dilemmas.

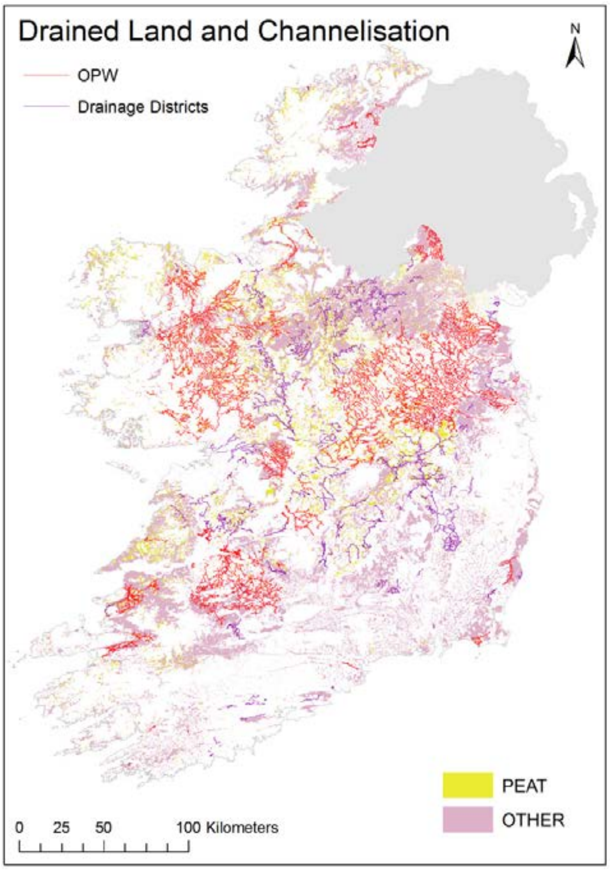


Figure 5.1. Map showing pressures in Ireland influencing flow regime related to potentially drained land (EPA and Mockler *et al*., 2014) and river channelisation.

5.3 Recommendations for Abstraction Policy in Ireland

5.3.1 *Start with a simple and flexible approach*

Ireland is in the process of defining abstraction licensing policies. The recommendation from the workshop was to start simple, using an approach that relies on currently available data, leaving room for enhancements over time as data and knowledge improve. Comments from the workshop and from our experience are summarised below.

1. We should start with current data without waiting until data are perfect, with the following priorities:
   (a) identify abstraction "what-ifs" to inform the setting of licenses, which requires an integrated abstraction database that allows assessment of the range of abstractions currently in Ireland, as well as anticipation of future abstraction pressure;
   (b) develop initial sensitivity assessments based on current data and knowledge, and, prior to developing new initiatives, assess the utility of existing monitoring and data collection projects for informing ecology–flow relationships and new monitoring efforts;
   (c) start work on ecological–flow relationships in tandem with the start of licensing system and use the outcomes to inform future iterations once information becomes available.
2. Prioritisation of rivers for additional protection should be considered; examples are high-status sites (and Special Area of Conservation/Special Protection Area sites), those on the threshold between good and moderate status, catchments most at risk to cumulative significant abstractions, either currently or in the future. As a side note, one workshop attendee suggested that all Irish rivers should be treated as potential salmonid rivers.
3. Hydrologic risk assessment should be compiled as part of WFD hydromorphology; research in the UK suggests that alterations in river morphology have a large influence on flow (Dunbar *et al.*, 2012) and therefore environmental flow assessments should go hand-in-hand with morphological assessments.
4. We should improve our understanding of existing data and the current knowledge base to help identify additional data gaps and priorities once the abstraction process is underway.

A starting point for an integrated abstraction strategy would be to develop a GIS- and catchment-based framework that combines spatially explicit data on abstraction (e.g. location, quantities, consumptive vs non-consumptive) and water discharges; ecological status and presence of protected species and habitats; river site-specific flow typologies; flow estimates (FDCs, for example); directional flow; and lake waterbodies. The national dataset on predicted BFI (maintained by the OPW), combined with the flow classes described here, would provide a basis for estimating sensitivity to abstraction, while the EPA Hydrotool can provide estimates of FDC for any river location; these data sources could provide data to develop flow typologies using approaches similar to those used in the UK, but with criteria revised to reflect the Irish context more accurately. Ecological status would set the boundaries for the flow standards required to protect and maintain high and good ecological status; information from the river passage studies on fish taxon-specific flow requirements (SNIFFER, 2010) could contribute towards setting HO flow requirements. The benefits of this framework for future abstraction licensing are that it integrates the data needed for setting abstraction goals and limits; allows assessment of spatial scaling of abstraction within a river system and definition of cumulative impacts to set abstraction limits; and links WFD ecological assessment and consideration of species, communities and habitats of special interest with flow regime and the potential effects of abstraction. This type of approach is currently in use in Northern Ireland (D. Quinn, NIEA and R. Soley, AMEC Foster Wheeler, personal communication, November 2015) and is an offshoot of CAMS (Catchment Abstraction Management System), which is in use in the UK (Klaar *et al.*, 2014).

5.3.2 *Maintain an adaptive flexible licensing framework to accommodate future knowledge*

A flexible licensing framework can be adjusted to future knowledge and learning. Currently, the data

and knowledge base that are required to develop a fully protective abstraction licensing system are not complete. From workshop participants and our research, we recommend that the issues described below should be considered as abstraction licensing evolves.

Integrate evolving insights into ecology–flow relationships

A research priority for both the management and scientific communities is to gain better insight into ecology–flow relationships. Insights from future research in Ireland and elsewhere will give us more confidence in our understanding of how altered flow influences ecological status and ecosystem function. There could be surprises; for example, upland systems are often considered most sensitive to abstraction, perhaps because they have fewer pressures and often have higher ecological status. However, recent work in progress in the UK suggests that upland macroinvertebrate communities may be more resistant to low flows, as they are adapted to a flashier hydrology (M. Dunbar, Environment Agency, personal communication, November 2016). It is unknown if such a result also applies to Ireland, but it does highlight the potential for new findings to alter the state of the knowledge.

Much of the focus of many assessments of flow alteration has been on low-flow changes. While these are undoubtedly important, water releases and changes to high-flow characteristics as the result of some types of discharge could also have ecological implications, particularly with regard to wetlands and floodplains that may be seasonally dependent. Environmental flows affect all the components of the flow regime, from low to high flows, to changes over short and long temporal scales (Poff *et al.*, 1997).

In line with WFD objectives, the regulation of abstractions is ecologically driven and takes account of the needs of water-dependent habitats, species-protected areas and other protected areas. Therefore, a catchment-scale approach is required that considers integration between rivers, groundwater, lakes and wetlands across space and time.

Include EFlow considerations in other policy and planning activities

As flow regime interacts with other pressures, it would be useful to integrate environmental flow considerations with other policy and planning activities during abstraction licensing. For example, abstraction may influence the efficacy of agricultural controls, particularly in relation to land drainage/drainage maintenance and land reclamation (regulated under agricultural EIA/Appropriate Assessment and/or planning and development). This is because of the impacts of agricultural abstractions on flows, in particular baseflow, and also on channel morphology alteration that is related to increased flood flows or livestock grazing in riparian zones. Consideration of environmental flows is also integral to meeting needs for the protection of sensitive ecosystems under the Habitats Directive.

Anticipate future abstraction pressures

A flexible abstraction-licensing framework is needed to address novel abstraction pressures, such as small HEP schemes, which are currently not very common in Ireland, but are increasing in number in Northern Ireland (D. Quinn, NIEA, personal communication, May 2015). Abstractions that are not regulated, such as the agricultural groundwater abstractions, of which there are more than 150,000, while locally unimportant, may have significant cumulative effects in some locations. Planned agricultural intensification in Ireland is likely to increase pressures on water resources that are currently not under stress.

5.3.3 Environmental flow assessment in an era of global change

Climate change is underway and understanding the implications for flow regime of Irish rivers is a priority, requiring the maintenance of hydrometric records and the flexibility to deal with future surprises (Döll and Zhang, 2010; Ceola *et al.*, 2014). While threats related to the combined effects of climate and socioeconomic water involve scenarios for environmental flow in Ireland that were assessed as unlikely compared with

other parts of Europe (Laize *et al.*, 2014), climate shifts have already been documented in Ireland, meaning that caution must be exercised in the use of historical records to develop a hydrologic foundation for future analysis. A number of studies have been carried out on the impact of climate change on precipitation and hydrology in Ireland (Kiely, 1999; Steele-Dunne *et al.* 2008; Leahy and Kiely, 2011). Steele-Dunne *et al.* (2008) observed an amplification of the seasonal cycle across Ireland, driven by increased winter precipitation, decreased summer precipitation and increased temperature. Kiely (1999) used observations from eight climate stations and hydrometric stations on four rivers to analyse annual precipitation and the frequency of extreme precipitation events in Ireland during the second half of the 20th century. He detected a change point in the mid-1970s for climate stations on the west coast, after which rainfall increased in parallel with a change in the seasonal distribution of precipitation, with most of the increase in annual precipitation resulting from increased storm intensity in March and October. Existing hydrometric models and tools (such as the Hydro Tool FD_based model) currently used by the EPA are reviewed approximately every 5 years and, therefore, can be used to update baseline conditions should there be directional flow responses to climate change; this review could provide a timeline for future abstraction licence modification where necessary (C. Quinlan, personal communication, September 2015). Climate change scenarios, such as those by Laize *et al.* (2014), could be applied to flow records, such as those used in Chapter 4, to assess the potential responses of Irish rivers to climate shifts.

Global change has been projected to have substantial effects on hydrology and ecosystem structure and function in the future. This is reflected in the historical shift of environmental flow assessment from an initial emphasis on mitigating the effects of large dams and water diversions to a global-scale focus on understanding how eco-hydrological systems could respond to rapid global change, as described by Poff and Matthews (2013). We are now considered to be entering a new geological epoch that has been named the Anthropocene to reflect the dominant influence of humans on global ecosystems. As a result of this influence, the world can no longer be considered stationary in terms of ecosystem status. Stationarity is a key assumption of time series analysis and refers to system properties of a constant mean, variance, and autocorrelation structure over time. For environmental flow assessment, non-stationarity complicates the use of the existing hydrologic foundation, as hydrology, ecosystems and their relationships can change as a result of pressures, such as land use change and urbanisation, consumptive water uses and diversion, and climate change (Poff and Matthews, 2013).
As we have limited information on the resilience or resistance of ecosystems to such large-scale and interacting pressures, any EFA (Environmental Flow Assessment) framework will need to be flexible and based on a robust scientific framework. Echoing these conclusions, Acreman *et al.* (2014b) argue that many freshwater systems have been so altered by multiple pressures that they can be considered novel ecosystems, for which we no longer have natural analogues or baselines for setting restoration targets.

As these challenges and research gaps are unlikely to be solved in the short term, incremental and flexible approaches to environmental flow assessment appear to be the most viable approaches to meet the mandates of the WFD and other national priorities. As discussed by Acreman *et al.* (2014b), the implications for existing monitoring and assessment include a larger role for management experiments, adaptive management, and learning and pooling of knowledge across different landscapes and settings within an ecosystem management context.

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Abbreviations

BFI	Baseflow index
CD	Coefficient of dispersion
CIS	Common Implementation Strategy
cms	Cubic metres per second
EFlow	Environmental flow
EIA	Environmental Impact Assessment
ELOHA	Ecological Limits of Hydrologic Alteration
EPA	Environmental Protection Agency
EU	European Union
ESB	Electricity Supply Board
FDC	Flow duration curve
GES	Good Ecological Status
GSI	Geological Survey Ireland
HEP	Hydroelectric power
HMWB	Heavily modified waterbody
HO	Hands-off
IHA	Indicators of hydrologic alteration
MAF	Mean annual daily flow
MDAF	Median annual daily flow
OOB	Out-of-bag
OPW	Office of Public Works
PAM	Partitioning around medoids
PC	Principal components
RF	Random forest
WFD	Water Framework Directive

Appendix 1 GIS Data Sources

Code	Source	Description	Data layer name or URL
a	EPA	River segments	vector_SDE_WATER_RivNetRoutes
b	EPA	Hydrometric catchments	Shapefiles grouped by hydrometric area
c	EPA	Elevation raster 20m pixels	alldtmmos_DTM_20m
d	EPA	Lakes	WFD_LakeSeg_FEB14_12K_point
e	EPA	River segments	vector_SDE_WATER_RivNetRoutes
f	MET	Temperature, 1981–2010 average	(see below)
g	MET	Precipitation, 1961–1990 average	(see below)
h	GSI	Effective rainfall (from recharge layer)	(see below)
i	MET	Potential evaporation, 1961–1990 average	(see below)
j	GSI	Recharge	(see below)
k	TEA	Irish National Soils Map	http://gis.teagasc.ie/soils/downloads.php
l	GSI	Sand/gravel aquifer	(see below)
m	GSI	Karst features	(see below)
n	GSI	Groundwater vulnerability index	(see below)
o	GSI	Bedrock aquifer	(see below)
p	EPA/ DAFM	5 ha Agriculture and Forestry layer, 2012	CLC2012_5ha_intermediate
q	EPA	Groundwater vulnerability, soil type	GEOL_Vulnerability_SG_Susceptibility
r	EPA	Modelled artificial land drainage; derived from Mockler et al. (2014)	LandDrainMap_Sept2015
s	OPW	OPW channelisation	OPW_CC_Channels_intersect20m
t	EPA	Drainage district drainage	Channels_DD_v1
u	EPA	Abstraction points	vector_SDE_WATER_AbstractionPoints

Data sources: DAFM, Department of Agriculture, Food and the Marine; EPA, Environmental Protection Agency; GSI, Geological Survey of Ireland (http://www.dcenr.gov.ie/natural-resources/en-ie/Geological-Survey-of-Ireland/Pages/Data-Downloads.aspx); MET, Met Éireann (http://www.met.ie/climate-ireland/30year-averages.asp); OPW, Office of Public Works; TEA, Teagasc.

Appendix 2 Aggregation Tables for LULC and Soil Drainage

Group	Variable	Components
LULC types	ag_hi	AG_NATVEG, ARABLE, CULT_CMPX
	past	PAS_NATGRASS, PAS_SAND, PAS_SPVEG, PASTURE
	pastpt	PAS_BARE, PAS_HEATH, PAS_MARSH, PAS_PEAT
Soil drainage derived from Irish National Soils	PD (poorly drained)	S_410a, S_660e, S_05MAR, S_700b, S_900f, S_700d, S_05RIV, S_700f, S_760e, S_760c, S_700a, S_760a, S_660c, S_05LAK, S_660d, S_410b, S_700c, S_05RIV, S_600a, S_843f, S_650a, S_700h, S_760f
	PD-ID (poorly to intermediate)	S_1000x, S_1160a, S_1130a, S_1030a, S_1000c, S_900a, S_1000a, S_1130b, S_1030b
	ID-WD (intermediate to well-drained)	S_960c, S_900b, S_920a, S_900e, S_900h, S_1000g, S_900g, S_1100e
	WD (well-drained)	S_1150a, S_300a, S_1100m, S_800a, S_1100n, S_1100ll S_1160c, S_960e, S_1100q, S_800c, S_1150c, S_1100s, S_1100h, S_960d, S_843b, S_360c, S_1150b, S_360a, S_1100a, S_1100d, S_1100c, S_843e
	PEAT	S_01_Bk
	ROCK	S_Rock
	OTH	S_01_Rs, S_Urban, S_01_RsMi, S_01xx, S_Water_Body, S_Tidal_marsh, S_Island, S_0xx, S_Salt_marsh, S_02_Mi

LULC, land use/land cover.

Appendix 3 Hydrometric Stations

Station number	Flow cluster	Data source	Station name	Water body	RBD	County	Easting	Northing	HM area	CA area (km^2)	Riv ord	Alt (m)	PPT (mm)	Yrs (n)	Silhouette width
IRL01041	C1F	OPW	Sandy Mills	Deele	NW	Donegal	227307	399030	01	116.2	4	140	1305	18	0.136
IRL01043	C1F	OPW	Ballybofey	Finn (Donegal)	NW	Donegal	213511	394674	01	313.3	6	214	1839	16	0.360
IRL01054	C1F	EPA	Croaghnagowna Frst.	Bunadaowen	NW	Donegal	206342	386277	01	4.9	3	301	2042	11	0.450
IRL01055	C2	EPA	Mourne Beg Weir	Mourne Beg	NW	Donegal	206477	388292	01	9.7	3	231	1915	14	0.188
IRL03051	C3s	EPA[a]	Faulkland	Blackwater (MO)	NB	Monaghan	270400	337900	03	143.2	5	121	1026	16	0.115
IRL03058	C4s	OPW	Cappog Bridge	Blackwater (MO)	NB	Monaghan	263799	335777	03	52.2	3	154	1060	13	0.142
IRL06011	C3s	OPW	Moyles Mill	Fane	NB	Monaghan	292049	307808	06	210.6	2	128	1009	16	0.166
IRL06012	C2	OPW	Clarebane	Fane	NB	Monaghan	287255	316847	06	162.8	3	135	1031	27	–0.007
IRL06013	C3s	OPW	Charleville	Dee	NB	Louth	304411	290763	06	309.1	5	84	905	26	0.160
IRL06014	C3s	EPA	Tallanstown	Glyde	NB	Louth	295298	297888	06	270.4	5	84	900	22	0.205
IRL06021	C3s	OPW	Mansfieldstown	Glyde	NB	Louth	302337	295243	06	345.8	5	73	881	20	0.145
IRL06030	C2	EPA	Ballygoly	Big (Louth)	NB	Louth	315108	309990	06	10.4	3	257	1098	16	–0.087
IRL07002	C3s	OPW	Killyon	Deel (Raharney)	EA	Meath	268401	249139	07	285	5	96	912	22	0.076
IRL07007	C5S	OPW[a]	Boyne Aqueduct	Boyne	EA	Meath	269207	245268	07	441.2	5	84	864	22	0.331
IRL07009	C3s	OPW	Navan Weir	Boyne	EA	Meath	287905	266761	07	1683.8	6	85	865	21	0.063
IRL07012	C3s	OPW	Slane Castle	Boyne	EA	Meath	294983	273962	07	2460.3	6	91	887	28	0.052
IRL07017	C4s	EPA	Rosehill	Moynalty	EA	Meath	271536	285144	07	70.5	4	148	995	19	0.154
IRL07023	C4s	EPA	Athboy	Athboy	EA	Meath	271741	264238	07	111.5	4	99	904	10	–0.130
IRL07044	C4s	EPA	Ballivor	Ballivor	EA	Meath	268938	253874	07	13.8	3	71	849	13	0.214
IRL08008	C3s	EPA	Broadmeadow	Broadmeadow	EA	Dublin	317451	248648	08	107.9	5	71	763	23	0.127
IRL08011	C3s	OPW[a]	Duleek d/s	Nanny	EA	Meath	305297	268519	08	190.8	5	76	819	17	0.131
IRL09001	C4s	OPW	Leixlip	Ryewater	EA	Kildare	300516	236430	09	209.6	4	80	788	17	–0.002
IRL09002	C5S	EPA	Lucan	Griffeen	EA	Dublin	303227	235137	09	35.0	4	105	845	13	0.139
IRL09009	C5S	EPA	Willbrook Road	Owendoher	EA	Dublin	314246	228508	09	20.5	3	264	1081	10	0.354
IRL09010	C5S	EPA	Waldron's Bridge	Dodder	EA	Dublin	315574	229739	09	94.3	4	256	1191	17	0.362
IRL09011	C5S	EPA	Frankfort	Slang	EA	Dublin	316908	228850	09	5.5	2	103	814	18	0.267
IRL09027	C5S	EPA	Broguestown	Hartwell River	EA	Kildare	294976	220897	09	12.4	3	221	1028	10	0.362
IRL09037	C4s	EPA	Botanic Gardens	Tolka	EA	Dublin	314735	237466	09	137.9	4	78	782	12	0.022
IRL09102	C5S	EPA	Cadbury's	Santry	EA	Dublin	319908	239611	09	10.4	2	60	696	11	0.139
IRL10002	C2	EPA	Rathdrum	Avonmore	EA	Wicklow	319427	188189	10	230.9	5	352	1471	11	–0.048
IRL10021	C3s	EPA[a]	Common's Road	Shanganagh	EA	Dublin	325116	222976	10	32.5	4	141	773	19	0.146
IRL10038	C5S	EPA	Druids Glen	Stream	EA	Wicklow	329312	206350	10	16.0	2	187	883	12	0.199

Station number	Flow cluster	Data source	Station name	Water body	RBD	County	Easting	Northing	HM area	CA area (km²)	Riv ord	Alt (m)	PPT (mm)	Yrs (n)	Silhouette width
IRL11001	C3s	OPW[a]	Boleany	Owenavorragh	SE	Wexford	316991	156044	11	154.4	5	64	913	20	–0.058
IRL12001	C5S	OPW[a]	Scarawalsh	Slaney	SE	Wexford	298380	145014	12	1030.8	6	161	1139	23	0.284
IRL14003	C3s	OPW[a]	Borness	Barrow	SE	Laois	246352	209287	14	206.8	5	144	1042	16	0.096
IRL14004	C5S	OPW[a]	Clonbulloge	Figile	SE	Offaly	260973	223504	14	247.0	4	80	835	19	0.210
IRL14007	C3s	OPW	Derrybrock	Stradbally	SE	Laois	261420	199062	14	94.9	4	135	886	22	0.035
IRL14009	C5S	OPW[a]	Cushina	Cushina	SE	Offaly	255237	216264	14	68.4	3	82	836	18	0.145
IRL14018	C3s	OPW	Royal Oak	Barrow	SE	Carlow	268904	161398	14	2419.4	5	99	862	25	0.065
IRL14019	C5S	OPW	Levitstown	Barrow	SE	Kildare	270623	187609	14	1697.3	5	94	856	20	0.257
IRL14029	C5S	OPW	Graiguenamanagh u/s	Barrow	SE	Carlow	271229	143706	14	2778.2	6	101	877	11	0.225
IRL14031	C5S	EPA	Japanese Gardens	Tully	SE	Kildare	273390	210804	14	15.1	1	107	852	11	0.291
IRL14057	C5S	EPA	Timolin	Bothogue	SE	Kildare	279875	193309	14	32.3	4	164	973	13	0.322
IRL14104	C5S	EPA	Greesemount	Greese	SE	Kildare	279923	195508	14	51.6	2	149	961	10	0.383
IRL15001	C4s	OPW	Annamult	Kings	SE	Kilkenny	254289	144376	15	444.3	5	118	941	24	0.109
IRL15002	C5S	OPW	John's Bridge	Nore	SE	Kilkenny	250795	155835	15	1644.1	6	150	959	21	0.173
IRL15003	C4s	OPW	Dinin Bridge	Dinin	SE	Kilkenny	247880	162807	15	299.2	5	208	1019	20	0.227
IRL15005	C3s	OPW[a]	Durrow Footbridge	Erkina	SE	Laois	240569	177483	15	379.4	5	127	916	15	0.081
IRL15006	C5S	OPW	Brownsbarn	Nore	SE	Kilkenny	261699	139098	15	2418.3	5	137	963	24	0.288
IRL15011	C5S	OPW	Mount Juliet	Nore	SE	Kilkenny	255083	142502	15	2225.7	6	139	952	19	0.230
IRL15021	C5S	EPA	Annagh	Delour	SE	Laois	228989	193543	15	6.0	4	273	1168	16	0.291
IRL16002	C3s	OPW[a]	Beakstown	Suir	SE	Tipperary	209205	155226	16	485.7	5	128	944	20	0.025
IRL16003	C3s	OPW	Rathkennan	Clodiagh	SE	Tipperary	205135	153102	16	243.2	5	158	1086	21	–0.035
IRL16004	C3s	OPW[a]	Thurles	Suir	SE	Tipperary	212895	158636	16	228.7	4	135	948	22	0.084
IRL16005	C5S	OPW[a]	Aughnagross	Multeen	SE	Tipperary	199091	141297	16	84	5	185	1071	20	0.277
IRL16006	C5S	OPW[a]	Ballinaclogh	Multeen	SE	Tipperary	198516	140867	16	75.8	4	197	1093	20	0.199
IRL16008	C4s	OPW[a]	New Bridge	Suir	SE	Tipperary	200220	134149	16	1090.3	6	138	1000	21	–0.104
IRL16009	C5S	OPW	Caher Park	Suir	SE	Tipperary	205297	122870	16	1582.7	6	140	1067	24	0.402
IRL16010	C5S	OPW[a]	Anner	Anner	SE	Tipperary	225309	125585	16	437.2	5	120	969	23	0.390
IRL16011	C5S	OPW[a]	Clonmel	Suir	SE	Tipperary	220798	122248	16	2143.7	6	149	1114	22	0.399
IRL16012	C5S	OPW[a]	Tar Bridge	Tar	SE	Tipperary	210709	113398	16	229.6	5	196	1316	16	0.295
IRL17001	C5S	EPA[a]	Kilmacthomas	Mahon	SE	Waterford	239381	106171	17	60.2	5	201	1163	15	0.185
IRL17002	C5S	EPA	Fox's Castle	Tay	SE	Waterford	234050	100435	17	33.5	4	225	1200	12	0.137
IRL18001	C3s	OPW	Mogeely	Bride (Waterford)	SW	Cork	195610	94146	18	334.1	5	126	1176	12	0.012

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IRL18002	C5S	OPW	Ballyduff	Blackwater (MU)	SW	Waterford	196410	99140	18	2333.7	6	166	1221	27	0.415
IRL18003	C5S	OPW	Killavullen	Blackwater (MU)	SW	Cork	164710	99738	18	1256.7	5	181	1321	26	0.300
IRL18005	C5S	OPW[a]	Downing Bridge	Funshion	SW	Cork	182294	101821	18	378.5	5	158	1137	24	0.377
IRL18006	C5S	EPA	CSET Mallow	Blackwater (MU)	SW	Cork	152546	97448	18	1054.8	5	188	1347	18	0.228
IRL18009	C3s	EPA	Riverview	Allow	SW	Cork	138315	100693	18	307.3	4	201	1258	21	–0.052
IRL18016	C4s	EPA	Duncannon	Blackwater (MU)	SW	Cork	118027	93123	18	116.7	4	212	1492	23	0.086
IRL18050	C2	EPA	Duarrigle	Blackwater (MU)	SW	Cork	124987	94359	18	248.8	5	211	1497	16	–0.055
IRL19001	C3s	OPW	Ballea	Owenboy	SW	Cork	170971	63276	19	103.3	4	100	1162	18	–0.016
IRL19020	C5S	EPA	Ballyedmond	Owennacurra	SW	Cork	185923	76618	19	74.0	4	141	1182	18	0.219
IRL20002	C5S	OPW[a]	Curranure	Bandon	SW	Cork	152932	57155	20	423.7	6	124	1615	23	0.175
IRL20006	C2	EPA	Clonakilty w.w. d/s	Argideen	SW	Cork	140399	44436	20	77.6	4	105	1466	10	–0.045
IRL21001	C2	EPA	Cummeragh Weir	Cummeragh	SW	Kerry	54762	69360	21	47.2	4	238	2004	12	–0.018
IRL21002	C1F	EPA[a]	Coomhola	Coomhola	SW	Cork	99825	54901	21	64.8	5	249	2223	20	0.396
IRL21003	C1F	EPA[a]	Ballylickey	Owvane	SW	Cork	101071	53469	21	77.8	5	179	1991	17	0.083
IRL21004	C2	EPA	Inchiclogh	Mealagh	SW	Cork	102681	51200	21	45.0	4	202	1709	20	–0.180
IRL21005	C1F	EPA	Adrigole	Adrigole	SW	Cork	81226	50583	21	27.5	5	285	2200	19	0.165
IRL22003	C2	OPW	Riverville	Maine	SW	Kerry	92615	106172	22	271.3	5	128	1332	20	–0.104
IRL22016	C2	OPW[a]	Old Weir Bridge	Long Range	SW	Kerry	93657	84996	22	119.5	5	288	2527	15	0.194
IRL22031	C5S	EPA	Killarney s.w.	L. Leane tributary	SW	Kerry	95592	89915	22	0.1	1	25	1538	10	0.202
IRL22035	C2	OPW	Laune Bridge	Laune	SW	Kerry	89188	91126	22	559.7	6	225	1885	14	0.160
IRL22041	C2	EPA	Dromickbane	Finow	SW	Kerry	100681	87147	22	38.7	4	284	2109	14	–0.015
IRL23001	C4s	OPW[a]	Inch Bridge	Galey	SH	Kerry	95729	136181	23	191.7	4	104	1107	17	0.253
IRL23002	C4s	OPW	Listowel	Feale	SH	Kerry	99700	133295	23	646.8	6	196	1376	22	0.137
IRL23006	C5S	EPA	Neodata	Feale	SH	Limerick	111311	126860	23	303.7	5	226	1478	10	–0.060
IRL23017	C4s	EPA	Trienearagh	Smearlagh	SH	Kerry	101355	131340	23	119.1	5	180	1390	19	–0.082
IRL23022	C4s	EPA	Tralee Clonalour	Big (Kerry)	SH	Kerry	83918	114672	23	10.9	4	103	1226	12	0.266
IRL24004	C5S	OPW[a]	Bruree	Maigue	SH	Limerick	155078	130369	24	242.1	4	114	1002	17	0.073
IRL24008	C4s	OPW[a]	Castleroberts	Maigue	SH	Limerick	148000	143779	24	806.0	6	96	968	18	–0.079
IRL24012	C4s	OPW[a]	Grange Bridge	Deel	SH	Limerick	130810	135013	24	366.3	6	116	1119	16	0.188
IRL24022	C4s	EPA	Hospital	Mahore	SH	Limerick	170565	136283	24	41.2	3	116	986	13	0.193
IRL24029	C4s	EPA	Inchirourke More	Deel	SH	Limerick	134386	149141	24	486.1	6	101	1105	15	–0.045
IRL24030	C4s	EPA	Danganbeg	Deel	SH	Limerick	131830	129038	24	258.9	5	120	1071	14	0.002

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IRL25001	C5S	OPW	Annacotty	Mulkear	SH	Limerick	164265	157679	25	647.6	6	153	1111	26	0.224
IRL25002	C5S	OPW	Barrington's Bridge	Newport	SH	Limerick	167908	154908	25	221.6	5	190	1183	26	0.268
IRL25003	C4s	OPW	Abington	Mulkear	SH	Limerick	171538	153428	25	399.1	6	140	1080	17	–0.076
IRL25006	C5S	OPW	Ferbane	Brosna	SH	Offaly	211536	224406	25	1162.8	6	89	935	17	0.201
IRL25016	C3s	OPW[a]	Rahan	Clodiagh	SH	Offaly	225669	225645	25	253.8	5	98	955	17	–0.003
IRL25020	C4s	OPW	Killeen	Killimor	SH	Galway	179761	211030	25	185.9	5	74	990	16	0.206
IRL25027	C5S	OPW	Gourdeen	Ollatrim	SH	Tipperary	188697	179707	25	118.9	4	149	1076	18	0.211
IRL25030	C2	OPW	Scarriff	Graney	SH	Clare	164180	184277	25	280.0	5	136	1158	23	0.154
IRL25034	C3s	EPA	Rochfort	L. Ennell tributary	SH	Westmeath	241597	246359	25	10.8	1	110	946	13	–0.020
IRL25038	C5S	EPA	Tyone	Nenagh	SH	Tipperary	187565	177807	25	136.1	4	169	1267	14	0.221
IRL25040	C3s	EPA	Roscrea	Bunow	SH	Tipperary	213572	189027	25	28.0	3	164	973	16	–0.046
IRL25044	C2	EPA	Coole	Kilmastulla	SH	Tipperary	170946	169510	25	92.5	5	126	1155	14	0.025
IRL25124	C5S	EPA	Ballynagore	Brosna	SH	Westmeath	235696	239704	25	215.5	4	102	946	12	0.119
IRL26002	C4s	OPW	Rookwood	Suck	SH	Roscommon	180656	257075	26	641.5	5	84	1071	16	–0.077
IRL26005	C2	OPW	Derrycahill	Suck	SH	Roscommon	182557	242372	26	1085.4	5	78	1056	24	0.032
IRL26007	C2	OPW	Bellagill	Suck	SH	Roscommon	184175	234570	26	1207.2	5	76	1047	19	0.089
IRL26008	C2	OPW	Johnston's Bridge	Rinn	SH	Leitrim	209006	286138	26	280.6	5	76	1044	22	–0.021
IRL26017	C3s	OPW[a]	Gillstown	Mountain	SH	Roscommon	196638	283325	26	202.1	4	79	1055	16	0.070
IRL26021	C3s	OPW	Ballymahon	Inny	SH	Longford	216107	256987	26	1098.8	5	90	952	23	0.101
IRL26029	C1F	EPA	Dowra	Shannon	SH	Cavan	199064	326947	26	116.9	4	217	1610	24	0.285
IRL26030	C5S	EPA	L. Allen d/s	Shannon	SH	Leitrim	196137	312418	26	442.1	6	193	1420	21	0.108
IRL26056	C2	EPA	Mountnugent Bridge	Mountnugent	SH	Cavan	249160	285744	26	88.3	4	114	991	13	–0.031
IRL26058	C5S	EPA[a]	Ballinrink Bridge	Inny Upper	SH	Meath	249465	280959	26	60.0	3	120	1004	21	0.331
IRL26059	C3s	EPA	Finnea Bridge	Inny	SH	Westmeath	240225	281429	26	256.6	4	104	983	22	0.030
IRL26108	C2	OPW	Boyle Abbey Bridge	Boyle	SH	Roscommon	180537	302625	26	527.3	5	94	1137	12	–0.034
IRL27002	C2	OPW	Ballycorey	Fergus	SH	Clare	134431	180323	27	511.4	5	70	1267	26	0.149
IRL27003	C2	OPW[a]	Corrofin	Fergus	SH	Clare	128653	188589	27	166.4	5	113	1435	14	0.227
IRL28001	C2	OPW[a]	Ennistymon	Inagh	SH	Clare	113299	188191	28	169.4	5	99	1444	17	0.001
IRL28002	C5S	OPW	Doonbeg	Doonbeg	SH	Clare	97248	165180	28	108.2	4	68	1189	12	0.032
IRL29007	C4s	OPW[a]	Craughwell	Dunkellin	WE	Galway	151006	219938	29	271.5	5	75	1081	17	0.044
IRL29071	C2	EPA	Cutra	L. Cutra	WE	Galway	148200	197900	29	123.8	4	133	1166	20	0.254
IRL30002	C3s	OPW	Ower Bridge	Black (Shrule)	WE	Galway	122994	248505	30	193.5	4	38	1128	17	0.032

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IRL30004	C5S	OPW	Corrofin	Clare	WE	Galway	142609	242991	30	699.9	5	69	1094	15	0.260
IRL30005	C2	OPW[a]	Foxhill	Robe	WE	Mayo	123771	268134	30	237.8	4	61	1158	19	–0.188
IRL30007	C5S	OPW[a]	Ballygaddy	Clare	WE	Galway	142000	253772	30	469.9	5	75	1105	18	0.134
IRL30012	C2	EPA	Claregalway	Clare	WE	Galway	137302	233237	30	1072.9	5	65	1095	15	–0.055
IRL30020	C5S	EPA	Ballyhaunis	Dalgan	WE	Mayo	149616	279434	30	21.4	4	98	1147	15	0.418
IRL30021	C4s	EPA	Christina's Bridge	Robe	WE	Mayo	134442	270996	30	103.6	4	75	1155	18	0.137
IRL30031	C2	OPW	Cong Weir	Cong	WE	Galway	114632	255046	30	890.9	5	82	1510	12	–0.013
IRL31072	C2	EPA[a]	Derryclare	Derryclare l.	WE	Galway	80279	247497	31	111.8	6	141	2288	18	0.223
IRL32004	C1F	EPA	Clifden	Owenglin	WE	Galway	67686	250463	32	32.3	4	199	1889	10	0.430
IRL32011	C1F	EPA[a]	Louisburg Weir	Bunowen	WE	Mayo	81604	280258	32	70.1	5	141	1677	16	0.504
IRL32012	C2	EPA[a]	Newport Weir	Newport	WE	Mayo	99773	294400	32	146.2	5	133	1686	18	0.002
IRL33001	C1F	EPA	Glenamoy	Glenamoy	WE	Mayo	89471	333675	33	76.1	5	110	1454	23	0.348
IRL33006	C1F	EPA[a]	Srahnamanragh	Owenduff	WE	Mayo	81662	315442	33	118.7	5	166	1606	17	0.420
IRL34001	C5S	OPW	Rahans	Moy	WE	Mayo	124367	317782	34	1974.8	7	81	1300	21	0.235
IRL34003	C5S	EPA	Foxford	Moy	WE	Mayo	126851	304097	34	1802.4	7	82	1309	24	0.141
IRL34007	C1F	OPW	Ballycarroon	Deel (Crossmolina)	WE	Mayo	112074	315968	34	151.7	5	104	1647	16	0.209
IRL34014	C1F	OPW[a]	Mill Bridge	Clydagh	WE	Mayo	122271	296103	34	52.9	5	135	1498	16	0.445
IRL34024	C4s	EPA[a]	Kiltimagh	Pollagh	WE	Mayo	133333	289236	34	127.2	5	83	1179	18	0.063
IRL34031	C5S	EPA	Charlestown	Charlestown	WE	Mayo	147725	301920	34	23.1	4	119	1214	15	0.180
IRL35002	C1F	OPW[a]	Billa Bridge	Owenbeg	WE	Sligo	163926	325739	35	81.1	5	182	1368	15	0.259
IRL35005	C5S	OPW	Ballysadare	Ballysadare	WE	Sligo	166832	329046	35	639.7	6	100	1204	20	0.200
IRL35012	C2	EPA	New Bridge	Garravogue	WE	Sligo	169396	335963	35	368.7	5	133	1357	12	0.188
IRL35072	C2	EPA	Trasgarve	L. Easky	WE	Sligo	144806	323780	35	10.7	4	308	1505	13	0.139
IRL36010	C3s	OPW	Butlers Bridge	Annalee	NW	Cavan	240817	310466	36	771.7	5	124	1010	21	0.174
IRL36018	C2	OPW	Ashfield	Dromore	NW	Cavan	257582	313986	36	220.2	4	121	995	11	0.205
IRL36019	C3s	OPW	Belturbet	Erne	NW	Cavan	235929	316606	36	1491.8	6	107	997	20	0.111
IRL36021	C1F	OPW	Kiltybardan	Yellow	NW	Leitrim	209141	311976	36	23.4	3	239	1419	24	0.386
IRL36029	C2	OPW[a]	Tomkinroad	Rag	NW	Cavan	231425	317734	36	34.7	3	68	1022	20	0.096
IRL36031	C3s	EPA	Lisdarn	Cavan	NW	Cavan	241552	306272	36	63.8	4	111	990	17	0.198
IRL36079	C2	EPA	Corlea	L. Bawn	NW	Monaghan	271420	311412	36	65.4	3	159	1038	16	0.126
IRL37020	C1F	EPA	Valley Bridge	Glenaddragh	NW	Donegal	164338	376737	37	14.0	3	256	1877	22	0.470

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IRL37071	C2	EPA	L. Eske	L. Eske	NW	Donegal	196691	382063	37	80.1	5	225	1989	23	0.118
IRL38001	C1F	OPW	Clonconwal Ford	Owenea	NW	Donegal	176584	392714	38	111.2	5	186	1842	22	0.448
IRL38004	C2	EPA[a]	Creeslough	Lackagh	NW	Donegal	209797	430067	38	125	5	181	1699	15	0.233
IRL38071	C2	EPA[a]	L. Anure	L. Anure	NW	Donegal	182369	417737	38	36.8	4	182	1674	22	0.172
IRL39006	C2	EPA[a]	Claragh	Leannan	NW	Donegal	220215	420084	39	245.1	5	131	1455	20	0.184
IRL39009	C2	OPW[a]	Aghawoney	Fern o/l	NW	Donegal	217926	421867	39	206.8	5	139	1493	19	0.182
IRL39010	C1F	EPA	Illies	Crana	NW	Donegal	241504	433874	39	36.5	4	214	1310	22	0.324

[a]EPA/OPW data records compiled by Pat Barrett in a pilot study.

Alt, altitude; CA area, catchment area of hydrometric station; HM, Hydrometric Area; PBM, hydrologic data analysed in pilot study by Pat Barrett for EPA; PPT, precipitation (annual); RBD, River Basin District; Riv ord, river order; Yrs, number of years of complete hydrometric data used in analysis.

Appendix 4 Workshop Agenda and Participants

Workshop title: Environmental Flow Assessment for Irish Rivers

Date: Tuesday, 24 November 2015

Time: 0930–1630

Agenda

Ian Donohue (Trinity College Dublin) – General introduction & workshop goals 0930–0940

Katherine Webster/Katie Tedd (Trinity College Dublin) – EFlow overview and application to Irish Rivers 0940–1040

Gabriel Gafney (Ulster University) – Environmental Change and High Status Water Bodies 1100–1110

Mike Dunbar (Environment Agency) – Describing macroinvertebrate response to antecedent river flow and flow pressure: from models to tools 1110–1140

Rob Soley (AMEC Foster Wheeler) – Practical Applications of EFlows to Rivers in the UK 1150–1230

Per-Erik Mellander (Teagasc) – Insights on Hydrology from Catchment Research 1345–1400

Pat Duggan (Department of the Environment, Community and Local Government) – Policy Context and Requirements 1330–1345

Ian Donohue (Trinity College Dublin) – Goals of break-out sessions 1400–1405

Break-out sessions 1405–1510

Reporting of breakout sessions 1530–1600

Ian Donohue/Catherine Coxon (Trinity College Dublin) – Summing up/General discussion 1600–1630

Workshop Attendees

Name	Affiliation
Ian Donohue	Trinity College Dublin
Catherine Coxon	Trinity College Dublin
Katherine Webster	Trinity College Dublin
Katie Tedd	Trinity College Dublin
Rob Soley	AMEC Foster Wheeler
Ahmed Nasr	Dublin Institute of Technology
Donal Grant	Department of the Environment, Community and Local Government[a]
Pat Duggan	Department of the Environment, Community and Local Government[a]
Luke Varley	Department of the Environment, Community and Local Government[a]
Rebecca Quinn	Environmental Protection Agency
Eva Mockler	Environmental Protection Agency
Emma Quinlan	Environmental Protection Agency
Anthony Mannix	Environmental Protection Agency
Matt Craig	Environmental Protection Agency
Conor Quinlan	Environmental Protection Agency
Colin Byrne	Environmental Protection Agency
Dorothy Stewart	Environmental Protection Agency
Brian Coghlan	Inland Fisheries Ireland
Brian Deegan	Irish Water
Martin McGarrigle	Limnos Consultancy
Áine O'Connor	National Parks & Wildlife
Deirdre Quinn	Northern Ireland Environment Agency
Greg McCleary	Northern Ireland Environment Agency
Mairead Shore	Teagasc
Per-Erik Mellander	Teagasc
Stephen Davis	Teagasc
Philip Schuler	Trinity College Dublin
Donata Dubber	Trinity College Dublin
Paul Hynds	Trinity College Dublin
Mike Dunbar	UK Environment Agency
Gabriel Gaffney	Ulster University
Mary Kelly Quinn	University College Dublin

[a]Now known as the Department of Communications, Climate Action and Environment.

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
- An Oifig um Cosaint Raideolaíoch
- 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.

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Environmental Flow Assessment for Irish Rivers

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

Authors: Katherine E. Webster, Katie Tedd, Catherine Coxon and Ian Donohue

Environmental flow assessment is a comprehensive approach to river management that considers multiple aspects of water flows required to protect river ecosystems and the valuable services that they provide (such as fisheries, drinking water, flood protection, etc.). Metrics of environmental flow include measurements of flow magnitude compiled at different temporal scales from daily to annual, frequency and duration of high and low flow periods, timing of events, and rates of change, all of which influence the structure and functioning of river ecosystems. River flow regime is determined by factors such as climate and catchment configuration (topography, geology, landcover) and is modified by pressures such as abstraction, catchment land use and channel modification. Thus, key first steps in applying environmental flow assessment approaches to management and policy are (1) development of a classification system that groups similar rivers by flow regime; (2) an understanding of the landscape features distinguishing groups; and (3) evaluation of the response of flow regime to current and projected abstraction pressures.

Identify Pressures

The overarching goal of this research was to evaluate state-of-the-art environmental flow methodologies to provide recommendations to the Environmental Protection Agency regarding the establishment of a landscape-based framework for setting environmental flow standards. The research used long-term (10+ year) records of daily flow from 166 river hydrometric stations to characterise five flow regime classes that differed in flow regime from flashy to stable and in landscape features such as subsurface permeability, soil drainage, precipitation and elevation. A national abstraction geodatabase was compiled to assess current abstraction pressures in relation to available water resources as measured by catchment annual effective rainfall (i.e. rainfall not evaporated or transpired) and low flow of the study rivers. Results of the study provide insights into how abstraction pressures differentially influence the flow regime of Irish rivers depending upon landscape setting and the presence of interacting pressures such as altered channel hydromorphology and land drainage.

Inform policy

The research identified future research needs for robust regulations such as development of ecology-flow relationships, improved understanding of flow modification as one of many interacting pressures influencing rivers, and investigation of flow regimes of under-monitored headwater streams not well-represented in our study rivers. Hydrometric monitoring data from the range of river hydrologic types found in Ireland are critical for evaluating effects of increased abstraction combined with expected climate change.

The research provides a river classification framework applicable to setting future abstraction standards for rivers in Ireland as well as for refinement of risk assessments required under the Water Framework Directive and River Basin Planning. The results highlight the difficulty in defining natural flow regime in the cultural landscape of Ireland where multiple pressures from land and channel modification, land use and abstraction interact to influence river flow. Development of an integrated national database of both abstraction and discharge with adequate temporal resolution and accurate designations of water sources was identified as a critical data need. Outputs from the research and from a stakeholder workshop provide recommendations for future research and a summary of alternative approaches to setting abstraction standards.

EPA Research: McCumiskey House,
Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie

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