



# A multi-scale analysis and classification of the hydrogeomorphological characteristics of Irish headwater streams

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Received: 22 February 2022 / Revised: 2 August 2022 / Accepted: 6 September 2022 / Published online: 1 November 2022  
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**Abstract** We present a spatially hierarchical, hydrogeomorphological stream classification, based on data collected in Ireland and reflecting our hypothesis that local (site scale) stream physical habitat characteristics are related to the physical properties of the extended reach within which a site is located, and, in turn, to the physical character of the catchment. Using a top-down approach, data on catchment, reach and site-scale stream physical properties were

collected for 42 Irish headwater streams. The summary catchment properties (rock type, topography, soil type and hydrology) were extracted from secondary sources. Reach-scale physical controls on stream hydrogeomorphology (planform, gradient, degree of confinement, bed material) were assembled mainly from secondary sources. Site-scale information on the stream physical habitat mosaic was collected by field survey. Data analysis identified six new ‘River Types’ for steep mountain streams that extend a pre-existing classification system developed for English streams and rivers. Five of the new types with sufficient replication were associated with ‘indicator’ habitats and characteristic habitat assemblages. The classification method is simple to apply and so it is suitable for operational use. We believe that it is applicable beyond Ireland and England to other areas of northern and western Europe with similar climate–landscape conditions.

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Handling editor: Sidinei M. Thomaz

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Guest editors: Mary Kelly-Quinn, Jeremy Biggs, J. Iwan Jones & William D. Riley / Small Waterbodies in the Landscape

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**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s10750-022-05013-5>.

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**Keywords** Hierarchical · Small streams · Stream classification · Catchment types · Stream types · Physical habitat assemblages · River condition assessment

## Introduction

Why stream and river hydrogeomorphology is ecologically important

The sedimentary structure, morphology and dynamics of stream and river reaches drive the physical habitat mosaic that is available to organisms inhabiting the river channel and its margins. The specific habitat mosaic dictates the suite of habitats available to organisms throughout their life cycle stages and so supports their functions within these stages. This interaction (between biology and hydrogeomorphology) has the capacity to filter the species pool for those that can persist in a given lotic environment; thus, structuring the biological community of the stream or river reach (Beisel et al., 1998, 2000; Wolter et al., 2016). It follows, therefore, that developing a methodology that accurately categorises the physical habitat mosaic is integral to understand the nature of the interaction between ecology and hydrogeomorphology in the small streams, which are the focus of this paper.

Interactions between physical processes and river channel morphology

The physical properties of stream and river reaches depend upon natural processes of water and sediment transfer and vegetation encroachment. They are also constrained by human interventions in a river reach, across a river network and within a catchment. Furthermore, as physical processes and human interventions and pressures change through time and space, reach characteristics may also change. Thus, the physical character of a stream or river and its assemblages of physical habitats adjust continuously through time and space (Fryirs & Brierley, 2021).

Regardless of the size of a river or stream, the same natural processes and local natural characteristics constrain channel morphology, the physical habitat mosaic and how these vary spatially and temporally. However, the relative importance of these controlling processes and the relative influence of local characteristics change with river or stream size (Church, 1992). In addition, Schumm (1977) defined three sediment-related process domains that may be present along river systems from a zone of net erosion in the headwaters through to a zone of erosion–deposition

balance in the middle reaches to a zone of net deposition towards the river mouth. Montgomery (1999) built on this domain concept to define suites of physical processes that may operate in each domain and their ecosystem relevance in terms of disturbance magnitude frequency, physical habitat dynamism and the presence/absence/extent of a hyporheic zone.

Fluvial geomorphology and river management texts (e.g. Schumm, 1977; Downs & Gregory, 2004; Brierley & Fryirs, 2005; Simon et al., 2011; Konold & Piégay, 2016) provide detailed accounts of the physical character and dynamics of streams and rivers. The following brief overview considers the key factors underpinning the research described here.

Stream power (a combination of flow and river gradient) is the fundamental control on the ability of any river or stream to move sediment particles of different sizes (boulders, cobbles, gravel, sand and silt). When deposited downstream, the resulting patches of bed sediments of different sizes provide physical habitats and also form the building blocks of larger physical habitat structures (e.g. bars, riffles) that may be present within a river channel. However, in many small streams, very coarse bed materials (e.g. boulders) are immobile because the stream does not have sufficient power to move them, even during the largest flow events. Indeed, when coarse materials are observed in small streams, they have often been placed there by processes other than flowing water, such as landslides or glacial activity. These coarse, relatively immobile, elements can control flow patterns in small streams, determining the locations and proportions of fast flowing or slow flowing hydraulic habitats. Stream flows may move finer components of the bed material across and around these coarse sediment particles, creating physical and hydraulic habitats as they are eroded, transported and deposited by flowing water. In contrast, all sediment particles can be moved in finer-bedded, truly alluvial, headwater streams as flow varies and the processes of sediment erosion, transport and deposition can create an entire mosaic of physical habitats and influence the distribution and variability in the hydraulic habitats that are present. However, in these finer-bedded small streams, vegetation can become an important controlling factor, with individual plants or large wood pieces acting in a manner similar to large sediment particles, influencing local flow patterns and the retention–mobilisation of sediment particles. As river

size increases, the influence of individual large particles, plants or large wood pieces becomes increasingly less important for channel morphodynamics and the river channel form becomes a reflection of flow regime and sediment interactions, with broad vegetation encroachment occasionally important where environmental conditions are suitable.

Furthermore, the potential for a stream or river to move laterally (i.e. to be unconfined) affects the space available for stream flows to erode the stream channel banks, deposit sediments and create new landforms (physical habitats) along the stream margins and for vegetation to colonise newly deposited sediments and so induce the development of additional physical habitat types. The potential for a stream or river to move laterally and build lateral landforms also affects its planform and so planform is an indicator of the types of physical habitat that may be present. Although many sizeable rivers are confined by their valleys, confinement in small headwater streams is more common and may strongly influence their morphology.

Human actions influence or constrain all of the above natural processes and related physical forms and habitats. For example, modifications of land cover and methods of land management affect the quantity and speed of water delivery to the stream and river network and the degree to which the water can access and transfer sediments to the fluvial system (e.g. Boardman et al., 2019). Water management measures related to both water resource development and flood control affect the magnitude and frequency of flows and the transfer of sediments through the stream and river network (e.g. Petts & Gurnell, 2021). Direct channel modifications such as realignment, resectioning and the reinforcement of channel bed and banks affect channel–floodplain connectivity, main channel flow velocities and sediment erosion–transfer–deposition processes and the degree to which the channel is able to adjust to these processes (e.g. Brookes, 1988). The impacts of these human actions, which accumulate along catchments, affect river channel forms and stability and are fundamentally changing the physical character of river systems in many parts of the world (Brown et al., 2018; Downs & Piégay, 2019).

## River classification

Despite their continuous nature, classifying complex river processes and forms can be useful when attempting to understand relationships amongst the hydrological, geomorphological and ecological properties of river systems and can be particularly helpful for the practical assessment of streams and the design and implementation of management approaches. Indeed, the complex linkages amongst processes, forms and ecological responses have provided the foundation for development of many multi-scale approaches and spatially hierarchical classifications to support a better understanding of how river and stream reaches, corridors, networks and catchments function (Brierley & Fryirs, 2005; Belletti et al., 2015; Gurnell et al., 2016a; Montgomery & Buffington, 1998; Buffington & Montgomery, 2021). These include bottom-up ‘scaffolding’ approaches (e.g. Belletti et al., 2017; Fryirs & Brierley, 2021) which build and integrate geomorphological knowledge from one level to the next and top-down ‘framework’ approaches (e.g. Rinaldi et al., 2013; Gurnell et al., 2016a) which aid the design of simple, operational syntheses and assessments and of course many hybrids of these.

Frissell et al. (1986) were probably the first to formally propose a multi-scale top-down framework to allow streams and their habitats to be classified. Their aims were to guide monitoring, allow generalisations from site data and determine the cumulative impacts of human activities. Frissell et al. (1986) did not propose any specific classifications, but they outlined the criteria that might be used in achieving a practical hierarchical classification.

In the ensuing decades, many researchers have developed approaches for classifying river and stream systems (see reviews by Kondolf et al., 2016; Gurnell et al., 2016a; Rinaldi et al., 2016) that have proved useful for structuring field investigations, recognising typical river and stream characteristics, assessing stream condition and guiding rehabilitation–restoration actions. Some classification approaches are entirely physically based (e.g. Montgomery & Buffington, 1997, 1998; Montgomery & MacDonald, 2002; Brierley & Fryirs, 2005; Rinaldi et al., 2013) but there is an increasing trend towards a broader, more ecological approach, particularly through the inclusion of vegetation as both a biological response and physical control on stream and river

morphodynamics (e.g. Gurnell et al., 2012, 2016b; Castro & Thorne, 2019).

Recently, a simple, top-down, geomorphologically informed, operational framework has been developed to link the broad geomorphic character of extended river reaches to local physical habitat assemblages to establish potential target conditions against which local river condition may be assessed (Gurnell et al., 2020). The method was developed and tested for application in England as part of the Biodiversity Metric 3.0 method for investigating the potential for Biodiversity Net Gain associated with land and river projects (Panks et al., 2021). However, the full specification of this River Condition Assessment approach was hampered by the small number of steep, high-energy mountain streams in the calibration data set. As a result, only a limited range of steep, mountain headwater river types were covered by the method, but this was deemed to be sufficient for its application to English river systems. However, the classification could benefit from some refinement for application in more mountainous environments within a similar biogeographical setting.

The analysis presented in this paper forms part of the SSNET research project (“Managing the small stream network for improved water quality and biodiversity and ecosystem services protection”) which is concerned with headwater streams in the Republic of Ireland (RoI). The hydrogeomorphological component of the project aims to build an integrated understanding of headwater stream hydromorphology across the RoI, emphasising their physical and vegetation-related morphological properties within different landscape settings. To achieve this, we adopted a hierarchical multi-scale approach that attempted to classify a representative set of Irish headwater streams. However, the data collection was necessarily constrained by the need to focus on sites that were relatively free of human impacts to assess the contribution of small streams to catchment biodiversity and the role of hydromorphology and hydrochemistry in controlling their biodiversity potential. This constraint resulted in many of the investigated sites being located in upland settings and so provided the data and the opportunity to revisit and refine the classification of steeper streams proposed by Gurnell et al. (2020).

The overall aim of the research was to devise a top-down hierarchical approach for characterising

the hydrogeomorphology of Irish headwater streams. Our hypothesis was that the very local ‘site’ scale (ca. 100 m channel length) physical properties of small streams reflect the physical character of the extended reaches (ca. 1–5 km channel length) in which they are located, which in turn reflect the broad physical characteristics of their headwater catchments. This overall aim and hypothesis gave rise to four specific research objectives. The first three focussed on delivering information and analysis at three nested spatial scales: catchment, reach and site. The fourth objective was to test the research hypothesis and; thus, establish the degree to which the outcomes of the analyses at the site scale could be linked to those at the reach and catchment scales to provide a hierarchical hydrogeomorphological characterisation of Irish headwater streams. The four specific objectives were as follows:

1. At the catchment scale, the aim was to identify a set of Irish headwater catchments whose stream hydromorphology, ecology and water quality were minimally impacted by human interventions, so that we could explore naturally functioning physical process–response systems that represent the broadest possible range of Irish headwater catchment types (hereafter catchment types: depending on combinations of rock type, topography and soil drainage).
2. At the reach scale, the aim was to investigate headwater streams within a representative set of catchments. Extended reaches were selected from the identified set of catchment types, which, based on the desk study, displayed consistent slope, planform, degree of valley confinement and limited evidence of longitudinal variation in discharge. Measurements of these variables coupled with information on channel-bed material, extracted from field observations, reflect the broad physical factors that are likely to constrain the assemblage of physical habitats that are present. These measurements were used to assign each extended reach to a hydrogeomorphological river/stream type (hereafter River Type).
3. At the site scale, the aim was to undertake field surveys to quantify the local presence and abundance of physical habitats within the selected reaches.
4. The final objective was to test our research hypothesis by establishing the degree to which

the physical habitats observed at the site scale showed statistically significant patterns in relation to the reach scale River Type to which each site and headwater stream had been assigned and whether they also reflected the broad catchment types within which they were located.

In pursuing the above objectives at relatively pristine sites, the research has the potential to identify the physical habitat characteristics that would be expected in naturally functioning headwater streams of each river type and catchment type. This is highly relevant to operational stream management in that it provides a hydrogeomorphological river type datum, extracted from a rapid desk study, against which a site-scale field-surveyed physical habitat assemblage can be compared to assess the degree to which a site appears to be in good hydrogeomorphological ‘condition’. Where that datum is not achieved at a site, the research results provide a target to which any restoration of a site could aspire, according to its River Type.

Although the research is specifically concerned with Irish headwater streams, the results are integrated into a pre-existing classification devised for application to small rivers and streams in England. Therefore, we believe our results are applicable to both geographical areas and are likely to be transferable to watercourses in similar environmental settings across much of northern and western Europe.

## Materials and methods

Catchment characteristics: selection of headwater reaches and sites

In this section, we provide an overview of the approaches used to define catchment characteristics, classify catchment types and then select stream reaches for in-depth study.

Catchment types were identified to ensure that the selected stream reaches were as representative of the physical character of the Irish headwater stream network as possible and to allow surveying effort to be focussed on the most common catchment types. The catchment types were discriminated using available information on geology (GSI, 2006), physiography (GSI 2018) and soil drainage (EPA, 2019). Three classes of each of these three physical descriptors

were established to provide a set of 27 combinations of descriptor classes or catchment types. These were mapped and the proportions of Irish 1st and 2nd order headwater streams, as defined in the EPA’s River Network Routes dataset (EPA, 2017), associated with each catchment type were calculated. An additional karstic catchment type with karstic bedrock and substantial karstic conduit flow was also defined.

Having established the spatial extent of the catchment types, four minimally impacted stream reaches were sought on 1st and 2nd order streams in each of the catchment types that together accounted for over 75% of the total Irish 1st and 2nd order stream length plus the karstic catchments that supported the highest lengths of first and second order streams (52 streams in total). Where possible, the human impact at potential stream reaches was assessed using river water quality information (Q value scores) assigned to streams by the Irish Environment Protection Agency (EPA), the EPA’s Significant Pressures dataset (EPA, 2018) and the location of river channels which are part of the Irish Office of Public Works’ (OPW) arterial drainage scheme (OPW, 2004). However, there are few biological monitoring points on Irish 1st and 2nd order streams. Furthermore, whilst the EPA’s Significant Pressures dataset does indicate whether a European Union Water Framework Directive waterbody is experiencing a significant pressure (i.e., one which is having a deleterious effect on water quality), the spatial resolution was typically insufficient to aid site selection, with 1st and 2nd order streams often located above the pressure which had been assigned to them. This paucity of information meant that candidate streams were frequently located using Google Earth aerial imagery followed by a field visit to confirm the level of human modifications or pressures.

Overall, the above-described approach to select first- and second-order streams for analysis attempted to ensure that the selected streams were representative of the range of physical landscape conditions under which such streams occur in the RoI and were also relatively free of human impacts. In this way, it was hoped that reach and site-scale analyses would reveal a set of representative headwater stream types and associated physical habitats.

## Reach and site-scale data assembly and analysis

### *The MoRPh survey*

Both reach and site-scale research employed data collected using a pre-existing survey method (MoRPh, Gurnell et al., 2019). MoRPh is a geomorphologically-informed habitat survey that is applied to short (10–40 m) lengths of a stream or river. It quantifies the overall bed surface sediment calibre (i.e. average and coarsest particle sizes) using a visual assessment, which is required at the reach scale to assign a river to a particular River Type and it also records the character and extent of all physical habitats, including bed material patches and thus, the physical habitat mosaic that is present at a site.

The MoRPh survey records physical and vegetation structural features and human pressures and interventions across the bank tops (up to 10 m from the stream), bank faces, channel edge-water margin and the bed of small rivers and streams. The cover abundance of observed features is recorded using a simple abundance scale [A=absent, T=trace (<5% cover), P=present (5–33% cover), E=extensive (>33% cover)], or a count, or for a small number of features, simply their presence/absence.

A single MoRPh survey records information for a short channel length equivalent to approximately twice the channel width. For the headwater streams in the current study, all MoRPh surveys recorded information for 10 m stream lengths. In order to characterise the full range of physical habitats within these streams two MoRPh5 surveys were undertaken on each stream, where each MoRPh5 survey consisted of five contiguous MoRPh surveys. The two MoRPh5 surveys were conducted adjacent to one another, at locations that were more than 1 km from the sources of all investigated headwater streams. These two surveys provided physical habitat information for two adjacent 50 m long study sites, allowing us to investigate. (i) The influence of local bed material variability on the reach scale classification of River Type and (ii) the degree to which the physical habitat assemblage at each site was sensitive to reach or site-scale controlling factors.

The field surveys were uploaded to an existing online information system ([www.modularriversurvey.org](http://www.modularriversurvey.org)) that stores and maps the survey data, stores up to

four photographs for each surveyed site and supports downloads into spreadsheets and GIS layers.

### *Hydrogeomorphological river reach classification*

The main controls on the morphodynamics of streams and thus the physical habitats that they support is their power (a combination of water discharge and downstream gradient); the size and quantity of the sediments available for the flow to erode, transport, sort and deposit; and the space available for the stream to move laterally. Riparian and aquatic vegetation can also be an important influence on the physical habitat mosaic of streams and rivers. Therefore, our approach to reach hydrogeomorphological classification synthesises available information on these controlling factors. In the absence of flow data, we considered stream planform, gradient, degree of confinement and bed material. We followed the classification principles proposed by Gurnell et al. (2020). However, because most of the Irish headwater streams selected for analysis were located in upland settings, a set of stream environments that are relatively rare in England, we developed a set of new River Types for the upland Irish headwater streams that were investigated.

We developed a River Type classification using information from extended reaches of stream (typically >1 km in length) enclosing the paired sites where MoRPh5 field surveys were undertaken. Google Earth imagery and topographic information were used to identify surrogates for some of the above-described controls within reaches unaffected by major tributary confluences (i.e. possessing limited variability in flow along the reach), with consistent stream planform (single or multi-thread, straight-sinuuous or meandering), valley gradient and degree of confinement of the stream by its valley. Eight indicators were used to assign reaches to a river type (Gurnell et al., 2020): A1—braiding index, A2—sinuosity, A3—anabranching index, A4—valley confinement, A5—valley gradient, A6—bed rock reaches, A7—coarsest bed material type, A8—average bed material size. Indicators A1 to A5 were estimated for each reach as follows:

1. For single-thread streams, the sinuosity (indicator A2) of the planform was estimated by dividing the length of the stream centre line along the selected reach by the valley length and then sepa-

rating straight-sinuuous from meandering channels using a ratio value of 1.5 (Leopold & Wolman, 1957).

2. Multi-channelled streams were characterised by counting the average number of stream channels (at low flow) that were intersected by ten, equally spaced cross-valley transects along the reach, using information extracted from a Google Earth image that showed the stream under baseflow conditions. If the average transect channel count exceeded 1.1 and the bed material was gravel or coarser (indicator A8, see below), the stream was identified as multi-thread wandering or braided (indicator A1). In addition, for streams that were sand bed or finer (indicator A8), if channels were counted only when they were separated by well vegetated islands and the ratio exceeded 1.5, the stream was identified as anabranching (indicator A3).
3. The degree of valley confinement (indicator A4) was assessed by considering the proportion of the stream bank length that was in contact with the valley side slopes. Confined reaches had more than 90% of the total river bank length in contact with the valley sides; unconfined reaches had less than 10% of their total river bank length in contact; and partly confined reaches had an intermediate level (between 10 and 90%) of bank–hillslope contact.
4. The valley gradient (indicator A5) was calculated from the ratio of the difference in elevation between the upstream and downstream ends of the reach and the valley length.

The values of these five indicators were combined with three bed material indicators (A6, A7 and A8) extracted from the MoRPh5 field surveys. MoRPh surveys recognise seven mineral bed material types: bedrock (BE), boulder (BO), cobble (CO), gravel–pebble (GP), sand (SA), silt (SI) and clay (CL). The abundance of each is recorded using the A, T, P, E abundance scale described above in subsection (i) (The MoRPh Survey). Based on the observed abundances over each MoRPh5 survey, bedrock reaches (indicator A6) are defined where the total abundance of exposed bedrock (BE) equals or exceeds either 3E (i.e. 3 of 5 MoRPh modules recording E) or 2E plus 2P. The coarsest bed material type (indicator A7) is that which shows an abundance of

P or E in at least one of the five surveyed modules. The average alluvial bed material size (A8) is calculated from all records of T, P or E for six of the bed material types BO, CO, GP, SA, SI, CL. The following equation applies the mid-point percentages of 2, 19 and 67, respectively, for abundances (percentages of bed area calculated from T, P, E observations) to calculate the average bed material size (in phi units) for each MoRPh5 survey:

$$A8 = \frac{10CL + 6.5SI + 1.5SA - 3.5GP - 7CO - 9BO}{CL + SI + SA + GP + CO + BO} \quad (1)$$

where *BO*, *CO*, *GP*, *SA*, *SI*, *CL* are the total abundances of each of the bed material types across the 5 modules of the MoRPh5 survey (the site).

The values of all eight indicators were explored for all surveyed sites to refine the River Type classification of Gurnell et al. (2020) for application to Irish headwater streams.

#### *Site-scale physical habitat characteristics and their association with reach-scale river types*

Information on physical habitat characteristics at the site scale was captured using the MoRPh field survey (Gurnell et al., 2019, 2020). Focussing on selected MoRPh survey fields that describe the abundance of physical patches and features within the stream channel, physical habitat information was extracted from the MoRPh5 surveys for each of the two adjacent sites surveyed in each stream reach. The selected fields record the abundance (A, T, P and E scale) of channel surface bed material patches (bedrock, boulder, cobble, gravel–pebble, sand, silt, clay, organic material and peat). They also record physical bed features using the A, T, P, E abundance scale (exposed bedrock, vegetated and unvegetated rocks (boulders), vegetated and unvegetated mid-channel bars, islands, cascades) and a count of the number of other physical features (pools, riffles, steps, waterfalls). Along the bank faces and channel margins, the A, T, P, E scale is used to record the abundance of unvegetated and vegetated side bars, berms, benches, stable and eroding cliffs, toe deposits, animal burrows and marginal backwaters (embayments). When using the MoRPh survey, these geomorphic features are recognised by their geometric form rather than any process evidence in order to be consistent in identification of habitats

across different sites. This also reflects the fact that the MoRPh survey was designed originally for application by non-specialist surveyors (Gurnell et al., 2019).

MoRPh surveys also captured information on terrestrial vegetation structure of the bank tops and bank faces (the abundance of bare earth, short grasses and herbs, tall grasses and herbs, scrub and shrubs, trees and saplings, fallen trees and large wood) and aquatic vegetation structure of the channel bed and immediate margins (the abundance of nine morphological types of aquatic plant as well as tree-related features, such as large wood, exposed roots and shade).

The abundances of the physical habitats across sites assigned to each River Type were investigated using Box and Whisker plots, focussing separately on the four groups of physical habitats: bed material habitats, bed physical features, bank–margin physical features and vegetation structural habitats. The aim was to assess whether the abundance and mosaic of physical habitats appeared to change according to the River Type across the 84 study sites. Note that here all bed material patches observed at each site are included, as they represent a range of distinct physical habitats, rather than the three bed material summary indicators (A6, A7 and A8) used to define the reach-scale River Types.

The same four groups of physical habitats were then explored to establish whether the River Types to which each site was assigned were distinguished by any specific gradients in the physical habitat assemblages. Where habitat abundance was surveyed using the A, T, P, E scale, each observed abundance was assigned a numerical mid-point value (0, 2, 19, 67%) and then the module numerical values were accumulated over the 5 modules surveyed at each site to give a maximum abundance of 335 for bed features and 670 for bank features (the sum for both banks). For habitats surveyed as counts, the total count across the 5 modules was used in the analysis. All analysis used non-parametric techniques. Principal Components Analysis (PCA) was performed on a Spearman's rank correlation matrix amongst the investigated variables within each of the three groups of physical habitats. PCA estimates new uncorrelated variables (Principal Components, PCs) which are linear combinations of the original variables and sequentially maximise

the variance in the original data set explained by each PC (Jolliffe and Cadima, 2016). We applied PCA to explore the degree to which the derived PCs defined interpretable geomorphic gradients and separated sites allocated to different River Types. Kruskal–Wallis tests were applied to the site scores on the first three PCs of each PCA to identify whether sites assigned to different River Types were associated with significantly different PC scores. Pairwise comparisons were then performed using Dunn's test with Bonferroni correction to identify the degree to which each River Type could be distinguished by their scores on the PCs.

Finally, the analysis returned to the observed abundances of the individual physical habitats with the aim of establishing whether there were any indicator habitats for particular River Types. Kruskal–Wallis tests were applied to the abundance data for each habitat type in turn, according to their River Type. Dunn's tests with Bonferroni's correction were then applied to establish which River Types could be distinguished by the abundance of each individual habitat type.

## Integration

A final research stage assessed the apparent hydrogeomorphological linkages amongst the site scale, reach scale and catchment scale analyses. This tested our research hypothesis. It also allowed the production of an integrative table that synthesised the types of indicator habitats and the character of the habitat assemblage that should be expected in association with headwater streams assigned to each River Type if the stream is functioning naturally.

All spatial analysis was carried out using ARCMAP version 10.7 (Esri, 2019). The statistical analysis was conducted using XLSTAT version 2020.5.1.1079 (Addinsoft, 2021).

## Results

Headwater catchment characteristics and the selection of headwater reaches and sites

The analysis stages performed and the data sources used to establish the catchment types are listed in

**Table 1** Development of SSNet catchment types, classification of small streams by catchment type and calculation of the most common 1st and 2nd order streams by catchment type

Step number	Step description	Dataset(s) used	Outcome	Comments
1	Select broad landscape characteristics likely to affect stream ecology, chemistry and hydromorphology	–	Catchment geology, physiography and soil drainage selected for SSNet Catchment type classification	–
2.1	Develop three geological classes	Geological Survey of Ireland (GSI) Hydrostratigraphic Rock Unit Groups (GSI, 2006)	Three classes created: (1) Calcareous Sedimentary, (2) Non-calcareous Sedimentary, (3) Igneous and Metamorphic	Sands and gravels omitted as represent a small fraction of ROI. See Supplemental Table 1 for detailed description
2.2	Develop three physiographic classes	GSI Physiographic Units Level 3 (GSI, 2018)	Three classes chosen: (1) Hill to Mountain, (2) Undulating to Hill, (3) Flat to Undulating	See Supplemental Table 2 for detailed description. Classes selected to align with those used by the EPA
2.3	Develop three soil drainage classes	Teagasc <sup>a</sup> -EPA National Wet/Dry Soils (EPA, 2019)	Three classes created: (1) Peat, (2) Poorly Drained, (3) Well Drained	Made ground and water omitted. Mineral alluvium included in poorly drained class. See Supplementary Table 3
3	Map the combination of the geological, physiographic and soil drainage classes across the Republic of Ireland (ROI)	Outputs of step 2	27 of the potential 82 catchment types (including karstic type) were identified as SSNet catchment types and were mapped across ROI (see Supplemental Fig. 1)	–
4	Classify the 1st and 2nd order streams of the ROI by SSNet catchment type	Output of step 3 and EPA River Network Routes dataset (EPA, 2017)	95% of 1st and 2nd order streams were classified by SSNet catchment type. Prevalence of SSNet catchment types calculated based on cumulative stream length assigned to each type (See Supplemental Table 4)	–

<sup>a</sup>Irish agriculture and food development authority

Table 1 with further detail in the supplementary information, including greater detail on the derivation of the geology, physiography and soil drainage classes (Supplementary Tables 1, 2 and 3). A GIS overlay analysis of the three classes of each of three catchment descriptors/characteristics (Table 1) established the extent of each of the 27 catchment types in the RoI (see Supplementary Fig. 1 for map of the catchment types). First and second order streams were extracted from the Irish Environmental Protection Agency (EPA) stream network data and their total length within each of the 27 catchment types

was calculated (Table 1). In addition, potential karstic study catchments were identified using Geological Survey Ireland's (GSI) Groundwater Resources Bedrock dataset which shows the location of karstic regions in Ireland and GSI's Groundwater Karst Features dataset which shows the location of karstic features (GSI, 2019). The summary information on the karst catchment type and the 12 catchment types containing the longest lengths of first- and second-order streams (including, in total, over 75% of the total RoI first and second order stream length) is provided in Table 2 (see Supplementary Table 4 for description of

**Table 2** Forty-two stream reaches selected in relation to the SSNet Catchment type and the proportion of the 1st and 2nd order stream network present within each catchment type

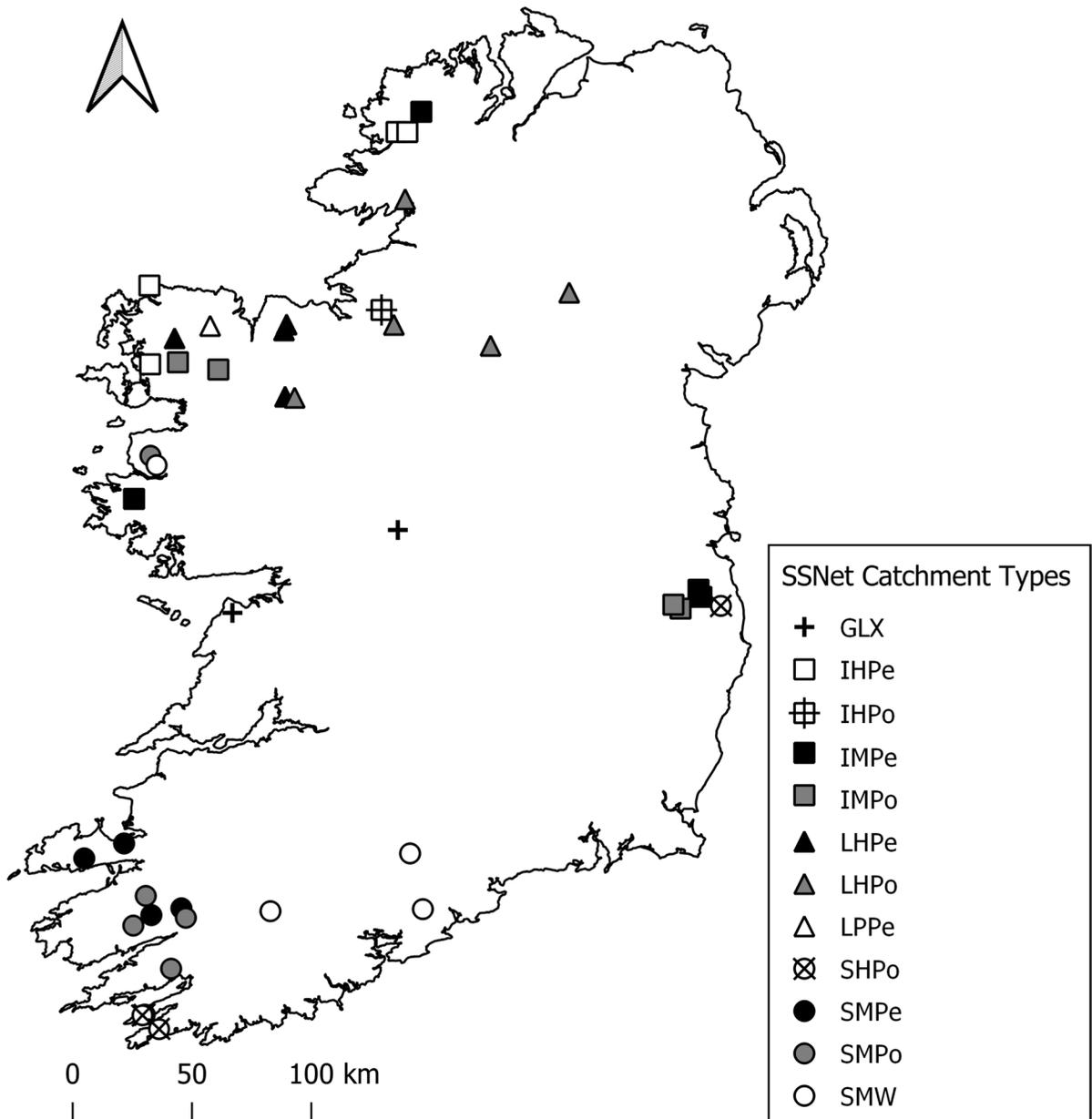
Prevalence by length	SSNet catchment type code	Geology	Physiography	Soil type	% of total 1st and 2nd order streams	Cumulative % of 1st and 2nd order streams	Number of stream reaches selected
1	SMPo	Non-calcareous sedimentary	Hill to mountain	Poorly drained	13.1	13.1	5
2	LHPo	Calcareous sedimentary	Hndulating to hill	Poorly drained	7.3	20.3	5
3	IMPe	Igneous and metamorphic	Hill to mountain	Peat	7.1	27.4	4
4	LPPo	Calcareous sedimentary	Flat to undulating	Poorly drained	6.9	34.3	0
5	IMPo	Igneous and metamorphic	Hill to mountain	Poorly drained	5.7	40.0	4
6	LHPe	Calcareous sedimentary	Undulating to hill	Peat	5.6	45.6	4
7	IHPo	Igneous and metamorphic	Undulating to hill	Poorly drained	5.5	51.1	1
8	SHPo	Non-calcareous sedimentary	Undulating to hill	Poorly drained	5.5	56.6	4
9	SMW	Non-calcareous sedimentary	Hill to mountain	Well drained	5.2	61.8	4
10	LPPe	Calcareous sedimentary	Flat to undulating	Peat	5.1	66.9	1
11	SMPe	Non-Calcareous sedimentary	Hill to mountain	Peat	4.9	71.8	4
12	IHPe	Igneous and metamorphic	Undulating to hill	Peat	3.3	75.1	4
–	GLX	Karstic geology with significant conduit groundwater flow paths	–	–	Approximately 20% of land cover	–	2

Note that only the 12 SSNet catchment types that enclose the highest proportions of 1st and 2nd order streams are tabulated as well those on karstic geology

all 27 catchment types and the proportion of 1st- and 2nd-order streams associated with each type).

It was not possible to find a full complement of four reaches meeting the research requirements within all 13 of the target catchment types (Table 2). In total 42 streams were identified and 84 study sites selected (two on each stream), whilst 52 streams and

104 study sites were sought. Identification of minimally impacted streams was a particular problem in low lying regions with well drained soils and calcareous bedrock, reflecting the increased human pressure in these areas, particularly from agriculture. Furthermore, water quality was typically poorer in these areas and straightening (realigning) and deepening



**Fig. 1** Distribution of the 42 stream reaches studied in the present research and their SSNet catchment type (see Table 1 for explanation of the catchment type codes)

(resectioning) of stream channels were also common. Therefore, most of the 42 stream reaches selected were located in upland areas on igneous and non-calcareous sedimentary geology (Table 2, Fig. 1) but should be representative of RoI headwater streams within these constraints.

### Hydrogeomorphological reach classification

The calculated indicators (A1 to A8) revealed that all 42 stream reaches were single thread (the braiding index (A1) and the anabranching index (A3) were both 1 in all cases) and only one reach had a sinuosity index (A2) that marginally exceeded 1.5. However, valley confinement (A4), valley gradient (A5) and the three bed material indicators all varied widely. Figure 2 presents scatter plots amongst indicators A2, A4, A5, A7 and A8, since these are the indicators (with A6) which show some variability across the sampled sites and so could support a River Type classification. Indicator A6 (bedrock rivers) is not explicitly explored in Fig. 2, because bedrock rivers are a subset of those whose coarsest bed material class is bedrock (A8).

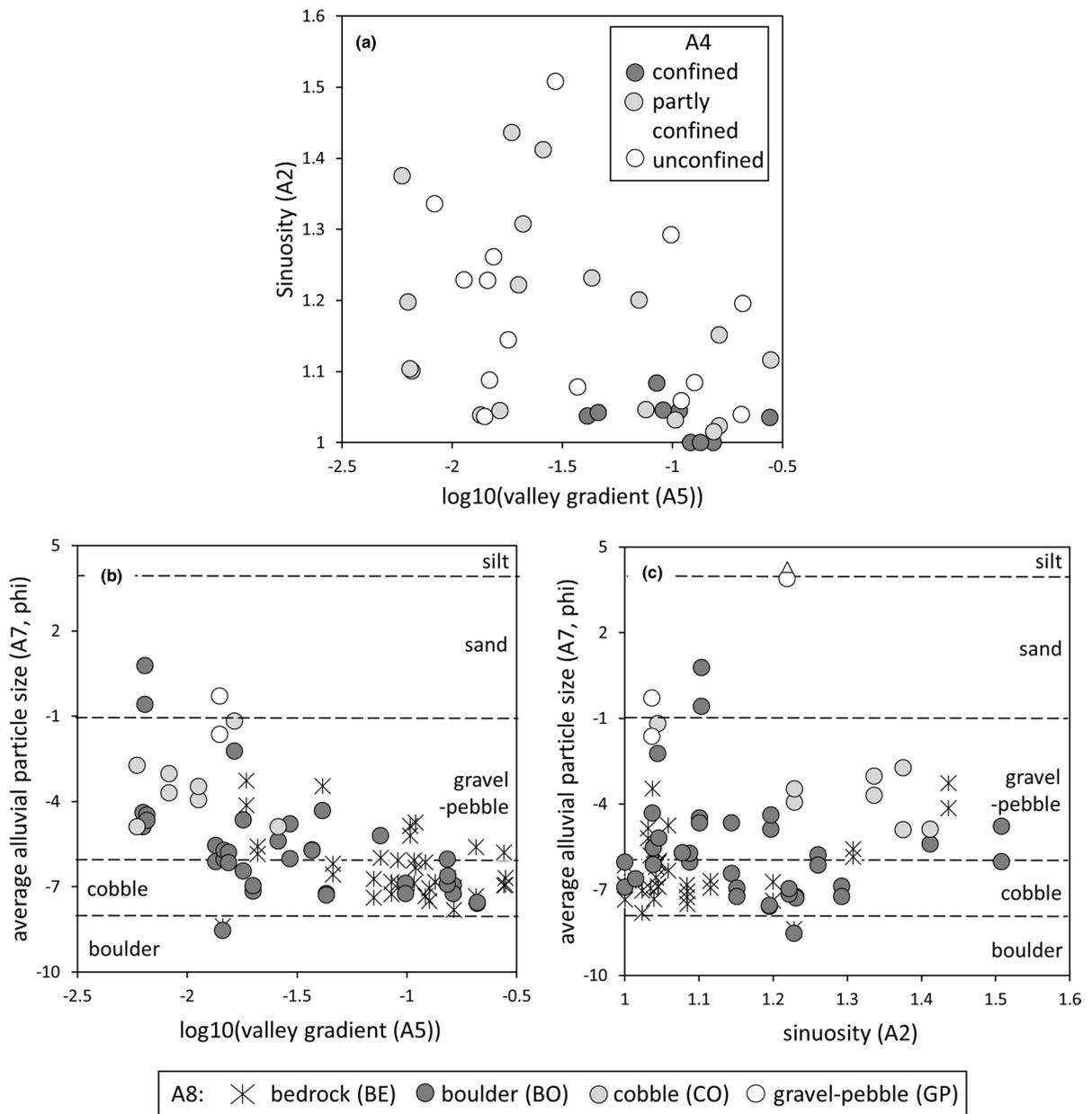
In the classification proposed for England by Gurnell et al. (2020), steep reaches were separated from other reaches using a valley gradient (A5) of 0.01 ( $-2$  when  $\log_{10}$  transformed). All but five of the reaches (10 sites) in the present analysis are steeper than 0.01 (Fig. 2a, b), indicating the potential of the present data set to support improved refined classification of such relatively steep streams. Furthermore, the data set includes a very wide range of valley gradients larger than 0.01 (the maximum was 0.28). Although confined sites (A4) display generally high valley gradients (A5) and low sinuosities (A2), there is little separation between partly confined and unconfined sites on the valley gradient—sinuosity scatter plot (Fig. 2a), suggesting that confinement (A4) is unlikely to be a strong discriminator of River Type. However, average bed material size (A7) and coarsest bed material size (A8) both become coarser as valley gradient (A5) increases (Fig. 2b, note that the phi scale gives smaller values as particle size increases) and there is some limited evidence that A7 and A8 become finer as sinuosity (A2) increases (Fig. 2c).

On the basis of this evidence, a refined classification of steeper streams was explored, which emphasised bed material size and then used the other indicators to confirm whether such a classification needed fine-tuning. For all streams where A6 indicated a bedrock stream or where the coarsest bed material (A8) was bedrock or boulder and the average bed material size (A7) was gravel–pebble or coarser, a classification was developed based on bed material alone. This defined six River Types: A (A6=bedrock rivers), B (A7=bedrock, A8=boulder), C (A7=bedrock, A8=cobble), D (A7=boulder, A8=cobble); E (A7=bedrock, A8= gravel–pebble); F (A7=boulder, A8= gravel–pebble).

The 6 new River Types for steeper streams were applicable to 66 of the 84 sites (A—13 sites, B—2, C—15, D—18, E—7, F—11), giving sufficient replication to support statistical analysis for all but type B. The remaining 18 sites with finer bed material were assigned to three classes (H—13 sites; J—4 sites; M—1 site) according to the original classification (Gurnell et al., 2020). In terms of bed material, H type streams are cobble (A7) and cobble or gravel–pebble (A8), J-type streams are gravel–pebble (A7) and sand (A8) and M type streams are sand (A7) and silt or clay (A8).

The scatter plots in Fig. 2b, c were replotted with the surveyed sites coded according to their River Type (Fig. 3a, b). Reasonably good separation of the River Types is apparent in relation to valley gradient (A5) and some separation is apparent according to sinuosity (A2). These observations are confirmed by box plots of valley gradient (A5) and sinuosity (A2) according to River Type (Fig. 3c, d) with the former progressively declining across the River Types and the latter showing predominantly higher sinuosities for types D to H in comparison with A and C. Bar graphs of the three confinement types (A4) observed in association with each River Type (Fig. 3e) confirm that confined sites are mainly associated with the River Types showing the coarsest bed material, but that sites may be partly confined or unconfined across the range of River Types. It is important to note the small sample sizes for type B ( $n=2$ ), J ( $n=4$ ) and M ( $n=1$ ) rivers.

Site-scale bed material data drives this classification of steeper streams and all pairs of surveyed

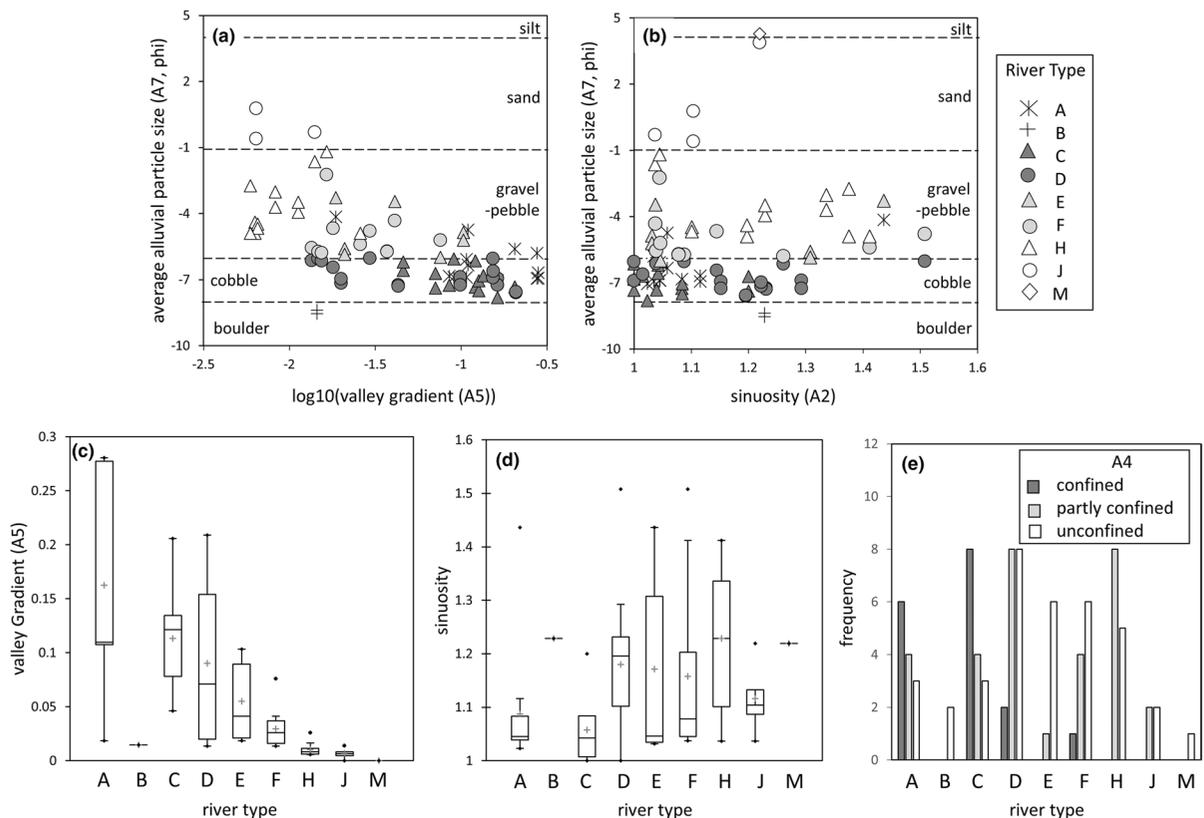


**Fig. 2** Scatter plots illustrating associations amongst **a** sinuosity, valley gradient and confinement at the 42 study reaches; and amongst average alluvial bed material particle size, coarse-

st bed material size class and valley gradient **(b)** and sinuosity **(c)** at the 84 study sites

sites were either assigned to the same or to adjacent river types. Differences in the bed material indicators amongst pairs of sites arose at 17 of the 42 reaches.

Five of these arose where a bedrock section was adjacent to a section with some alluvial sediment cover and the remaining 12 reflected a shift by one sediment



**Fig. 3** Scatter plots illustrating associations between River Types at the 84 study sites, average alluvial bed material particle size and **a** valley gradient, **b** sinuosity. Box plots (**c**) and

**(d)** and a bar graph (**e**) illustrating associations between River Types at the study sites and **c** valley gradient, **d** sinuosity and **e** valley confinement

size class in either the coarsest or the average bed material size classes. The six new River Types were integrated into the previous classification proposed by Gurnell et al. (2020) and the revised flow diagram underlying the classification of hydrogeomorphological types is shown in Fig. 4.

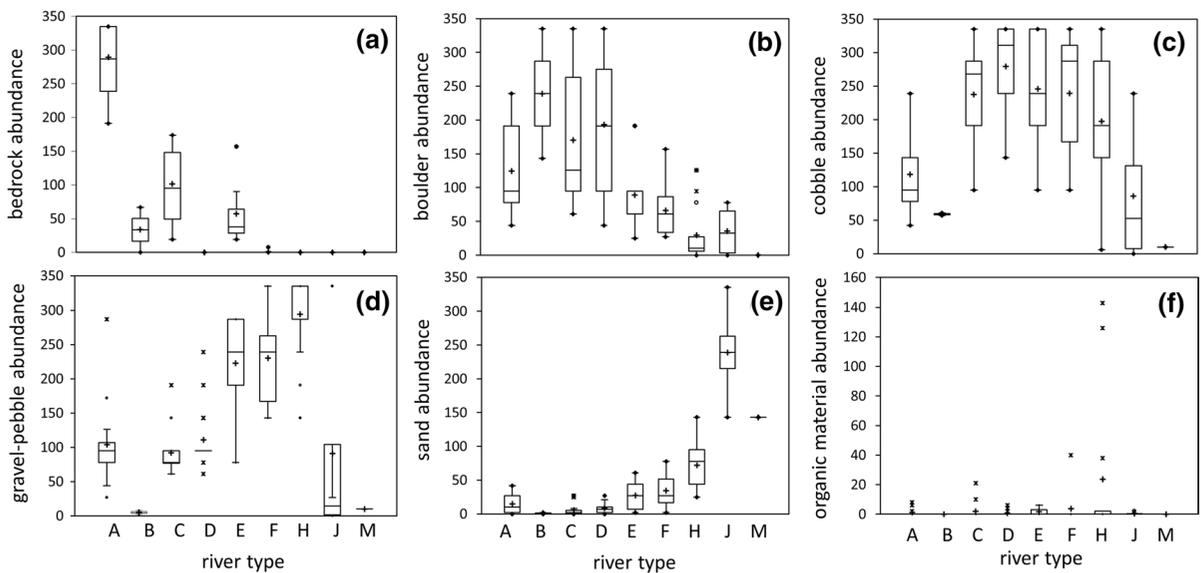
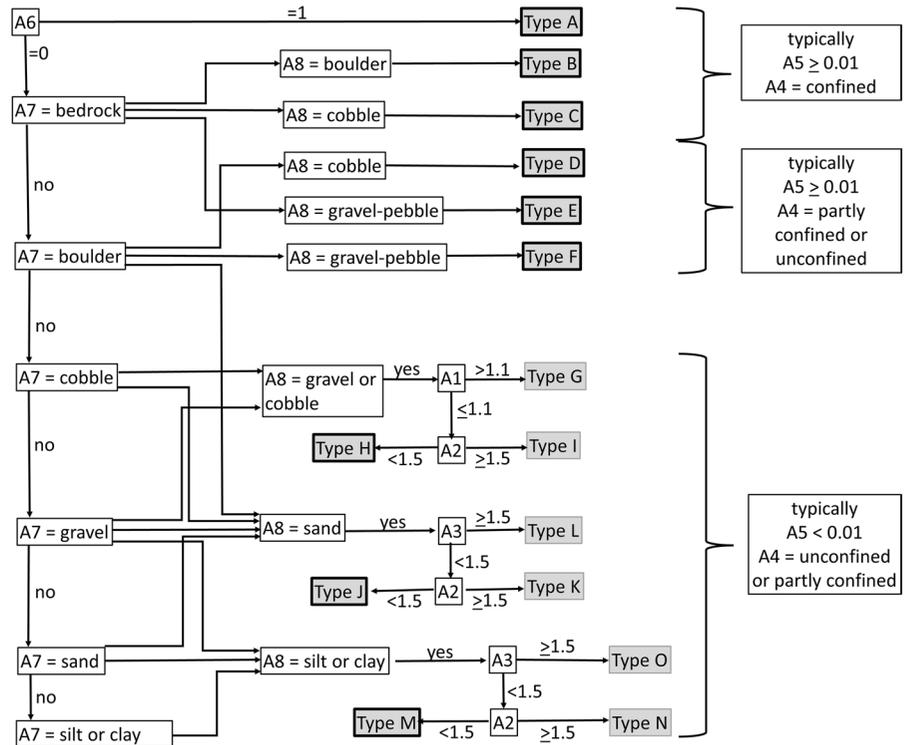
Site-scale physical habitat characteristics and their association with reach-scale River Types

#### Data description

Box and whisker plots reveal a clear fining in the particle sizes within the mosaics of bed sediment patches that are present from River Type A to M (Fig. 5), indicating distinctive patch mosaics associated with each River Type and particularly notable changes in the relative abundance of bedrock, boulder, gravel–pebble and sand patches (Fig. 5a, b, d,

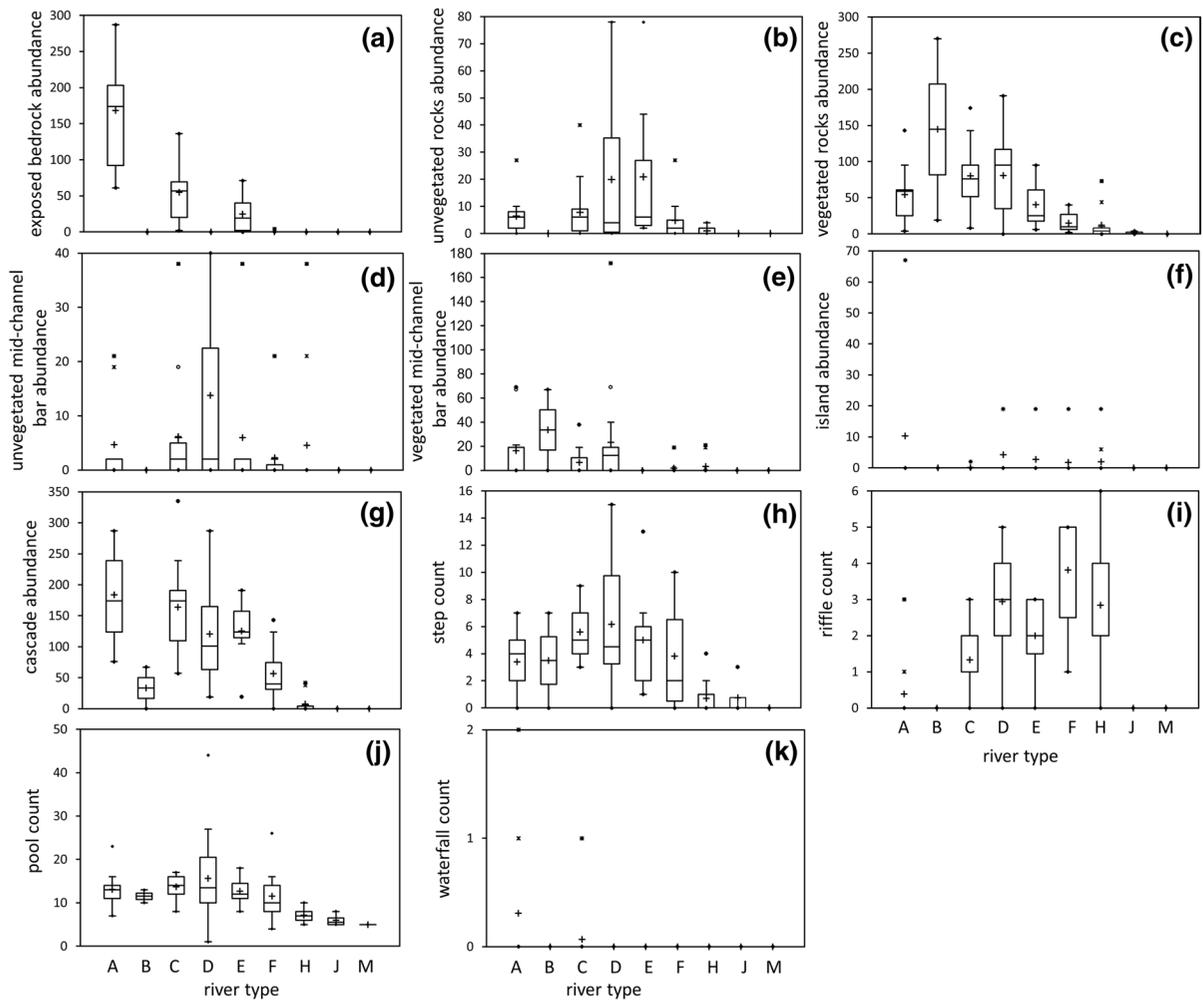
e). Certain bed features also show notable changes as the River Type changes (Fig. 6), with the relative abundance of exposed bed rock, vegetated rocks, and cascades (Fig. 6a, c, g) gradually decreasing to be replaced by unvegetated rocks and steps (Fig. 6b, h) and then by riffles (Fig. 6i) across the River Types from A to M. Amongst the bank face and margin features recorded (Fig. 7), the abundance of marginal backwaters (Fig. 7j) gradually declines as unvegetated and vegetated side bars (Fig. 7a, b, c), berms and benches (Fig. 7d, e, f) increase in abundance, and, in turn, the abundance of eroding cliffs progressively increases (Fig. 7h) from River Type A to M. Finally, not only does the abundance of vegetated and unvegetated mid-channel and side bars change as the River Type changes but also the size of the sediment within the bars also changes (Fig. 8) to produce a wide range of sediment calibre—feature combinations reflecting sediment fining across the River Types. In summary,

**Fig. 4** Flow diagram used to assign study sites to River Types based on the values of indicators A1 to A8. (River Types in emboldened boxes are those identified across the study headwater streams)



**Fig. 5** Box and Whisker plots of the abundance of different bed material patches observed in association with sites assigned to different River Types (note that different scales are

used on the graph vertical axes in order to highlight contrasts between river type classes according to each of the characteristics that are being plotted)



**Fig. 6** Box and Whisker plots of the abundance of different bed physical habitats observed in association with sites assigned to different River Types (note that different scales are

used on the graph vertical axes in order to highlight contrasts between river type classes according to each of the characteristics that are being plotted)

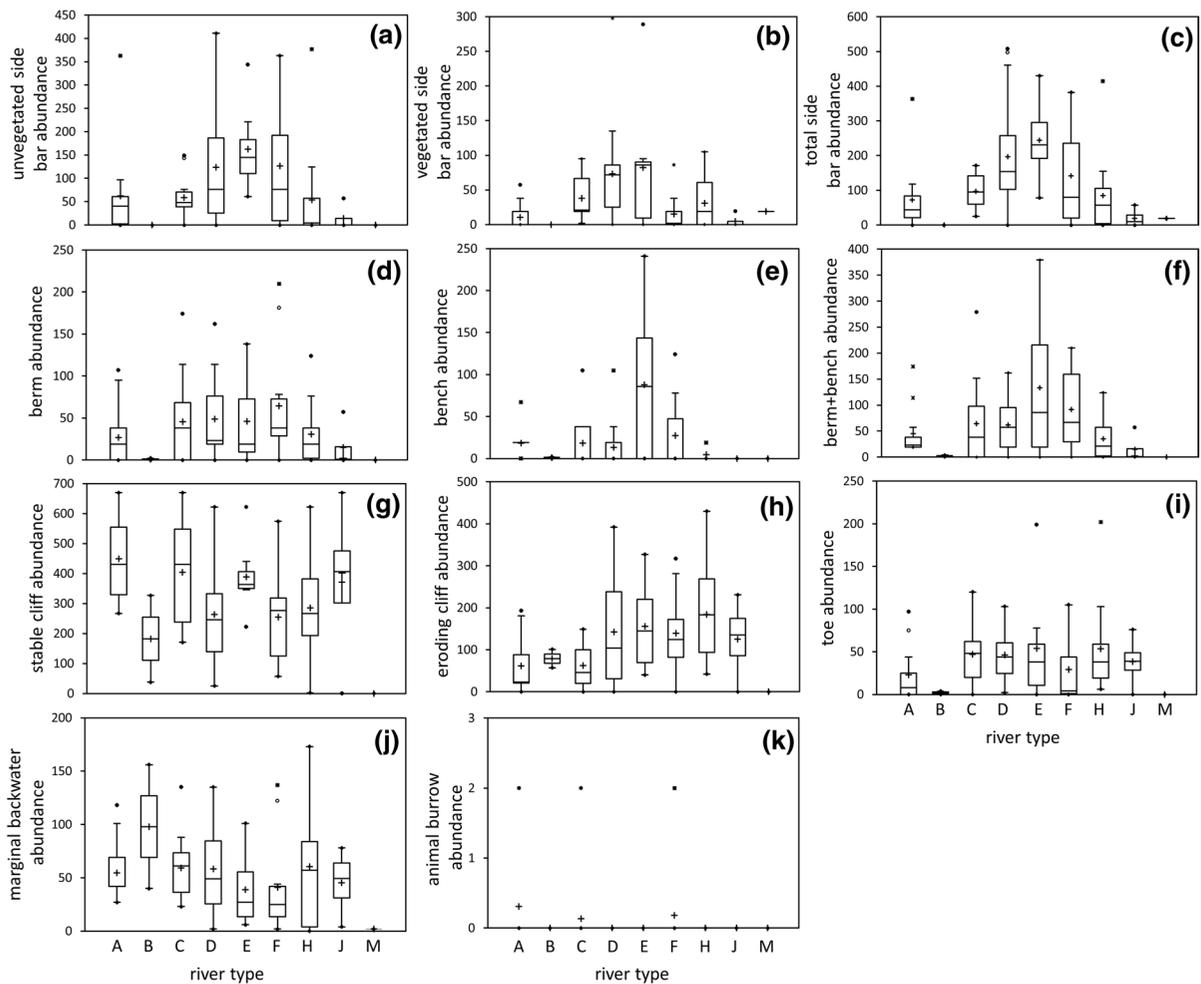
there appears to be characteristic assemblages of physical habitats associated with the different River Types.

We do not present survey data on riparian and in-channel vegetation structural habitats, because these showed limited variability. In particular, trees and related features and also almost all of the aquatic vegetation morphotypes were largely absent from the collected data. As a result, no notable distinguishing features of the vegetation structure across the generally steep streams were revealed.

#### *Gradients in physical habitat mosaics and abundances across River Types—principal components analysis*

Although four PCAs were performed on the habitat abundance data for bed material patches, bed physical features, bank-margin physical features, and vegetation structural habitats, the vegetation analysis revealed no notable patterns across the river types and so we focus on the other three PCAs.

The analysis of bed material patches reveals a strong sediment size gradient along PC1 from boulder (strong negative loading) to gravel—pebble, sand and silt (strong positive loadings), which explains 35% of



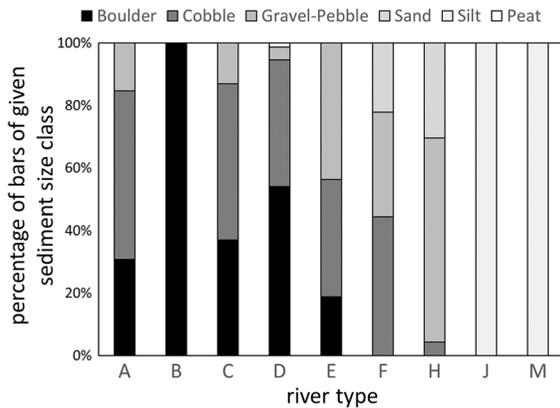
**Fig. 7** Box and Whisker plots of the abundance of different bank-margin physical habitats observed in association with sites assigned to different River Types (note that different

scales are used on the graph vertical axes in order to highlight contrasts between river type classes according to each of the characteristics that are being plotted)

the variance in the data set (Table 3). PC2 explains a further 17% of the variance and describes a gradient of increasing cobble and organic material (strong positive loadings). PC3 has an eigenvalue close to 1 and displays less strong variable loadings than PC1 and PC2 but appears to separate the small number of sites with peat bed material (negative loading and a weaker negative loading on organic material) from cobble sites (positive loading). Both biplots of PC1-PC2 and PC1-PC3 (Fig. 9a, b) show separation amongst river types, but the PC1-PC2 biplot (Fig. 9a) shows particularly good separation amongst river types A, B, C, D, E, F and H+J+M. Site scores on PCs 1, 2 and

3 show statistically significant separations amongst types A, C, D, F, J and H (Table 4).

The PCA of bed physical features (Fig. 9c, d) reveals a strong gradient along PC1 of increasing exposed vegetated rocks, cascades, steps and pools (strong positive loadings), which explains 34% of the variance in the data set. PC2 explains a further 15% of the variance and describes a gradient of increasing riffles (strong positive loading) and decreasing exposed bedrock (strong negative loading). PC3 explains a further 13% of the variance with a high positive loading on islands. The PC1-PC2 biplot (Fig. 9c) shows the clearest separation amongst River Types with types D and F separated from H, J and M,



**Fig. 8** The relative abundance of the dominant sediment size class forming unvegetated and vegetated, side- and mid-channel bars across sites assigned to different River Type

which are in turn separated from A. Site scores on PCs 1 and 2 show statistically significant separations amongst types A, C, D, F, J and H (Table 4).

The PCA of bank-margin physical features (Fig. 9e, f) reveals a strong gradient along PC1 of decreasing stable cliffs (strong negative loading) and increasing vegetated side bars and berms (strong positive loadings), which explains 22% of the variance in the data set. PC2 explains a further 17% of the variance and, describes a gradient of increasing numbers of animal burrows (strong positive loading) and benches (weaker positive loading) and decreasing unvegetated side bars (weaker negative loading). PC3 explains a further 14% of the variance with a strong positive loading on eroding cliffs. The PC1-PC2 and PC1-PC3 biplots (Fig. 9e, f) do not show strong separation amongst River Types, but site scores on PC1 show a statistically significant difference between River Types A and D (Table 4).

#### *Contrasts in the abundance of individual physical habitats across River Types*

Kruskal Wallis tests followed by pairwise comparisons using Dunn's test with Bonferroni correction (Table 5) revealed that higher abundances of bedrock, boulder, cobble, gravel–pebble, sand and silt were all statistically significantly associated with different subsets of River Types. In relation to bed physical features, high abundances of exposed bedrock, exposed unvegetated and vegetated rocks, cascades,

steps, riffles and pools were all associated with particular subsets of River Types. Finally, in relation to bank-margin physical features (Table 5), high abundances of unvegetated and vegetated side bars and eroding cliffs were each associated with particular subsets of River Types.

#### Integration

Synthesising the results of the above analyses and thus revisiting our research hypothesis, it is possible to summarise linkages between the abundance and mix of physical patch/feature habitats observed at a site and the River Type for the seven River Types that were represented by at least four sites in the 84 site data set. Table 6 summarises the reach-scale characteristics, key indicator physical habitats and the typical assemblage of physical habitats that are associated with each River Type. However, it is important to note that the steepest River Types are distinguished according to bed material, which is observed at the site scale. Associations between River Type and catchment type are fairly weak (Table 7), but there is a broad progression of river types from M through to A as the catchment becomes increasingly hilly and mountainous.

#### Discussion

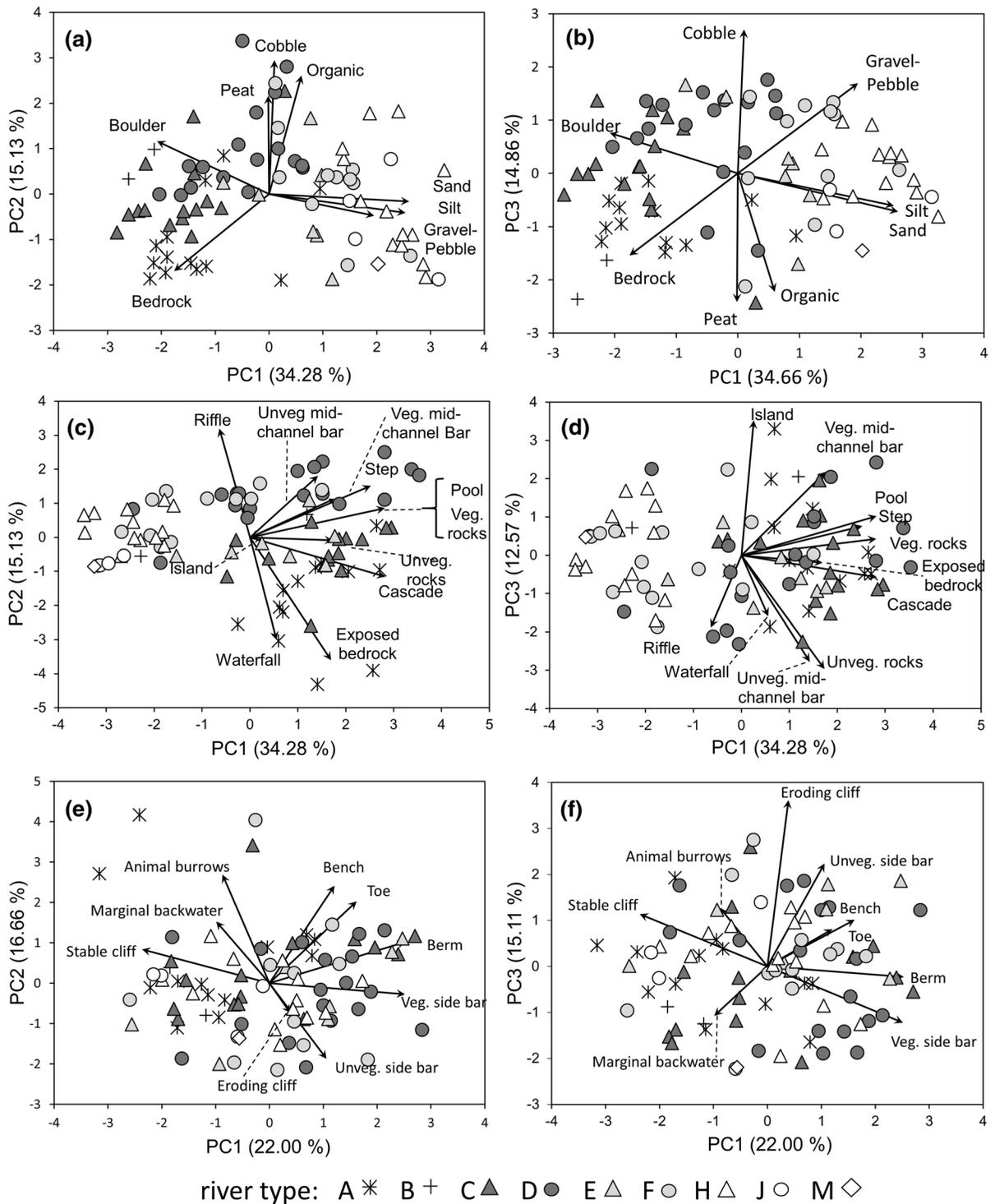
##### Catchment selection

Our aim was to produce a classification of headwater catchments that captured the broad geological, physiographic and soil drainage properties present in the Republic of Ireland. We have delivered 27 catchment types based on these criteria plus one additional karst type with significant conduit groundwater flow paths. These 28 catchment types should be representative of the range of Irish headwater catchments. However, when we investigated the 13 catchment types that included the greatest lengths of Irish headwater streams, we were only able to find the required four sufficiently unimpacted streams for nine catchment types and there were no suitable streams for one type, streams on calcareous flat to undulating terrain with poorly drained soil (LPPo). As a result, the 42 headwater streams and 84 sites investigated here were biased towards locations in undulating-hill and

**Table 3** Eigenvalues, percentage and cumulative explained variance and factor loadings on the first four principal components performed on Spearman rank correlation matrices for bed material patches, bed physical features and bank physical features

	PC1	PC2	PC3	PC4
<b>Bed material patches</b>				
Eigenvalue	2.773	1.399	1.189	1.040
% variance explained	34.662	17.482	14.862	13.006
Cumulative % variance explained	34.662	52.144	67.006	80.012
<b>Loadings</b>				
Bedrock	<i>-0.589</i>	-0.402	-0.337	-0.330
Boulder	<b><i>-0.695</i></b>	0.277	0.167	-0.322
Cobble	0.033	<b><i>0.700</i></b>	<i>0.592</i>	-0.174
Gravel-pebble	<b><i>0.652</i></b>	-0.112	0.371	0.253
Sand	<b><i>0.870</i></b>	-0.039	-0.157	-0.285
Silt	<b><i>0.848</i></b>	-0.097	-0.133	-0.287
Organic	0.201	<b><i>0.619</i></b>	-0.487	-0.415
Peat	-0.005	<i>0.514</i>	-0.529	<b><i>0.631</i></b>
<b>Bed physical features</b>				
Eigenvalue	3.771	1.664	1.383	0.949
% variance explained	34.278	15.129	12.569	8.631
Cumulative % variance explained	34.278	49.407	61.976	70.607
<b>Loadings</b>				
Exposed bedrock	<i>0.507</i>	<b><i>-0.718</i></b>	-0.036	-0.098
Exposed Unvegetated rocks	<i>0.520</i>	-0.018	-0.538	0.316
Exposed vegetated rocks	<b><i>0.843</i></b>	0.172	0.077	-0.037
Unvegetated mid-channel bar	0.427	0.360	-0.504	-0.263
Vegetated mid-channel bar	<i>0.527</i>	0.226	0.396	-0.190
Island	0.077	-0.015	<b><i>0.641</i></b>	<b><i>0.601</i></b>
Cascade	<b><i>0.847</i></b>	-0.230	-0.104	0.122
Pool (count)	<b><i>0.844</i></b>	0.171	0.186	0.030
Riffle (count)	-0.191	<b><i>0.637</i></b>	-0.341	0.494
Step (count)	<b><i>0.756</i></b>	0.303	0.138	-0.011
Waterfall (count)	0.167	-0.599	-0.289	0.334
<b>Bank physical features</b>				
Eigenvalue	1.980	1.499	1.360	1.108
% variance explained	21.999	16.660	15.106	12.316
Cumulative % variance explained	21.999	38.659	53.765	66.081
<b>Loadings</b>				
Unvegetated side bar	0.296	-0.454	<i>0.518</i>	-0.057
Vegetated side bar	<b><i>0.702</i></b>	-0.066	-0.283	0.084
Berm	<b><i>0.706</i></b>	0.249	-0.053	-0.108
Bench	0.337	<i>0.587</i>	0.188	-0.430
Stable cliff	<b><i>-0.660</i></b>	0.204	0.264	0.003
Eroding cliff	0.109	-0.178	<b><i>0.837</i></b>	0.295
Toe	0.452	0.493	0.234	<i>0.556</i>
Animal burrows	-0.244	<b><i>0.655</i></b>	0.293	-0.307
Marginal Backwater	-0.276	0.371	-0.249	<b><i>0.642</i></b>

Loadings those  $\geq 0.5$  but  $< 0.6$  are in italics, those  $\geq 0.6$  but  $< 0.7$  are in boldface and italics and those  $\geq 0.7$  are in boldface, italics and are underlined



**Fig. 9** Biplots showing site scores and variable loadings on PC1–PC2 and PC1–PC3, respectively, of PCAs conducted on bed material patches (a, b), bed features (c, d) and bank features (e, f) at the 84 study site

**Table 4** Results of the Kruskal–Wallis test on the site scores of the first three principal components for each of the three physical habitat groups analysed: bed material patches, bed physical features and bank physical features

	Principle component	Kruskal–Wallis statistic (degrees of freedom = 6)	Probability ( $P < 0.05$ )	Dunn–Bonferroni pairwise comparison of river types ( $P < 0.0024$ )
Multiple pairwise comparisons were made using the Dunn–Bonferroni procedure	Bed material patches			
	PC1	61.039	<0.001	F, H, J > A, C and H > D
	PC2	24.255	<0.001	D > A
	PC3	30.061	<0.001	D, F > A and D > J
	Bed physical features			
	PC1	48.343	<0.001	A, D > H, J and C > F, H, J
	PC2	55.178	<0.001	D, F, H > A and D, F > C
	PC3	4.110	N.S	N.S
	Bank physical features			
PC1	17.262	0.008	D > A	
PC2	5.081	N.S	N.S	
PC3	6.606	N.S	N.S	

hill–mountain physiographic types, but their limited exposure to human interventions and pressures allow them to be considered ‘reference’ sites for exploring the physical habitat characteristics of Irish headwater streams within these catchment types.

#### Reach scale, hydrogeomorphological river classification

We have modified a River Type classification proposed by Gurnell et al. (2020) for English rivers and streams to make it applicable to Irish headwater streams. In particular, this study has provided an opportunity to refine the original classification by developing six new River Types (A to F) for steeper streams to extend the already well supported remaining River Types proposed in the original classification. We believe the revised classification is appropriate for application to all streams and small rivers, across the Republic of Ireland and England, and most probably to other areas of similar climate–landscape conditions across northern and western Europe.

The aim of the original classification, which can be extended to this revised classification, is to define a set of River Types and then identify the physical habitats that characterise streams and rivers of each type when they are functioning ‘naturally’. This provides a reference against which the condition of human-impacted streams and rivers of the same type can be judged, allowing the degree of alteration of their physical condition to be assessed (Gurnell et al., 2020). Although the River Type is based primarily on

a desk study, it also requires information on bed material, which is collected during a field survey. For the new River Types developed here, we found that several of the desk study indicators were invariant (e.g. the braiding and anabranching indices) or showed very limited variability (e.g. the sinuosity index) across the investigated streams in the RoI, whereas others varied more widely than in the original data set used for English rivers. Most of the English rivers showed valley gradients that were less than 0.01, most of the Irish headwater streams showed gradients that were greater than 0.01, and many of the Irish streams were confined or partly confined whereas most of the English streams were unconfined. Overall, these show the complementarity of the English and Irish data sets, but also the heavy dependence of the Irish classification of steeper streams on a small number of desk-based indicators and thus the increased importance of the three bed material River Type indicators extracted from field surveys.

The three bed material indicators (A6, A7 and A8) are usually extracted from a MoRPh5 field survey located within the river reach. Where more than one MoRPh5 survey is available, the coarsest value is usually used for each indicator to define the River Type. Based on several hundred applications of the Gurnell et al. (2020) methodology to date, this approach is very effective in relatively low-gradient, alluvial streams and rivers. However, in the present analysis, we extracted the indicators from two adjacent MoRPh5 surveys in order to test the sensitivity of both the River Type and the habitat mosaic to

**Table 5** Results of the Kruskal–Wallis test on the observed abundances of the different habitat types for River Types A, C, D, E, F, H and J

Physical habitat	Kruskal Wallis statistic (degrees of freedom=6)	Probability ( $P < 0.05$ )	Dunn-Bonferroni pairwise comparisons of River types ( $P < 0.0024$ )
<b>Bed material patches</b>			
Bedrock	76.990	<0.001	A, C > D, F, H, J and E > D
Boulder	38.685	<0.001	A, C, D > H and D > F, J
Cobble	28.714	<0.001	C, D, F > A and D > J
Gravel–Pebble	46.234	<0.001	F, H > A, C and H > D and H > J
Sand	47.252	<0.001	H, J > A, C, D and F > C
Silt	39.376	<0.001	H, J > A, C, D
Organic	2.857	N.S	N.S
Peat	7.417	N.S	N.S
<b>Bed physical features</b>			
Exposed bedrock	73.466	<0.001	A > D, F, H, J and C > D, F, H, J
Exposed unvegetated rocks	20.143	0.003	E > H
Exposed vegetated rocks	39.301	<0.001	A, C, D > H and C, D > F, J
Unvegetated mid-channel bar	13.490	0.036	N.S
Vegetated mid-channel bar	13.958	0.030	N.S
Island	2.829	N.S	N.S
Waterfall	11.892	N.S	N.S
Cascade	49.078	<0.001	A > F, H, J and C > H, J and D, E > H
Step	30.487	<0.001	C, D > H
Riffle	39.363	<0.001	D, F, H > A and C > F and D > J
Pool	29.952	<0.001	A, C, D > H and C > J
<b>Bank physical features</b>			
Unvegetated side bar	16.838	0.010	E, F > H, J
Vegetated side bar	22.563	0.001	D > A
Berm	4.937	N.S	N.S
Bench	11.299	N.S	N.S
Stable cliff	15.177	0.019	NS
Eroding cliff	15.920	0.014	H > A
Toe deposit	8.128	NS	NS
Animal burrows	5.633	NS	NS
Marginal backwater	5.201	NS	NS

Multiple pairwise comparisons were made using the Dunn-Bonferroni procedure

local variations in bed material within the very small and generally steep headwater streams that were investigated. Our results show the robustness of the river typing approach in that the bed material indicators from adjacent reaches either delivered the same River Type or an adjacent River Type in every case, but also the importance of site-scale bed material in defining the River Type of steep headwater streams. If the method is applied to lower gradient, alluvial streams, the pre-existing rule of using the coarsest values for the bed material indicators should deliver

an acceptable working River Type for assessing the physical habitat condition of rivers.

Furthermore, the small differences in River Types allocated to adjacent sites on some reaches, which largely reflect the bed material, most probably indicate slight changes in the local stream gradient or confinement that could alter local stream power (for the same discharge) within a river reach. Any change in stream power alters the sediment grain sizes that can be mobilised, transported and deposited locally by a given discharge. Such local variability in stream

**Table 6** River Types A, C, D, E, F, H, J, their reach-scale characteristics, key indicator habitats and characteristic habitat assemblages

River type, reach-scale characteristics	Key indicator habitats	Characteristic habitat assemblage
<b>A:</b> Steep bedrock rivers, typically confined	Extensive exposed bedrock and boulders forming steep cascades. Steep to vertical bedrock banks	Bed material is typically bedrock and boulder with some cobble and little finer material. Large areas of cascade typically often interspersed with step-pool sequences. Few vegetated or unvegetated rocks and mid-channel bars. Marginal habitats are simple with some backwaters but few sidebars, berms or benches
<b>C:</b> Steep bedrock-boulder, rivers, typically confined	Frequent sections of exposed bedrock. Wide-spread boulder and bedrock cascade sections and stable bedrock and boulder cliffs	Bed material dominated by boulder and cobble with some gravel–pebble and little fine material. Cascades and steps separated by pools are typical. Large stable boulders common. Occasional boulder and cobble mid-channel bars
<b>D:</b> Steep boulder-cobble, typically confined or partly confined	Predominantly boulder and cobble bed with occasional bedrock exposure. Frequent steps and unvegetated midchannel bars	Bed material typically cobble and boulders common with occasional finer material, bedrock is rare. Cascades and steps common but less frequent than for type C. Riffles, small pools, stable vegetated boulders and vegetated bars comprised of boulders and large cobbles are frequent
<b>E:</b> Moderately steep gravel–pebble rivers, typically partly confined	Predominantly gravel–pebble bed with some boulders and occasional bedrock exposure. Frequent side bars, berms and benches	Bed material typically gravel–pebble interspersed with cobbles and also small amounts of bedrock, boulder and sand. Step-pools are common. Cobble-boulder cascades, riffles, sidebars, berms, benches and both stable and eroding cliffs are frequent
<b>F:</b> Moderately steep gravel–pebble rivers, typically partly confined or unconfined	Predominantly gravel–pebble bed with some cobbles. Frequent riffles, sidebars, berms and benches	Bed material typically gravel–pebble interspersed with cobbles. Occasional boulders and sand in low velocity areas. Pools, riffles, steps, sidebars, berms, benches are common, as are vertical sections of stable and eroding cliff
<b>H:</b> Moderate gradient straight-sinuuous gravel–pebble rivers, typically partly confined or unconfined	Predominantly gravel–pebble bed with some cobbles. Frequent riffles and eroding cliffs	Bed material dominated by gravel–pebble and interspersed with cobbles and sand. Riffles, pools and sections of eroding cliff are frequent. Occasional sidebars, berms, benches
<b>J:</b> Moderate gradient straight-sinuuous sand-bed rivers, typically partly confined or unconfined	Predominantly sand bed with few indicator physical habitats	Bed material primarily sand with some cobbles and gravel–pebble. Long sections of pool or slow flowing water (glide)



**Table 7** Frequencies of sites associated with different Catchment and River types

Catchment type	Geology class	Physiography class	Soil type class	River Type										Total sites			
				A	B	C	D	E	F	H	J	M					
LPPo	Calcareous sedimentary	Flat to undulating	Poorly drained														0
LPPe	Calcareous sedimentary	Fat to undulating	Peat											2			2
LHPo	Calcareous sedimentary	Undulating to hill	Poorly drained	1			3	1	2	1	2						10
LHPe	Calcareous sedimentary	Undulating to hill	Peat							2	6						8
SHPo	Non-calcareous sedimentary	Undulating to hill	Poorly drained	1		3		1	1	1	2						8
IHPo	Igneous and metamorphic	Undulating to hill	Poorly drained						1	1							2
IHPe	Igneous and metamorphic	Undulating to hill	Peat	1	2	1	1	2	1								8
SMPo	Non-calcareous sedimentary	Hill to mountain	Poorly drained			3	5	1	2	2	1			1	1		10
SMW	Non-calcareous sedimentary	Hill to mountain	Well drained	2													8
SMPe	Non-calcareous sedimentary	Hill to mountain	Peat			4	4										8
IMPe	Igneous and metamorphic	Hill to mountain	Peat	3		1	3			1							8
IMPo	Igneous and metamorphic	Hill to mountain	Poorly drained	5		3											8
GLX	Karstic geology with significant conduit groundwater flow paths	Hill to mountain					1			1				1	1		4
Total sites				13	2	15	18	7	11	13	4			1	4		84

power and sediment dynamics in these small, steep headwater streams is probably another special characteristic of them, in that they are very frequently not self-formed, truly alluvial systems but their form and dynamics are controlled by bedrock or large boulders or non-fluvial geomorphic structures which in turn control the types and abundances of physical habitats created by local flow-sediment interactions. The strength of the bed material-based approach to typing these steep streams is that MoRPh surveys are quick to apply and give detailed information on bed material, whereas the other local controls, particularly gradient, are challenging to measure accurately and consistently at a local scale (i.e. over 10 to 50 m river lengths).

There were no truly lowland headwater streams in our sample, because we were unable to find examples that were free of significant human interference. Such streams would be expected to have much finer bed material and thus be less subject to local variations in hydraulics due to the presence of individual bedrock outcrops or boulders. However, as we surmised in the introduction to this paper, it is possible that lowland headwaters may show considerable local variability in their habitat characteristics as a result of the influence of vegetation. Large wood and fallen trees, channel encroachment of terrestrial plants, particularly trees and the growth of physically-robust aquatic macrophytes could all exert complex local hydraulic impacts on small streams that do not have the energy to remove, undermine, scour or streamline plants and associated landforms. All of these local factors may have an important additional influence on the physical habitat characteristics of small streams in addition to reach-scale planform, slope, valley confinement and less spatially variable bed material that affect the habitat characteristics of larger streams. This suggests a greater granularity in natural stream characteristics within extended reaches of small streams in comparison with larger ones. This is broadly the theme explored by Church (1992) as part of his consideration of the character of streams of different size.

#### Site-scale indicator features and typical assemblages of physical habitats

In association with the River Types, we have demonstrated shifts in the relative abundances of a range of physical habitats from type A steep bedrock streams to type J moderate gradient predominantly sand streams

with some gravel–pebble bed material (Figs. 5, 6, 7, 8). Indeed, most of these River Types are discriminated by estimated gradients (PCs) through the mosaics of bed material patches, bed physical features and bank-margin physical features that are present (Table 4, Fig. 9). Seven of the nine investigated River Types represented by 4 or more sites, were distinguished by a range of statistically significant ‘indicator’ habitats. This suggests that the River Types are relatively robust. Furthermore, the River Types present clear gradients in the relative abundances of different bed material patches, channel bed physical features and bank-margin physical features from type A through to type M, representing a shift in habitat assemblages for each investigated River Type.

MoRPh surveys capture vegetation structure as well as details of sediment patches and the physical habitat features that are present. Riparian and aquatic vegetation structure and related tree features are used to characterise distinct habitat assemblages when assessing the condition of River Types G to N but vegetation was not used to characterise types A to F because of the lack of trees and aquatic plants (apart from mosses, lichens and algae) and the lack of vegetation structural discrimination amongst these River Types. However, the small sample of surveyed sites that were assigned to types G to N showed the expected vegetation structural characteristics (Gurnell et al., 2020).

#### The river classification and the research hypothesis

Our analysis has shown associations amongst physical properties at site, reach and catchment scales, which support our hypothesis that linkages exist across these scales. The associations are relatively weak from catchment to reach scales, largely because of the narrow range of catchment types investigated. Furthermore, although stronger, the associations from reach to site scales are heavily constrained by site scale bed materials because of the narrow range of predominantly steep River Types and small streams incorporated in the analysis.

The revised River Type classification provides a basis for defining ‘reference’ habitat assemblages and judging the degree of degradation in the condition of all river and stream types (A to N, Fig. 4) in the context of the Republic of Ireland, England and probably other countries of similar landscape characteristics across northern and western Europe. However, some

caution may be required. We have adopted a top-down ‘framework’ approach in the present analysis, which needs to be independently tested and validated or possibly adjusted in the light of bottom-up ‘scaffolding’ insights from MoRPh5 surveys conducted on a different, preferably larger sample of sites. The previous classification is undergoing such testing as Biodiversity Metric 3.0 (Panks et al., 2021) and its River Condition Assessment (Gurnell et al., 2020) are applied by numerous professional river scientists across England. Furthermore, three River Types in the present analysis were represented by very small numbers of sites (type B—2, type J—4, type M—1) and, whereas types J and M have been robustly investigated in England, type B is a completely new River Type that needs further investigation.

### Comparison with other river classifications

In the introduction to this paper, we cited or referred to reviews of many river classifications proposed by other researchers and to a recent review by Buffington and Montgomery (2021). Therefore, it is appropriate to consider the degree to which our classification of steep Irish headwater streams may mirror the results of other classifications. Most relevant to the classification we have developed are the classifications that have linked flow, gradient and sediment size dynamics to river channel form and ‘indicator’ landforms/habitats. These include the classification of Schumm (1985) and its development by Church (2006), which classify river types across all three process domains mentioned in the introduction to this paper. However, a classification of river channel types in mountain basins by Montgomery & Buffington (1997, 1998) is the most relevant to the present analysis, because it is biased towards steep stream and river systems and the domain of net erosion in headwaters. Montgomery & Buffington (1997, 1998) give a detailed description and analysis of the types of stream and river that may be encountered in this domain, and, they adopt a similar top-down hierarchical approach. They define five mountain river types (bed rock, cascade, step-pool, plane-bed, pool-riffle) that can be compared with the five types (A, C to F) for which we have some statistical support. Montgomery & Buffington (1997) describe each type in detail and present summary graphs using information from a sample of sites (ca. 70 sites) located in four catchments in

western Washington and coastal Oregon, USA. Based on this information, there are clear similarities with our classification that provides further confidence in our River Types and physical habitat observations. Indeed, our type A appears to correspond with their bed rock type, our type C with their cascade type, our type D with their step-pool type, our type E with their plane-bed type and our type F with their riffle-pool type. The key differences are that their catchments are generally larger than ours, suggesting wider streams, and the valley/channel gradients associated with each type, particularly types B and C, are steeper. This supports our suggestion that local variations in stream gradient are important in defining the stream types for the small streams that we investigated.

### Conclusions

We have developed a reach-scale classification of River Types that is applicable to steep Irish headwater streams and shows some association with a classification of headwater catchment types that reflects physiographic, geological and soil characteristics. At the site scale, we have identified ‘indicator’ physical habitats and characteristic physical habitat assemblages for those River Types for which we had a sample of site-scale field surveys. Furthermore, based on the site-scale observations, we have shown that local small variations in river type may occur on the surveyed steep streams. These can be summarised as local fluctuations between adjacent River Types, that we believe to reflect local variations in downstream slope and local external geomorphic factors that constrain the morphodynamics of these small, steep streams.

The new River Types extend a previous classification that was developed for predominantly lower-gradient alluvial streams to provide a classification that could be applied more widely across Ireland and accompany the catchment types that we have defined but were unable to sample because of a lack of relatively naturally-functioning streams. Furthermore, each River Type in our extended classification, which includes lower gradient types previously-investigated in England, can be associated with a characteristic physical habitat and vegetation structural assemblage for naturally-functioning streams of each type. These physical habitat and vegetation structural assemblages

provide targets against which degraded streams of each type can be compared and assessed.

The hierarchical approach that we have developed is fairly simple to apply and so is suitable for supporting operational hydrogeomorphical river assessment and monitoring, and for contributing to the design of river habitat restoration actions. The ecological distinctiveness of the various types remains to be established.

Finally, it is important to stress that our analysis is based on the modest sample of headwater streams within a single country and biogeographical setting. Testing of the method at more sites and within a greater range of environmental settings is required to confirm its robustness and to highlight where improvements might be made.

**Acknowledgements** This research is funded as part of the Irish Environmental Protection Agency Research Programme 2014–2020 (contract 2017-W-LS-14). The programme is financed by the Irish Government. It is administered on behalf of the Department of Communications, Climate Action and the Environment by the EPA, which has the statutory function of co-ordinating and promoting environmental research.

**Funding** The funded was provided by Irish Environmental Protection Agency (Grant No. 2017-W-LS-14).

**Data availability** The data generated and analysed in this publication are available from the corresponding author upon reasonable request.

#### Declarations

**Conflict of interest** The authors have no competing interest to declare that are relevant to the content of this article.

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