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Associating Local-Scale Physical Habitat Assemblages With Reach-Scale Stream Hydrogeomorphological Types in Mountain Headwater Catchments

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ABSTRACT

Building an understanding of river ecosystems often involves integrating information from different locations, spatial scales and points in time. Geomorphologists and ecologists have long considered ways to explore river ecosystems at different, hierarchical, spatial scales so that features observed locally can be linked to the character of the larger spatial units within which the features are located. The present research builds on a classification of mountain stream reach types and their associated physical habitat assemblages proposed by Cox et al. for headwater streams across the Republic of Ireland. In this article we augment physical habitat and bed material data collected as part of an integrated investigation of within-catchment variations in water quality, physical habitat and biota in two small, Irish, mountain headwater catchments to explore two main research questions. Do the associations among mountain headwater stream types, physical habitat assemblages and bed material, identified at a national level, persist across short stream reaches *within* small, Irish, mountain headwater catchments? To what extent do the properties used to assign a stream hydromorphological type to a reach vary spatially along these headwater streams and what are the implications of these variations for identifying 'homogenous' reaches that can be associated with particular physical habitat assemblages? Our analysis and results from these two small catchments are necessarily exploratory and indicative. Nevertheless, we reveal a number of patterns, associations, and scale-related issues that need to be considered when surveying such streams and which could contribute to a larger, purpose-designed and more comprehensive study.

1 | Introduction

In this article we consider the physical characteristics of mountain headwater streams in Ireland and how these vary with the spatial scale of investigation. This research builds on long-established interests of fluvial geomorphologists and freshwater ecologists, particularly those working in mountain environments. For example, from a geomorphological viewpoint, Schumm (1985) suggested that 'the pattern (planform) of a river can be considered at vastly different scales depending on both the size of the river and the part of the fluvial system' (5). He identified four scales across which he considered that there were hydrological, hydraulic, geological and geomorphological interactions: drainage network; reach; land form; sediment grain. Similarly, but from a freshwater ecological perspective, Frissell et al. (1986) proposed a hierarchical framework for stream habitat classification to view streams and their ecosystems within a watershed context. Frissell et al. identified five levels of organisation of stream physical habitats, which they termed watershed, stream, segment, reach, pool-riffle and microhabitat systems. They suggested these were associated with different approximate linear spatial scales (10^3, 10^2, 10^1, 10^0 and 10^{-1} m, respectively) and with development processes that allowed them to persist over different approximate time scales (10^6 to 10^5, 10^4 to 10^3, 10^2 to 10^1, 10^1 to 10^0 and 10^0 to 10^{-1} years, respectively). Finally, an early example relating to the mountain stream focus of the research reported in this article, Grant et al. (1990) proposed a hierarchical framework for considering the stepped-bed morphology often observed in steep, mountain streams. Grant et al. noted that alternating steep- and gentle-gradient 'segments' such as pools and riffles are found in a wide range of stream channels, but that in steep mountain streams distinct stepped long profiles are observed. They also identified four spatial scales for studying such streams, for which they proposed the terms reach (delineated according to factors constraining the reach: constrained-bedrock, constrained-earthflow, unconstrained), channel unit (e.g., pools, riffles, rapids, cascades and isolated steps [log/boulder/bedrock]), channel sub-unit (e.g., within-unit step), and sediment particle. They associated each of these with different approximate linear channel lengths (10^3 to 10^2, 10^1 to 10^0, 10^0 to 10^{-1} and 10^0 to 10^{-2} channel widths, respectively). These three examples illustrate how fluvial geomorphologists and freshwater ecologists were considering the importance of spatial scale within fluvial systems when exploring the physical structure of fluvial systems and how this might link to biological communities.

These early ideas on relevant spatial scales for investigating river forms and processes were built on process-based research in the context of river morphodynamics. For example, using the spatial scaling terminology of Grant et al. (1990), geomorphologists have long identified different styles of alluvial river (e.g., meandering and braided) extending over river reaches of varying length, which display different characteristic assemblages of channel units (e.g., pools, riffles, steps, bars and islands), composed of a variety of sediment particle sizes (patches of different particle size and degrees of sorting, areas of exposed bedrock). Alluvial rivers develop channels within the sediments they transport and so their channel size, form and temporal dynamics reflect the ability of the river's flow to mobilise, transport and deposit available sediment particles of different sizes. Current understanding of these associations among flow, sediment and channel morphodynamics is founded on early work by Lane (1955), Leopold and Wolman (1957), Bagnold (1966), and Schumm (1963, 1985). Over subsequent decades much experimental and theoretical research has been devoted to understanding the relevant process-form interactions, including (at the reach scale) why different hydrogeomorphological styles of river channel evolve and may change, and (at the channel unit and particle scales) the nature, stability and turnover of the related assemblages of landforms and physical habitats. The enormous body of literature on this topic has been widely synthesised and reviewed, highlighting reach—channel unit—particle assemblages and related river classifications that emanate from these process-form interactions (e.g., Church 2006; Kondolf et al. 2016; Buffington and Montgomery 2022; Fryirs and Brierley 2021; Khan et al. 2021).

From a biological perspective, not only have researchers explored the way that physical factors may structure freshwater organisms and communities at different spatial scales (e.g., Johnson et al. 2007; Lapointe 2012), but they have also illustrated how the number of aquatic species sampled increases with sampling effort and the number of sampled habitats (e.g., Angermeier and Smogor 1995; Li et al. 2001; Reynolds et al. 2003). Research on sampling effort not only emphasises the importance of the method of sampling and the number of samples taken, but also the length of river needed (i.e., the range of habitats sampled) for the number of species to level off and asymptotically approach a maximum value. For example, an early study of fish by Angermeier and Smogor (1995) showed how the number of species and number of microhabitats increased with the number of habitat units (riffles, runs and pools) sampled, and that sampling a reach length of 22 to 67 stream widths was typically required in the studied streams in Virginia, USA to reveal 90% of the species that were present. Similar results were reported by Li et al. (2001) and Reynolds et al. (2003) following sampling of a larger number of streams in Oregon, USA, to investigate macroinvertebrates and fish, respectively. They suggested that reach lengths of at least 80 channel widths (Li et al. 2001) or 150 m (Reynolds et al. 2003) were necessary to satisfactorily characterise the species present. These results indicate the multi-scale structure of the biological community that inherently links species to habitats and microhabitats (i.e., channel units and subunits) and the reaches within which they are studied.

Following from this scale-related research, Cox et al. (2023) applied a simple, operational, geomorphologically based assessment method developed in England (Gurnell et al. 2020) to Irish headwater streams. Once again using the terminology of Grant et al. (1990), the assessment method incorporates information drawn from three spatial scales (reach, channel unit [physical habitat] and particle). The method links reach-scale stream geomorphic types (based on their slope, planform, valley confinement and bed material) to the assemblage of physical habitats that stream reaches of a given type may contain when relatively free of human pressures and interventions. Cox et al. (2023) assembled and analysed a data set for near-naturally functioning headwater streams across Ireland and identified several mountain headwater stream types that displayed contrasting physical habitat assemblages.

In this paper, we explore the degree to which the outcomes from the national study of Cox et al. (2023) are reproduced when multiple reaches are considered *within* small, mountain, headwater catchments. We employ research data collected as part of a broader integrated investigation of within-catchment variations in water quality, physical habitat and biota in two small, Irish, mountain headwater catchments (part of the SSNet research project 'Managing the small stream network for improved water quality and biodiversity and ecosystem services protection'). The data gathered for this project provided physical habitat and bed material information for a sizeable sample of sites (42) within the two headwater catchments. We augmented this data set to allow us to explore two main research questions:

I. Do the associations among mountain headwater stream types, physical habitat assemblages and bed material, identified at a national level by Cox et al. (2023), persist across short stream reaches *within* small, Irish, mountain headwater catchments?

II. To what extent do the properties used to assign a stream type to a reach vary spatially along small, Irish, mountain headwater streams and what are the implications of these variations for identifying 'homogenous' reaches?

Our analysis and results from these two small catchments are exploratory and indicative rather than comprehensive. Nevertheless, we reveal patterns, associations, and scale-related issues that need to be considered when surveying such streams and which could contribute to the specification of a larger, purpose-designed and more comprehensive study.

2 | Terminology

As discussed above, widely varying terminology has been used to refer to different spatial units of river and stream systems. Following Cox et al. (2023), we define the following terms and use them throughout the remainder of this article:

A 'reach' is a length of stream or river to which we assign a (hydrogeomorphological) type. Given the small streams investigated here, we refer to this as a 'stream type'.

A 'physical habitat survey site' or 'site' is a shorter length of stream or river, typically several channel subunits *sensu* Grant et al. (1990), where a physical habitat survey is used to record the habitat assemblage, vegetation structure, sediments, and any human pressures or interventions.

We confined data gathering to extended lengths of headwater streams, which are hereafter referred to as 'studied tributaries'.

3 | A Classification of Irish Mountain Headwater Streams

Cox et al. (2023) assembled a data set from field survey and secondary sources for near-naturally functioning 'homogenous' headwater stream reaches across the Republic of Ireland. They then explored relationships between reaches assigned to different stream types and their physical habitat assemblages. In this section, we briefly summarise this research (hereafter referred to as the 'national study'), which is the foundation for the research reported in this article.

3.1 | Identifying 'Homogenous Reaches'

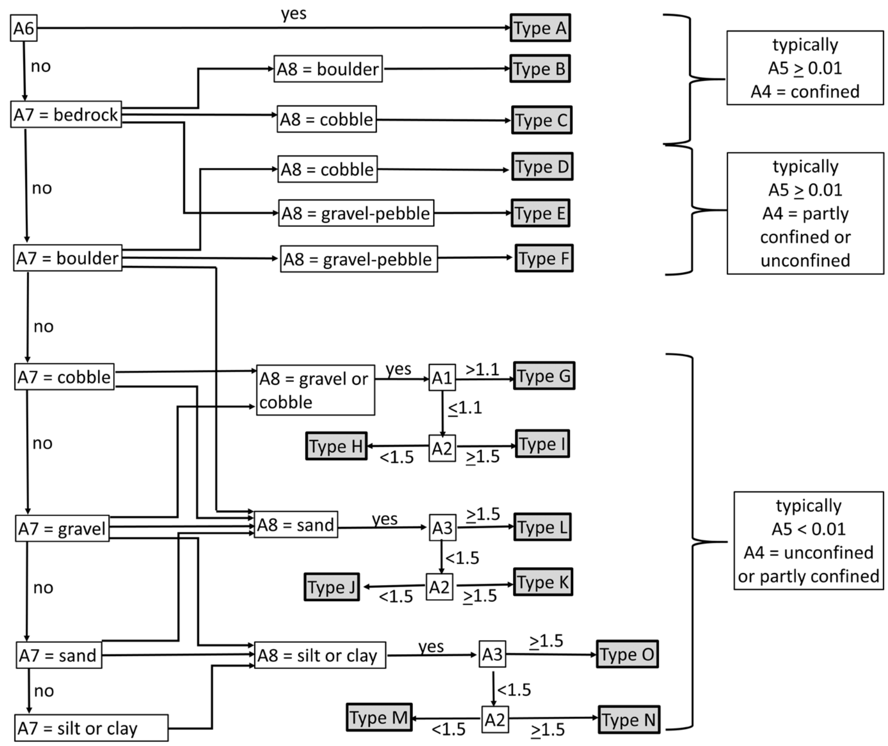
In the national study homogenous reaches displayed reasonably consistent stream planform, slope and degree of valley confinement and included no major tributary confluences or breaks of slope in the stream long profile. Homogenous reaches were identified from widely available secondary sources (topographic maps, air photographs, Google Earth images and digital elevation models [DEMs]). All reaches were of the order of 1 km in length and were comprised of stream channels with an average width of 2.4 m (upper quartile = 3.5 m, lower quartile = 1.6 m).

Eight indicators were computed to assign a reach to a stream type (see Figure 1 for fuller definitions) and were visually assessed to be reasonably consistent during homogeneous reach identification. Indicators A1 to A5 were extracted from secondary sources. Planform (A1-braiding index, A2-sinuosity index and A3-anabranching index) was computed from the channel centre-line sinuosity for single-thread channels (A2) and the number of active channels and the degree to which those channels were separated by bars (A1) or islands (A3) for multithread channels. The level of valley confinement (A4) was computed from the length of each stream bank that was adjacent to the valley side or a major terrace. Valley slope (A5) and stream slope were computed from elevation estimates at the upstream and downstream ends of the reach divided, respectively, by the valley and stream channel lengths. Following field survey at a physical habitat survey site within each reach (see Section 3.2), three bed material indicators (A6—bedrock reach, A7—coarsest bed material and A8—average mineral bed material size class) were computed to complete the set of eight indicators needed to assign a homogeneous reach to a stream type.

3.2 | Determining Bed Material and Physical Habitat Assemblages at the Site Scale

Within each reach, channel dimensions, bed and bank materials, physical habitats, vegetation structural components and human interventions and pressures were surveyed within 50 m long sites using the MoRPh survey (Gurnell et al. 2019). Five contiguous 10 m long MoRPh surveys were conducted at each physical habitat survey site. The MoRPh survey data were then combined to extract aggregate abundances for a list of features across each site.

MoRPh surveys record abundances as the areal/linear extent or number/count of a list of features observed along short stream lengths (10, 20, 30 or 40 m, depending on the channel width). A 10 m survey length was used in the national study to reflect the narrow stream channels investigated (i.e., typically < 5 m wide). Each MoRPh survey records the dimensions of a channel cross section at a central location. It then records features separately within the areas of each bank top (to 10 m from the channel edge), each bank face and the stream bed (see Table S1 for details of the features recorded). The abundance/extent of most features is recorded using an absent, trace, present, extensive scale (A, T, P and E) where A means absent, T indicates < 5%, P indicates 5%–33%, and E indicates > 33% areal/linear extent. By assigning mid-point values of 0%, 2%, 19% or 67% to A, T, P and E records, respectively, and then accumulating these values across several contiguous MoRPh surveys, approximate 'abundance' estimates can be extracted for each recorded feature across a physical habitat survey site. The MoRPh survey also records the abundance of some features as a count (e.g., pools, riffles, steps and waterfalls). For these features the total abundance is computed as the sum of the counts across the set of contiguous MoRPh surveys within a physical habitat survey site. These abundance estimates support computation of the three bed material indicators A6, A7 and A8 that are required to determine the reach stream type and site-scale feature



ESTIMATED FROM SECONDARY (MAP/IMAGE/DEM) SOURCES	ESTIMATED FROM MoRPh SURVEYS
A1 = braiding index (average number of flowing threads at low flow across 10 equally-spaced cross-sections of the river corridor) A2 = sinuosity index (stream channel length / valley length) A3 = anabranching index (average number of flowing threads separated by vegetated islands at low flow across 10 equally-spaced cross-sections of the river corridor) A4 = level of confinement (>90% bank length confineD = 'confined', <10% bank length confined = 'unconfined', 10%-90% bank length confined = 'partly confined' A5 = valley gradient (upstream elevation-downstream elevation)/(valley length)	A6 = bedrock reaches (over one third of channel bed is exposed bedrock) A7 = coarsest bed material size class (coarsest class exposed for at least >5% channel bed area – includes bedrock as 'coarsest' possible class) A8 = average mineral bed material size class (area-weighted average of observed bed material size classes (boulder, cobble, gravel-pebble, sand, silt, clay) where size classes are represented by their mid-point size expressed in phi units (excludes bedrock))

FIGURE 1 | Decision tree for assigning a stream/river type (boxes shaded grey) to a stream/river reach based on eight indicators (A1 to A8—white boxes). The Figure is developed from Gurnell et al. (2020) to incorporate modifications for mountain stream types A to F proposed by Cox et al. (2023).

abundances for investigating associations among reach stream types and site physical habitat assemblages.

3.3 | Headwater Stream Types

The requirement for near-naturally functioning streams in the national study yielded a sample of headwater stream reaches that were predominantly located in mountain catchments where grazing was often the only significant human pressure. Analysis of both the physical habitat assemblages at the surveyed sites and the properties displayed at the reach scale identified six mountain stream types (A–F) and a further three lower gradient stream types (H, J and M) in the national study, each associated with a distinctive assemblage of physical habitats. Type B was a local mountain stream type found in a specific geographical area of Ireland. The other five mountain stream types (A, C, D, E and F) occurred widely and appeared to correspond to the bedrock, cascade, step-pool, plane-bed and pool-riffle types identified by Montgomery and Buffington (1997) in mountain catchments in western Washington and Oregon (Table 1). All stream types are identified using a decision tree that was established in the national study (Cox et al. 2023, figure 1).

4 | Methods

4.1 | Catchment and Stream Selection

Two headwater catchments in the Wicklow Mountains, Ireland, that drain to the Ballinagee and Dargle rivers, were selected for study (Figure 2) as they were minimally impacted by human activities and, therefore, displayed near-natural hydrogeomorphology. Typical of many steep Irish headwaters, both catchments are in glacial valleys with steep valley sides and rounded mountain tops. This glacial morphology was created by erosion of the schist cap that originally covered the area (Ballantyne et al. 2006). Although the landscape is minimally impacted by

TABLE 1 | Five widely occurring Irish, mountain, headwater stream types identified in the national study with their nearest equivalent types as defined by Montgomery and Buffington (1997) and also the moderate gradient H stream type, their distinguishing reach-scale characteristics and their key indicator physical habitats.

Cox et al. (2023) stream type (Montgomery and Buffington (1997) nearest equivalent type)	Distinguishing reach-scale characteristics	Key indicator physical habitats
A (bedrock)	Steep (~> 0.10), bedrock, some boulder-cobble, typically confined-partly confined	Extensive exposed bedrock and boulders, often forming cascades. Steep to vertical bedrock channel margins.
C (cascade)	Steep (~0.08–0.13), boulder-cobble-bedrock, typically confined-partly confined	Frequent exposed bedrock. Widespread boulder and bedrock cascades. Stable bedrock and boulder channel margins.
D (step-pool)	Steep (~0.02–0.15), boulder-cobble, typically confined-partly confined	Predominantly boulder and cobble bed with occasional bedrock exposure. Frequent steps, and unvegetated, mid-channel and side boulder-cobble bars.
E (plane-bed)	Moderately steep (~0.02–0.10), cobble-gravel, some bedrock exposure and boulders, typically confined-partly confined	Predominantly gravel-pebble bed with some boulders and occasional bedrock exposure. Frequent berms, side bars, and benches.
F (riffle-pool)	Moderately steep (~0.02–0.05), cobble-gravel-pebble, typically confined-partly confined	Predominantly gravel-pebble bed with some cobbles and occasional boulders. Frequent riffles, berms, side bars, and benches.
H	Moderate gradient (~0.005–0.01), sinuous, gravel-pebble, some cobbles, typically partly confined	Predominantly gravel-pebble bed with some cobbles. Frequent riffles.

humans when considered within the broader Irish context, a long history of grazing by sheep and deer has resulted in negligible tree or shrub cover and structurally simple riparian vegetation.

Within both catchments, the three largest headwater streams were selected using the Irish Environment Protection Agency's (EPA) River Network Routes dataset (EPA 2017, figure 2). The stream length for the six studied tributaries, one within each of these six headwater streams, was then determined in the field, commencing at the most upstream point at which a clearly defined channel was observed. The length of stream to be studied was terminated at the downstream end to define the ca. 1300 to 1900 m lengths of the six studied tributaries (Figure 2). The studied tributaries were coded as follows: Dargle river headwaters—Dar_t1, Dar_t2 and Dar_t3; Ballinagee river headwaters: Bal_t1, Bal_t2 and Bal_t3. In three cases (Dar_t2, Dar_t3 and Bal_t2) the studied tributary terminated at a junction with a higher order stream. It should be noted that the downstream site on tributary Bal_t1 was also part of the national study.

4.2 | Data Collection

4.2.1 | Site-Scale Surveys

The MoRPh survey (Gurnell et al. 2019) was used to capture channel dimensions, bed material and physical habitat information at sites along the six studied tributaries. The surveyed streams were typically < 5 m wide and so each MoRPh survey was 10 m in length. Each physical habitat survey site was 30 m long (three contiguous MoRPh surveys) and 42 sites were distributed at approximately 200 to 300 m intervals along the six studied tributaries (Figure 2).

The abundance of a range of physical habitats and the three bed material indicators (A6, A7 and A8) needed to assign a reach to a stream type were extracted from the MoRPh surveys for each physical habitat survey site. Where feature abundance was recorded using the ATPE scale described in Section 3.2, this yielded a maximum abundance estimate of 201 for stream bed features (i.e., 3 surveys × 67 abundance) and 402 for bank face and bank top features (i.e., 2 banks × 3 surveys × 67 abundance). Where features were recorded using a count, the abundance estimate was the total count over three MoRPh surveys. MoRPh surveys record the abundance of many features (Table S1) but the present research focuses on river bed and bank face features including bed material types, water surface (hydraulic) flow types, bed, bank face and margin physical features and vegetation (Table 2).

4.2.2 | Reach-Scale Indicators

The close-spacing of the 42 physical habitat survey sites prevented the use of the same methods and secondary sources adopted for defining reaches in the national study (described in Section 3). Instead, the six studied tributaries were split systematically into 97 reaches each 100 m long, ensuring that all 42 physical habitat survey sites were located within mutually

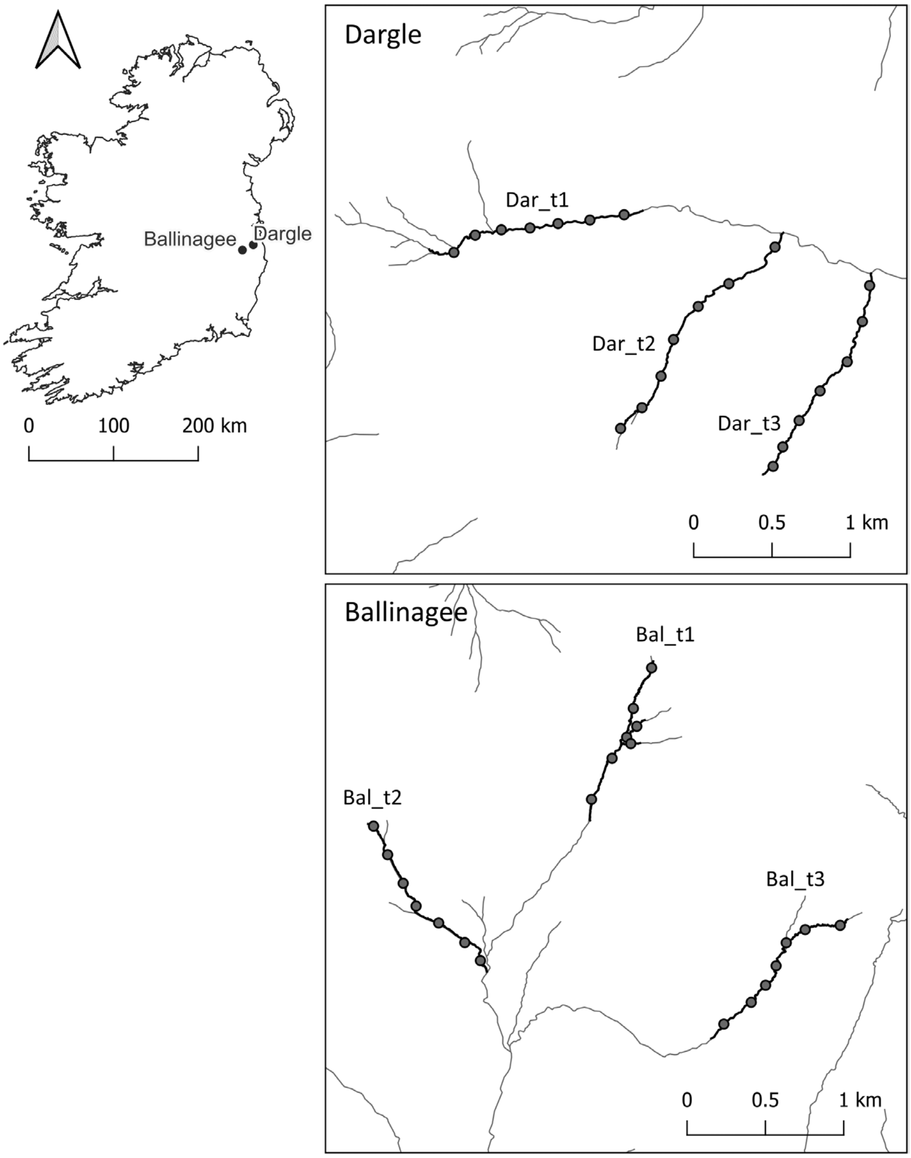


FIGURE 2 | Locations of the two headwater catchments (Ballingee, Dargle), their stream networks (from the Irish EPA's River Network Routes dataset; EPA 2017; marked by thin black lines), the six studied tributaries (three in each catchment, marked by thicker black lines), and 42 physical habitat survey sites (seven along each studied tributary, marked by grey dots) (each studied tributary commenced at the source of a clearly defined stream channel identified in the field, which did not always correspond to the stream network shown in the figure).

exclusive reaches. Although we used a systematic approach to defining reaches, we still needed to compute reach-scale indicators (A1–A8) to assign each reach to a stream type. Reflecting the small reach lengths, the indicators were extracted from three sources with a greater spatial resolution than the more widely available sources used in the national study:

i. Walkover surveys: These were conducted along the entire length of each studied tributary to obtain detailed spatial information on stream planform and valley confinement (indicators A1, A2, A3 and A4, Figure 1). During the walkover surveys, stream planform extracted from the Irish EPA's River Network Routes dataset was ground-truthed and adjusted where necessary. Longitudinal locations of changes in stream planform (single-thread, multi-thread and sinuosity) and valley confinement (presence or absence on each stream bank) were recorded. In addition, the longitudinal extent of bedrock exposure was recorded as the start and end points of stream lengths within which bedrock was near-continuously visible in at least 1 m long patches.

ii. DEM data: A DEM with a spatial resolution of 5 m and a vertical accuracy of between 0.5 and 1 m (NextMap 5 m DEM [Intermap Technologies 2007]) was used to compute valley and channel slopes for each 100 m reach (indicator A5).

iii. Bed material data: Of the total of 97 individual 100 m reaches, 55 did not contain a physical habitat survey site. In these reaches, the bed material component of the MoRPh survey was applied to three contiguous 10 m sections of the stream to extract the bed material indicators (A6, A7 and A8), enabling all eight stream type indicators to be computed for every 100 m reach and providing bed material information for 30% of the length of the studied tributaries (30 m in every 100 m).

4.3 | Data Analysis

Summary statistics were extracted from the channel dimensions recorded at the mid-point of 126 full MoRPh surveys distributed across the six studied tributaries and 42 physical habitat survey sites. These data allowed the typical sizes of the surveyed streams to be computed.

Using the above-described sources (Section 4.2.2) with a higher spatial resolution and accuracy than the widely available secondary sources used in the national study, Indicators A1 to A8 were determined and stream types were allocated to each of the 97,100 m reaches using the indicator computations and stream type decision tree (Figure 1).

Associations between site physical habitat assemblages and stream types for the 42,100 m reaches containing physical habitat survey sites were visualised using box and whisker plots of the abundance of individual features grouped according to stream type. The statistical significance of these patterns was assessed using non-parametric tests (Kruskal–Wallis [Kruskal and Wallis 1952] and Dunn–Bonferroni [Dunn 1961]) because of differing subsample variances and small sample sizes.

In addition to supporting the computation of indicators A1 to A8 for each 100 m reach, the detailed data gathered for the 100 m reaches provided an opportunity to explore whether longer reaches of the studied tributaries displayed reasonably consistent (homogenous) properties. For this, 93 100 m reaches distributed longitudinally along the six studied tributaries were considered (four reaches located on two short side streams along Bal_t1 were excluded, Figure 2).

The spatial distribution of stream types and the three bed material indicators (A6, A7 and A8) was explored to establish the degree to which groups of adjacent 100 m reaches displayed the same stream type and similar bed material properties. The near-continuous distributions captured from the DEM and walkover surveys were also explored to establish the extent and nature of any homogenous reaches associated with indicators A1 to A5.

The DEM provided an opportunity to consider changes in the slope of the studied tributaries (indicator A5). A longitudinal stream elevation profile was generated for each of the six studied tributaries by querying the DEM at 1 m horizontal intervals along each stream centre line. Moving averages were calculated for 5 m (the spatial resolution of the DEM) and then 10 to 300 m stream length smoothing windows in 10 m increments (i.e., 31 different window lengths). In every case, the moving averages were computed every 5 m along the studied tributary profiles. This provided a simple way of visualising elevation (and slope) longitudinal variability with different degrees of smoothing; the presence of local sizeable topographic features (e.g., cascades, bedrock outcrops and waterfalls); the generalised longitudinal profile of the studied tributaries and thus the extent of reaches of reasonably homogenous slope.

The spatial distributions of indicators A1 to A4 were explored visually using the walkover survey data. These were combined with the outputs from the DEM analysis (indicator A5) to establish whether extended homogenous reaches were evident along any of the studied tributaries and whether these showed any correspondence with the longitudinal extent of bedrock exposure, which was also captured during the walkover surveys.

All statistical analyses were conducted in Excel version 17.0 using the add-on XLSTAT version 2023.3.1 (Lumivero 2024).

5 | Results

5.1 | Channel Dimensions

A summary of the channel dimensions recorded at the mid-point of the 126 MoRPh surveys distributed across the six studied tributaries confirmed that almost all individual cross sections were narrower than 5 m, with an average (standard deviation) active bed width, bankfull width, and bankfull depth of 2.1 m (1.2 m), 2.8 m (1.6 m) and 0.6 m (0.3 m) respectively (Table S2). Only two sites had an active bed width greater than 5 m, while bankfull width exceeded 5 m at only 6 sites.

5.2 | Stream Types

Stream types were calculated for each of the 42,100 m reaches centred on the physical habitat survey sites (Figure 2). Ten reaches were allocated to stream type A, 10 to C, 6 to D, 4 to E, 10 to F and 2 to H, providing samples of reaches for five of the widely occurring mountain stream types (A to F). The mountain stream types depend almost entirely on the bed material indicators (A6, A7 and A8) (Figure 1, types A–F). The remaining indicators A1–A5 showed little variation across the 42 reaches with respect to the thresholds used in the decision tree to assign a reach to any of the possible 15 types. All reaches were single-threaded (indicators A1 and A3 all equal to 1.0); had a valley slope greater than 0.01 apart from those allocated to type H (indicator A5, mean = 0.104, SD = 0.039, Figure 3a) and a sinuosity less than 1.5 (indicator A2, mean = 1.090, SD = 0.094, Figure 3b). However, indicator A4 (degree of confinement, Figure 3c) crossed some of the threshold values distinguishing confined, partly confined and unconfined reaches, although the majority of reaches fell into the partly confined category (4 reaches were unconfined, 9 were confined and 29 were partly confined). Although indicators A2 and A5 did not cross any of the threshold values embedded in the decision tree apart from the slope values displayed by type H streams, indicator A2 displayed increasing values and indicator A5 displayed decreasing values across the sampled stream types from A to H (Figure 3a,b).

5.3 | Associations Between Site Physical Habitat Assemblages and Reach Stream Types

Despite the small sample sizes for some of the stream types, especially type H, Kruskal–Wallis tests indicated that many of the physical habitats displayed statistically significant differences in abundance ($p < 0.05$) across stream types, with the

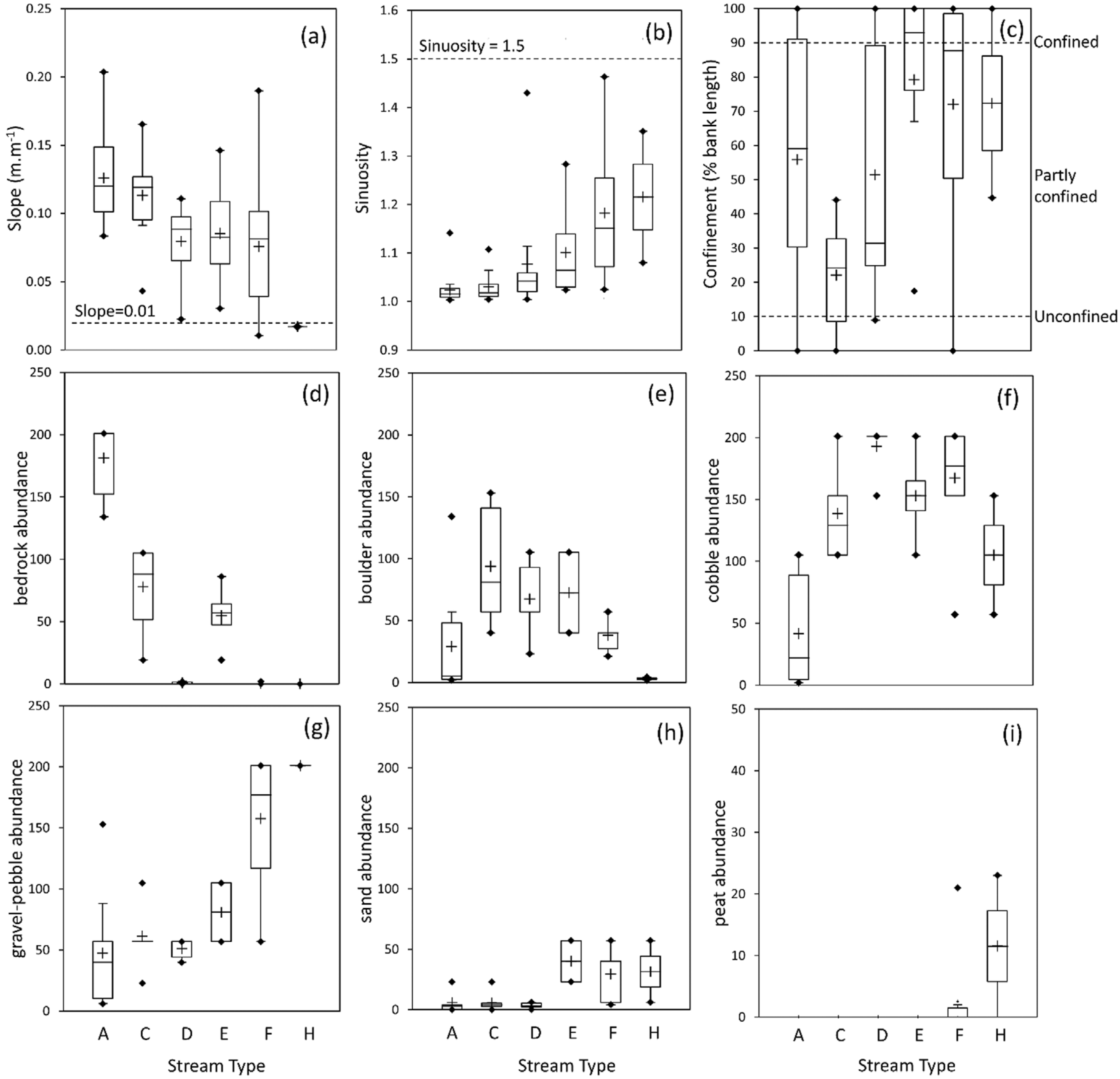


FIGURE 3 | Box and whisker plots a, b and c illustrate the variability in slope, sinuosity and confinement for 42 100 m reaches according to their stream type, based on detailed observations collected during walkover surveys. Note that the horizontal dashed lines on plots a, b and c indicate the boundaries used in the decision tree (Figure 1). Plots d–i show the abundances of different bed material types according to the stream type. Note the different scales of the vertical axes for plots d–i and that the maximum achievable abundance is 201. Outliers are shown as diamonds.

Dunn–Bonferroni tests identifying which stream types are discriminated by each of the habitats and their abundances ($p < 0.005$, Table 2). However, statistical results for stream type H should be treated with caution because only two reaches were assigned to this type. The results of the Dunn–Bonferroni pairwise comparisons are compared with those found for stream types A to H in the national study, where the same features were analysed in both studies (Table 2).

Box and whisker plots revealed a number of visual trends across the stream types from A through H (Figures 3–5, S1 and S2). These visual trends are tentatively described below as they may represent underlying trends. The visual trends are compared with the characteristics of stream types A to H identified in the national study (Table 1).

Kruskal–Wallis tests showed significant differences ($p < 0.001$, Table 2) in the abundance of all bed material types across stream types A to H with the exception of silt and peat. All stream types showed significant differences (Dunn–Bonferroni, $p < 0.005$, Table 2) in the abundance of at least one bed material type, with most (stream types A, C, D, F) showing significant differences for three or more bed material types. This association between bed material and stream type appears to be replicated in the visual trends displayed in box and whisker plots for different bed material

TABLE 2 | The results of Kruskal–Wallis and Dunn–Bonferroni tests applied to assess whether river bed and bank face features show statistically significant differences in abundance according to the hydromorphological reach type across 42 100 m reaches.

River bed and bank features	Mean (SD)[a]	Kruskal–Wallis Statistic (degrees of freedom = 5)	Probability ($p < 0.05$)	Dunn–Bonferroni pairwise comparisons of river types ($p < 0.005$)	Dunn–Bonferroni pairwise comparisons of river types in the national study[c] ($p < 0.0024$)
Bed material types					
Bedrock	67.02 (75.42)	38.055	< 0.0001	A > D, F, H[b] and C > F	A, C > D, F, H and E > D
Boulder	54.93 (43.82)	19.672	0.001	C > A, H[b]	A, C, D > H and D > F
Cobble	129.88 (66.82)	25.474	0.000	D, F > A	C, D, F > A
Gravel-pebble	88.17 (62.15)	24.310	0.000	F > A, C, D	F, H > A, C and H > D
Sand	15.52 (19.46)	21.879	0.001	E, F > A	H > A, C, D and F > C
Silt	0.38 (1.10)	6.207	N.S	N.S	H > A, C, D
Peat	1.14 (4.75)	11.870	0.037	N.S	N.S
Water surface flow types					
Free fall	13.19 (13.15)	17.247	0.004	C > H[b]	—
Chute	49.00 (21.23)	9.155	N.S.	N.S	—
Broken standing wave	15.36 (18.02)	13.891	0.016	C > H[b]	—
Unbroken standing wave	103.95 (54.73)	6.186	N.S	N.S	—
Upwelling	0.38 (1.01)	4.157	N.S	N.S	—
Rippled	101.83 (45.15)	8.120	N.S	N.S	—
Smooth	68.33 (58.71)	9.421	N.S	N.S	—
No perceptible flow	17.24 (14.94)	8.454	N.S	N.S	—
Bed physical features					
Exposed unvegetated rocks	1.88 (3.96)	15.460	0.009	E > A, C	E > H
Exposed vegetated rocks	23.76 (20.86)	15.373	0.009	C > A	A, C, D > H and C, D > F
Unvegetated mid-channel bar	2.24 (5.73)	4.022	N.S	N.S	N.S.
Vegetated mid-channel bar	4.24 (8.67)	7.664	N.S	N.S	N.S.
Cascade	71.12 (57.33)	18.913	0.002	N.S.	A > F, H and C > H and D, E > H
Step	3.19 (2.25)	15.157	0.010	F > A	C, D > H

(Continues)

TABLE 2 | (Continued)

River bed and bank features	Mean (SD)[a]	Kruskal–Wallis Statistic (degrees of freedom = 5)	Probability ($p < 0.05$)	Dunn–Bonferroni pairwise comparisons of river types ($p < 0.005$)	Dunn–Bonferroni pairwise comparisons of river types in the national study[c] ($p < 0.0024$)
Riffle	2.26 (1.74)	13.447	0.020	F > A	D, F, H > A and F > C
Pool	9.64 (3.07)	4.995	N.S	N.S	A, C, D > H
Bank and margin physical features					
Marginal backwater	58.17 (33.38)	3.42	N.S.	N.S.	N.S.
Unvegetated side bar	29.29 (36.54)	14.68	0.012	F > A	E, F > H
Vegetated side bar	57.21 (61.27)	13.72	0.017	C > A	D > A
Berm	24.62 (30.38)	8.81	N.S.	N.S.	N.S.
Bench	8.79 (20.53)	7.51	N.S.	N.S.	N.S.
Stable cliff	147.95 (91.68)	9.94	N.S.	N.S.	N.S.
Eroding cliff	68.14 (84.02)	18.63	0.002	F > A, C	H > A
Toe deposit	29.67 (28.58)	13.83	0.017	F > A	N.S.
Bed vegetation					
Unvegetated	188.43 (31.91)	18.156	0.003	C, D, F > A	—
Liverworts/mosses/lichens	63.07 (45.46)	13.998	0.016	A > F	—
Emergent reeds/linear leaved	0.33 (0.75)	5.271	N.S	N.S	—
Riparian vegetation interacting with channel bed					
Vegetation shading channel	8.02 (33.50)	9.721	N.S	N.S	—
Submerged tree roots	0.05 (0.31)	3.200	N.S	N.S	—
Large wood	0.10 (0.43)	2.255	N.S	N.S	—
Discrete organic accumulations	3.48 (4.46)	7.777	N.S	N.S	—
Water margin vegetation					
Liverworts/mosses/lichens	328.93 (96.16)	16.15	0.003	A, C > F	—
Emergent reeds/linear leaved	9.26 (19.77)	8.96	N.S.	N.S.	—
Filamentous algae	77.24 (90.51)	17.23	0.002	A > E, F	—

[a]Steps, riffles, and pools were recorded as counts; all other bed features/habitats have a maximum possible abundance of 201 and bank face features/habitats have a maximum possible abundance of 402.
[b]Results for Type H should be treated with caution because only two streams of this type were sampled.
[c]Statistically significant pairwise comparisons for bank and margin physical features identified in the national study (the national study only considered these features).

types (Figure 3d–i). Bedrock (Figure 3d) is only exposed on the beds of stream types A, C and E. Boulders show a trend of decreasing abundance from type C through to H (Figure 3e). Cobble abundance appears to increase from type A through to F (Figure 3f) and gravel-pebble appears to increase from type A through to F (Figure 3g). Sand is only observed in small but notable quantities in types E, F and H (Figure 3h). There were very small abundances of silt (not illustrated) and peat (Figure 3i), with peat only observed in types F and H. These visual trends and the outcomes of the statistical tests are in broad agreement with the national study (Table 2), where bed material was found to vary significantly across stream types A to H for all bed material types except peat. In the national study there was also a progressive fining of bed material from stream types A to H, with stream types F and H associated with lower abundances of bedrock, boulder, and cobble (Tables 1 and 2).

Although there were no statistically significant differences in the abundances of the water surface flow (hydraulic) types across the sampled stream types (Table 2) apart from two differences between types C and H (Kruskal–Wallis, $p<0.016$, Dunn–Bonferroni, $p<0.005$), some broad trends can be observed across the different stream types in the box and whisker plots (Figure S1). A wide variety of flow types were associated with stream types A, C, D, E and F, indicating that they are all hydraulically complex. In contrast, the two reaches assigned to type H display no free fall, chute or upwelling flow types, lower abundances of broken and unbroken standing waves and ripples, and higher abundances of smooth and no perceptible flow types (Table 2). This is consistent with the lower hydraulic complexity and higher abundances of low velocity flow types found in type H in the national study.

The abundance of most bed physical features differed significantly (Kruskal–Wallis, $p<0.02$, Table 2) across the stream types. For exposed vegetated and unvegetated rocks, steps and riffles, there were significant differences between one or more pairs of stream types (Dunn–Bonferroni, $p<0.005$, Table 2). In all instances those bed physical features that exhibited differences across the stream types also displayed differences in the national study, although fewer pairwise differences were observed on average and the same pairwise differences were not always observed in the present study (Table 2). Some visual trends in the abundance of bed physical features are present in the box and whisker plots (Figure 4). Small quantities of exposed unvegetated rocks (boulders) are observed in all stream types apart from H, with the highest abundances in types E and F (Figure 4a). There are more exposed vegetated rocks (boulders) than unvegetated rocks in all stream types with a trend of decreasing abundance from type C through to H (Figure 4b). Mid-channel bars, whether unvegetated or vegetated, occur in low abundances across all stream types and are not present in the two type H reaches (Figure 4c,d). Cascades show a pattern of decreasing abundance from stream type A through to H (Figure 4e), whereas steps (<2 m high) appear to increase in frequency from type A through to F (Figure 4f). Riffles show a trend of increasing frequency from type A through to F and H (Figure 4g) and pools are present in similar frequencies across all stream types (Figure 4h). These visual trends are consistent with the trends identified in the national study which found a decrease in the abundance of exposed rocks/boulders and cascades and an increase in riffles from stream types A to H, with steps most abundant in type D streams (Tables 1 and 2).

Bank and water margin physical features (Figure 5) also show some trends across the range of stream types. There are statistically significant differences in abundances of vegetated and unvegetated side bars, eroding cliffs, and toe deposits across the stream types (Kruskal–Wallis, $p<0.017$, Table 2), with pairwise comparisons primarily differentiating between type A streams and type C and F streams (Dunn–Bonferroni, $p<0.005$, Table 2). As shown in Figure 5a, marginal backwaters are present in all stream types. Unvegetated side bars show a visual trend of increasing abundance from stream type A through to F (Figure 5b), whereas vegetated side bars show a trend of increasing abundance from type C through to H (Figure 5c). Berms and benches are scarce with no clear trend in abundance across stream types (Figure 5d,e). However stable cliffs appear to decrease in abundance from type A through to H (Figure 5f) and eroding cliffs to increase in abundance from type A through to F (Figure 5g). These visual trends align with those observed in the national study which also recorded high abundances of stable cliffs in bedrock rivers and an increasing trend in eroding cliff abundance from stream types A to H (Tables 1 and 2). Similar patterns in the abundance of marginal depositional features to those seen here were also observed in the national study, with unvegetated side bars more common in type E and F streams (Tables 1 and 2).

The bed of most streams was largely unvegetated (Figure S2a). However, where vegetation was present on the bed, liverworts/mosses/lichens were the main vegetation type, with the highest abundances associated with stream type A, although abundances were only significantly greater than those in type F streams (Kruskal–Wallis, $p=0.016$, Dunn–Bonferroni, $p<0.005$, Table 2, Figure S2b). Tiny abundances of emergent reeds and other linear-leaved macrophytes were recorded in all stream types (Figure S2c). For vegetation along the water margin, three different structural vegetation types (filamentous algae, emergent reeds and other linear-leaved macrophytes, liverworts/mosses/lichens) show quite high abundances (Figure S2d–f). Liverworts/mosses/lichens are very abundant along the water margins of stream types A to E and then appear to decline slightly in abundance through types F and H (Figure S2e), although there was only a statistically significant difference between stream types A, C and F (Kruskal–Wallis, $p=0.003$, Dunn–Bonferroni, $p<0.005$, Table 2). The abundance of emergent reeds and other linear-leaved plants along the water margin did not differ significantly with stream type (Kruskal–Wallis, $p>0.05$, Table 2), although there was a visual trend of increasing abundance from stream types A to H (Figure S2f), while the opposite trend was observed for filamentous algae (Figure S2d) with significantly greater abundances recorded in type A streams than types E or F (Kruskal–Wallis, $p=0.002$, Dunn–Bonferroni, $p<0.005$, Table 2). These results are in keeping with the national study where the beds of most steep to moderate gradient stream types were largely unvegetated, and the margins, particularly where bedrock or large stable boulders were present, were colonised by mosses and liverworts.

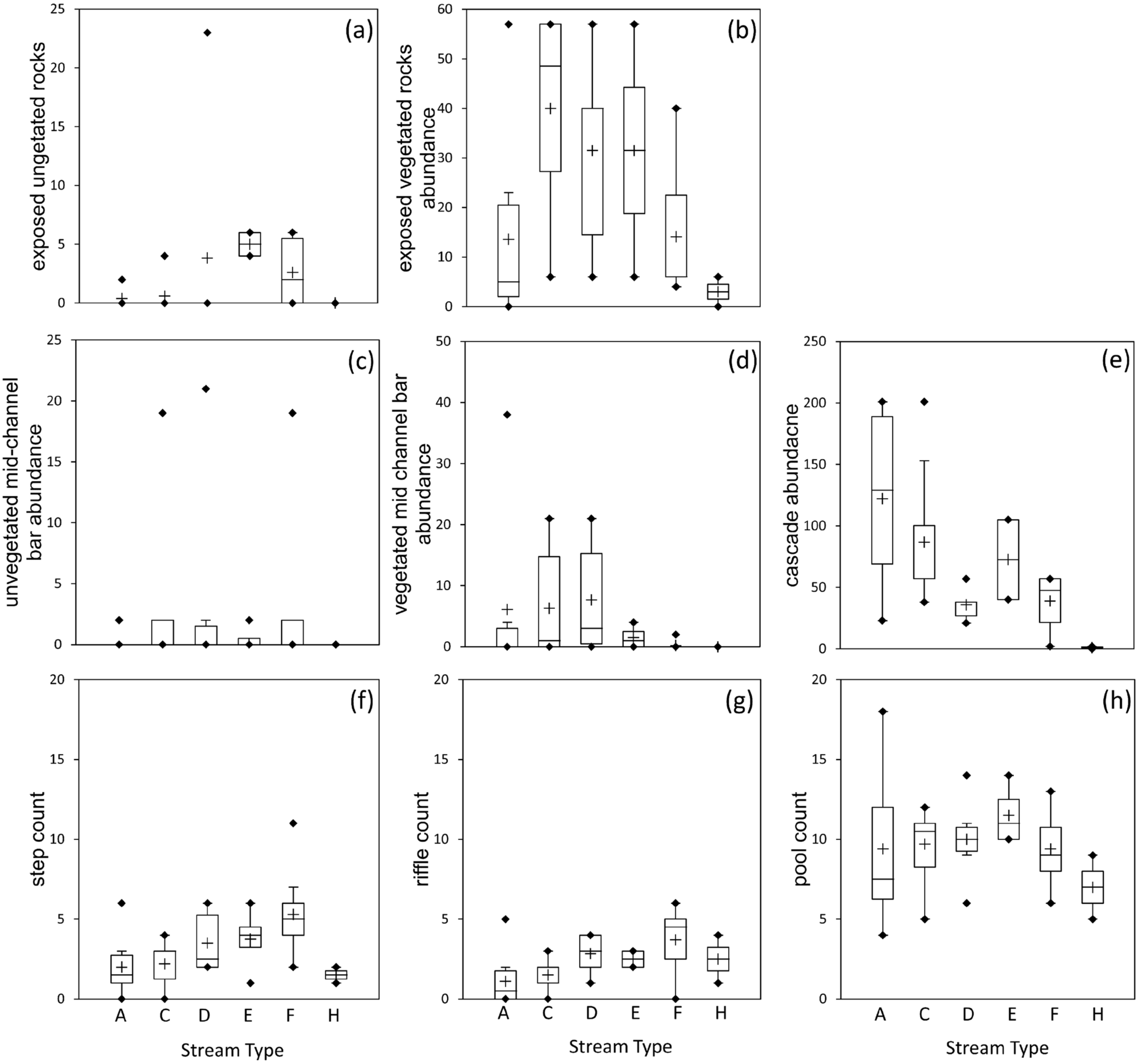


FIGURE 4 | Box and whisker plots of the abundances of different bed physical features according to the stream type of the 42 100 m reaches analysed. Note the different scales of the vertical axes and that the maximum achievable abundance in a–e is 201 and has no limit for the counts displayed in f–h. Outliers are shown as diamonds.

5.4 | Variability in Stream Types and Indicators

5.4.1 | Stream Long Profiles Computed From a DEM

Simple running mean analyses progressively smoothed the long profiles of the studied tributaries (Figure 6a,c,e—tributary Bal_t3; Figure 6b,d,f—tributary Dar_t3, Figures S3–S5—tributaries Bal_t1, Bal_t2, Dar_t1 and Dar_t2). There was a progressive reduction in the variance of the deviations of the smoothed profiles as the smoothing window increased from 5 to 300 m (Figure 6a,b), with intermediate scale spatial patterns revealed as the smoothing progressed (Figure 6c,d). The resulting smoothed long profiles (Figure 6e,f) illustrate clear local topographic variations associated with shorter smoothing windows that give way to clearer background trends in elevation extending over several 100 s of metres as the smoothing windows increase in length, which could be used as surrogates for indicator A5 when attempting to identify homogenous reaches.

5.4.2 | Homogenous Reaches

Approximately 60% and 40% of the 100 m reaches, respectively, were allocated to the same stream type as one or both adjacent reaches, effectively forming homogenous 200 and 300 m stream lengths (Figures 7 and 8) with the largest number of adjacent reaches of the same type being seven (Figure 8, Dar_t3). Reach lengths of a single stream type depend almost entirely on the continuity of the bed material indicators (A6, A7

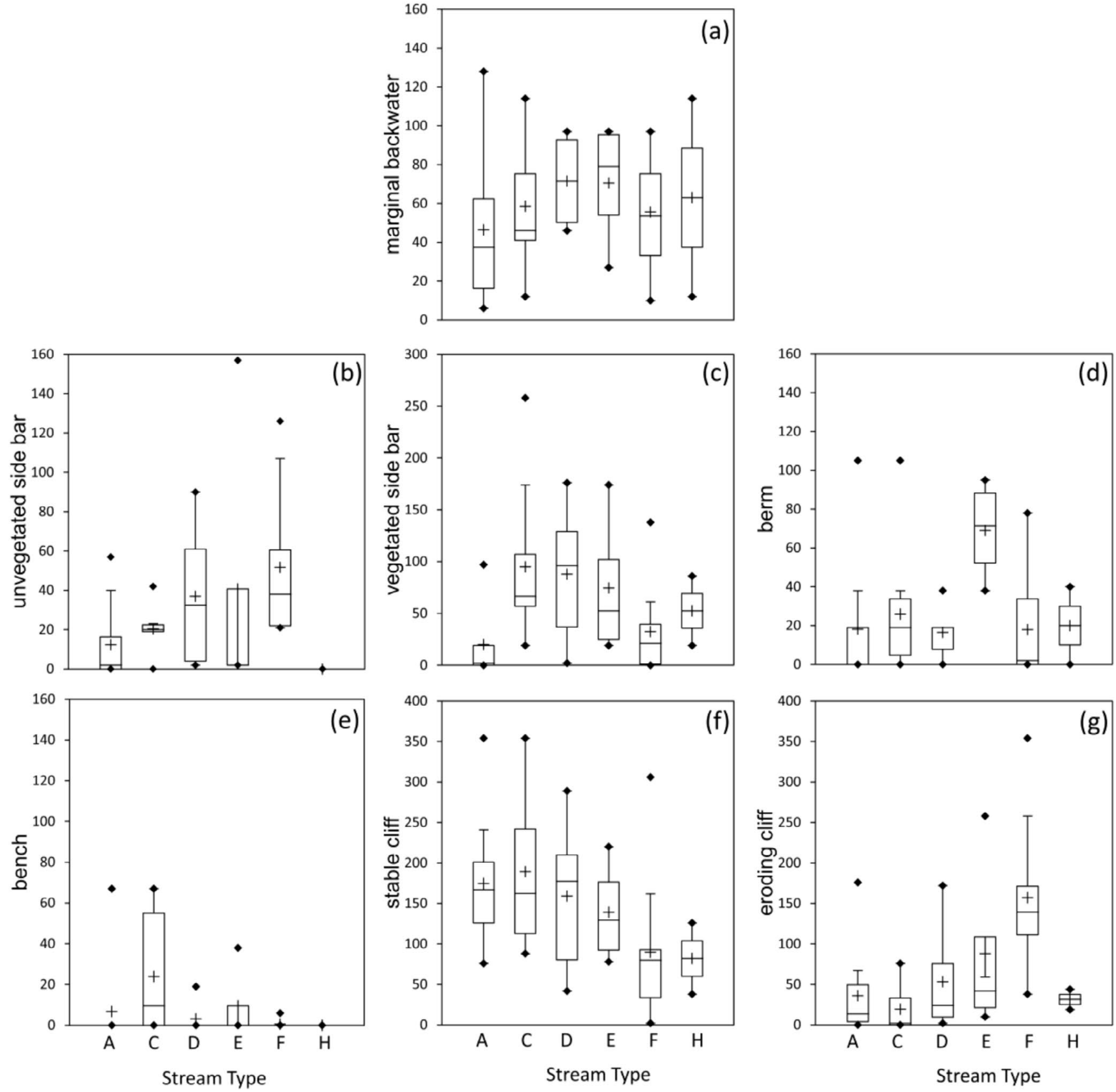


FIGURE 5 | Box and whisker plots of the abundances of different bank and water margin physical features according to the stream type of the 42 100 m reaches analysed. Note the different scales of the vertical axes and that the maximum achievable abundance is 402. Outliers are shown as diamonds.

and A8). Reaches where A6 indicates a bedrock reach (stream type A) were part of continuous bedrock reaches (bedrock extent in Figures 7 and 8) that were at least 200 or 300 m long in 94% and 73% of cases, respectively, with the longest bedrock reach being 900 m (Figure 8, Dar_t3). The equivalents for reaches with the same coarsest bed material (indicator A7) were 84%, 77% and 800 m, and for reaches with the same average bed material particle size class (indicator A8) were 83%, 70% and 1300 m.

The walkover survey and DEM information allowed homogenous reaches to be defined using the method adopted by Cox et al. (2023) but based on higher resolution data sets. The walkover surveys showed that all studied tributaries are single-thread (indicators A1 and A3 are invariant) with low sinuosity, although indicator A2 (sinuosity) appears to inversely co-vary with slope (Figure 3a,b), leaving slope and degree of confinement (indicators A4 and A5) as the main variables that can be used to identify the end points of homogenous reaches. Using the longitudinal profile and confinement observations (Figures 7 and 8), end points for homogenous reaches were visually interpreted and are represented by vertical lines in Figures 7 and 8. Although the lines are simply a visual interpretation, they identify reach lengths that also frequently correspond with bedrock extent, a component of the bed material identified during walkover surveys. The median reach length of these homogeneous reaches, estimated to the nearest 50 m, was similar for both the Dargle and Ballinagee catchments at 400 and 300 m respectively (Table S4). Across all tributaries, the median homogenous reach length was 400 m with an upper quartile length of 500 m (Table S4).

6 | Discussion

Although our analysis, based on observations from only two small headwater catchments and six mountain headwater streams, is exploratory rather than definitive, we have revealed a number of indicative patterns, associations, and scale-related issues that in many cases concur with other studies and that need to be considered when surveying such streams for ecogeo-hydrological purposes.

6.1 | Research Question 1: Do the Associations Among Mountain Headwater Stream Types, Physical Habitat Assemblages and Bed Material, Identified at a National Level by Cox et al. (2023), Persist Across Short Stream Reaches *Within* Small, Irish, Mountain Headwater Catchments?

The abundances of every investigated physical habitat in our study displayed some statistically significant differences across the stream types recognised (Table 2) and visual trends were

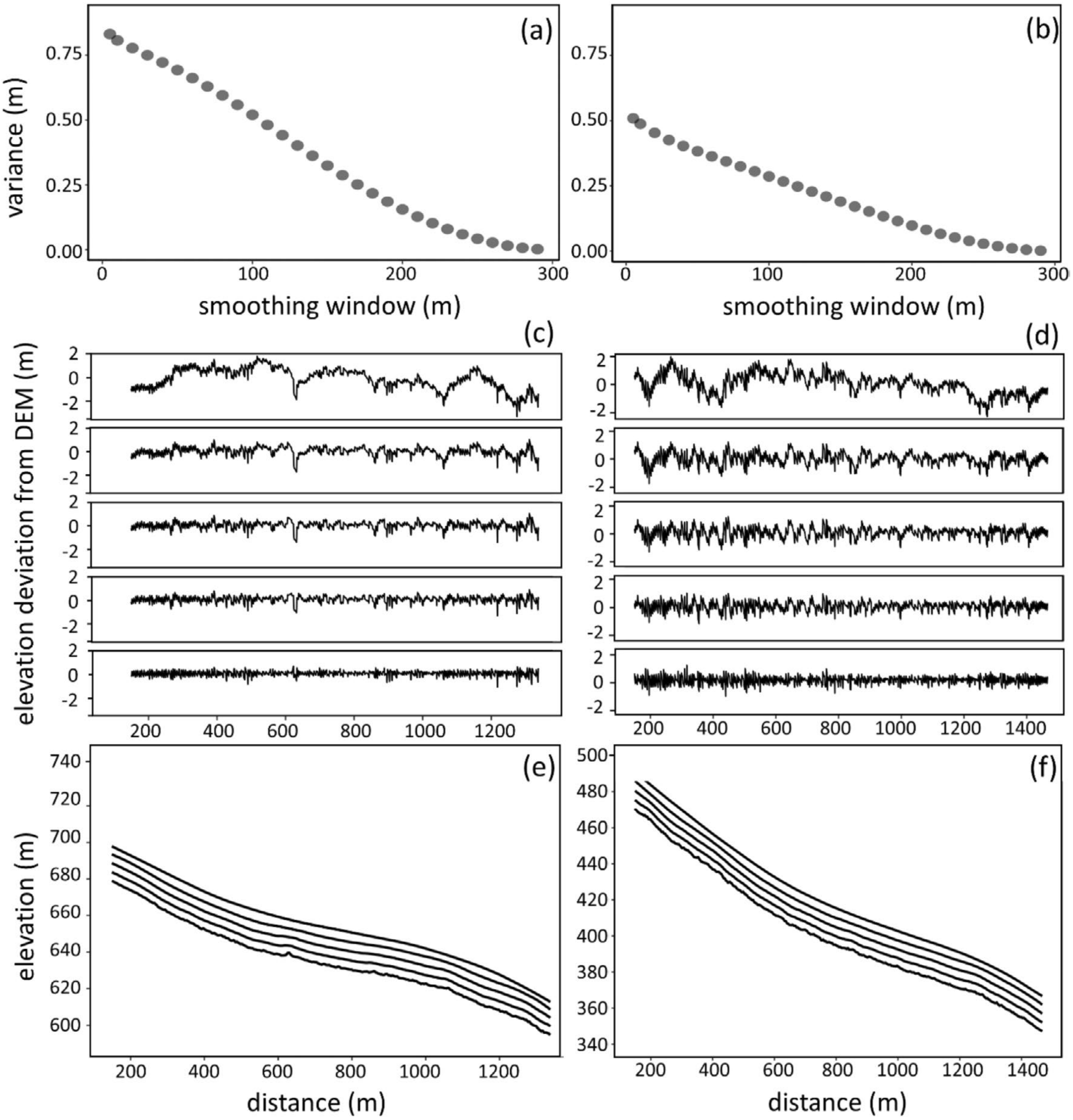


FIGURE 6 | Results of smoothing the long profile extracted from a DEM for Bal_t3 (a, c, e) and Dar_t3 (b, d, f). (a, b) The variance of the deviations in elevation of running means computed using a 5 m window and 10–300 m windows (in 10 m increments) from the 300 m window running mean values. (c, d) The difference in elevation between the long profile computed using a 5 m window running mean and (from bottom to top) long profiles computed using 10, 30, 50, 100 and 300 m window running means. (e, f) smoothed long profiles computed using 10, 30, 50, 100 and 300 m window running means (the profiles are offset by 4 m to allow visual comparison, and the upstream and downstream 150 m of each profile are removed so that smoothing windows are compared over the same channel length).

observable across the stream types in box and whisker plots (Figures 3–5, S1 and S2). These contrasts in physical habitat assemblages among stream types within two small catchments reproduced many of the contrasts recognised by Cox et al. (2023) at a national scale (summarised in Table 1).

Box and whisker plots (Figures 3–5, S1 and S2) confirm the criticism frequently levelled at attempts to split streams and rivers into homogenous lengths (see Kondolf et al. 2016, 137–138), that many features and properties gradually appear, disappear and change in abundance along stream systems with no distinct boundaries on such changes. However, in combination, Figures 3–5, Figures S1 and S2 suggest that a composite of feature abundances can usefully be related to specific stream types, justifying the time and cost-effectiveness of nesting detailed, time-consuming, field-based surveys within a hierarchy of spatial units identified from secondary sources.

There is a large body of literature on generally applicable hierarchical stream classification, stream-landform types and their associations (see reviews by Church 2006; Gurnell, Rinaldi,

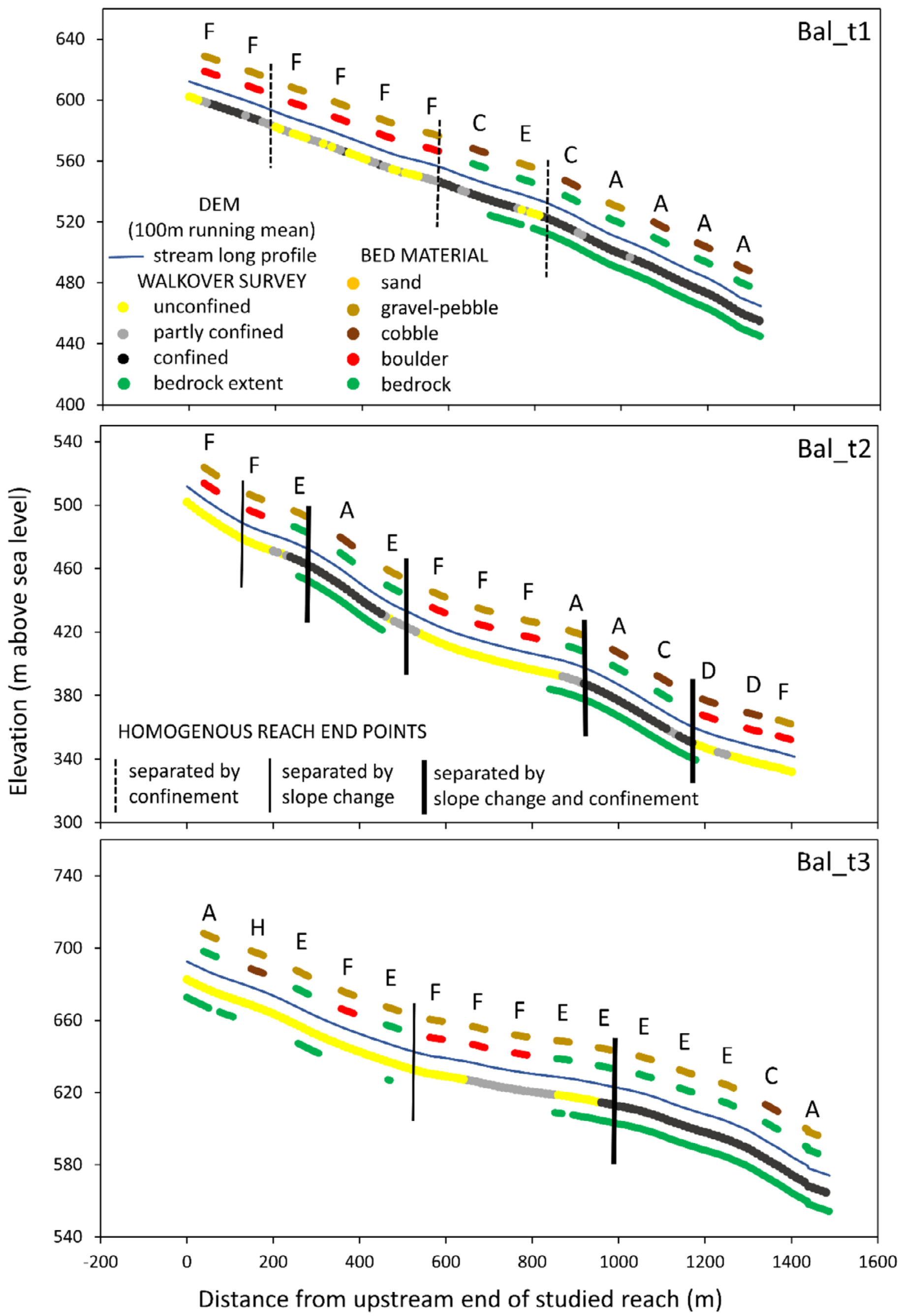


FIGURE 7 | For each of the tributaries Bal_t1 (top graph), Bal_t2 (middle graph), Bal_t3 (bottom graph), longitudinal variations in (from top to bottom in each graph) stream type, average bed material size (indicator A8), coarsest bed material (indicator A7), the stream profile (100 m smoothing window), confinement, bedrock extent. The vertical lines separate homogeneous reaches based on confinement alone (dashed line), change in slope alone (thin solid line) or both confinement and slope (thick solid line). [Color figure can be viewed at wileyonlinelibrary.com]

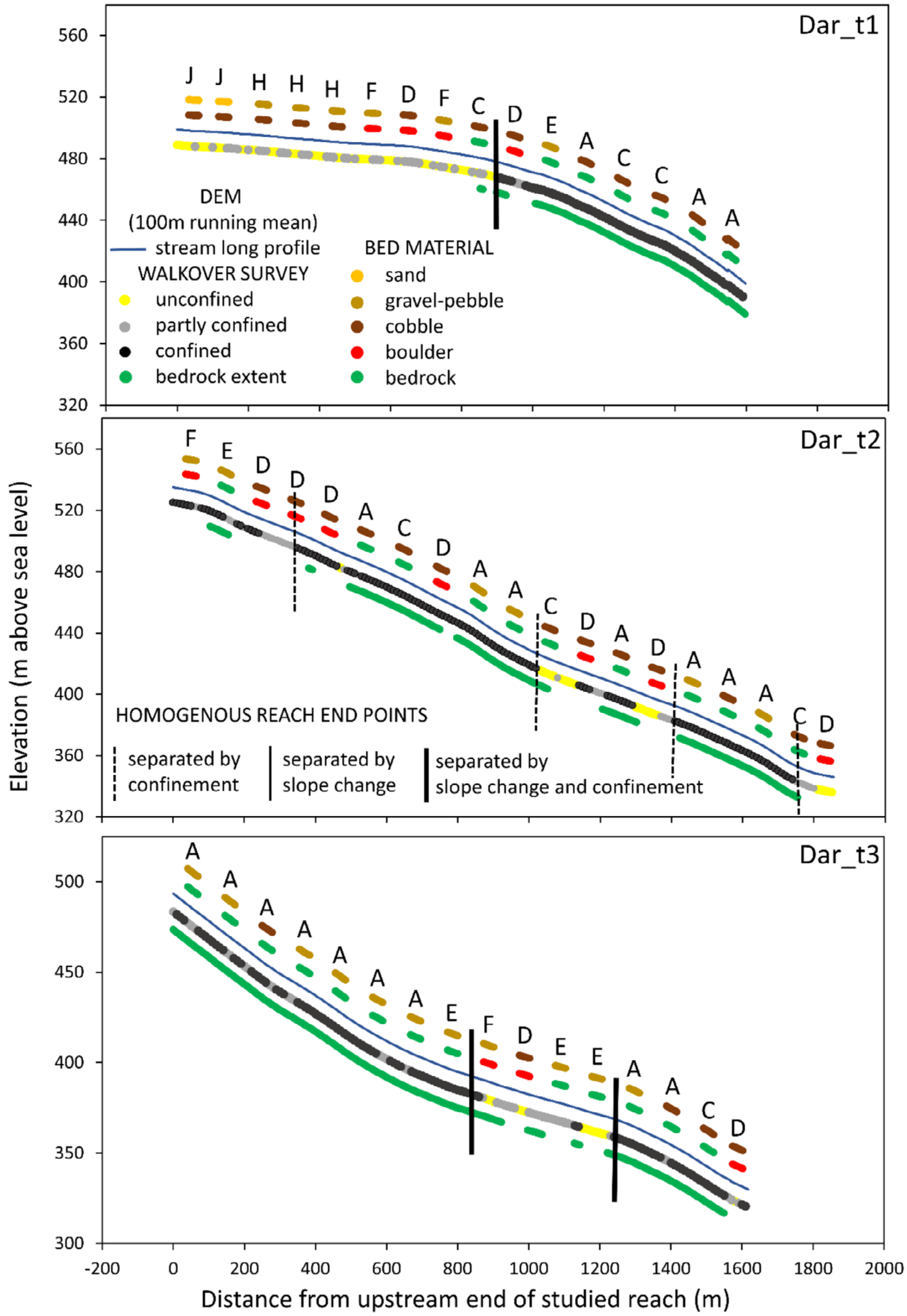


FIGURE 8 | For each of the tributaries Dar_t1 (top graph), Dar_t2 (middle graph), Dar_t3 (bottom graph), longitudinal variations in (from top to bottom in each graph) stream type, average bed material size (indicator A8), coarsest bed material (indicator A7), the stream profile (100 m smoothing window), confinement, bedrock extent. The vertical lines separate homogenous reaches based on confinement alone (dashed line), change in slope alone (thin solid line) or both confinement and slope (thick solid line). [Color figure can be viewed at wileyonlinelibrary.com]

et al. 2016; Buffington and Montgomery 2022) and also classifications relevant to specific environmental settings such as headwater, mountain, glacially modified, gravel-bed or bedrock dominated streams (e.g., Prestegaard 1983; Grant et al. 1990; Wohl and Merritt 2001; Halwas and Church 2002; Brardinoni and Hassan 2007; Church 2013; Addy et al. 2014; Livers and Wohl 2015). In the cases of steep, headwater streams, especially those affected by bedrock exposure, Church (2013) integrated the findings of previous researchers and referred to bedrock chaotic, cascade, step-pool, chute, rapid, riffle and pool types arranged along a gradient of decreasing bed slope. Our mountain streams appear to conform to the range of channel slopes and stream types indicated by Church's integrative analysis and to his bedrock chaotic, cascade, step-pool, rapid and riffle types. Furthermore, our mountain stream types also conform to Buffington and Montgomery's (2022) illustration of how their mountain channel types (Montgomery and Buffington 1997) follow gradients in slope, confinement, and bed material size from bedrock dominated through cascade, step-pool, plane-bed, pool-riffle types and on to other lower gradient, unconfined, finer bed types. In summary, our mountain stream types and characteristic physical habitats conform to these previously proposed hierarchical patterns, stream types and their key physical habitats.

6.2 | Research Question 2: To What Extent Do the Properties Used to Assign a Stream Type to a Reach Vary Spatially Along Small, Irish, Mountain Headwater Streams and What Are the Implications of These Variations for Identifying 'Homogenous' Reaches?

Gurnell et al. (2020) and Cox et al. (2023) visually identified homogenous reaches based on their planform, degree of confinement and slope, separating the reaches at major changes in slope and tributary confluences. In the present research, the close proximity of physical habitat survey sites led to 100 m reaches being defined systematically along the investigated tributary streams. At the site scale, our approach incorporated additional bed material observations, which were collected for reaches lacking physical habitat survey data, providing bed material information for 30% of the length of the investigated tributaries.

Based on these data, we illustrated how the properties used to define a stream type varied spatially and their implications for identifying homogenous reaches. Spatial sequences of stream types and supporting indicator variables revealed that many adjacent reaches showed similar properties over 300+ m (40% of cases) with individual bed material indicators also persisting over 300+ m (70% of cases). These estimates are at the lower end of the reach length range suggested by Grant et al. (1990), which was lengths of 10^2 to 10^3 stream widths (i.e., 260–2600 m for our typical median stream width of 2.6 m, Table S2). Reach end points were occasionally located in the middle of one of the 100 m reaches, showing that a systematic determination of reach end points may introduce within-reach heterogeneity even when the reaches are very short. The visually assessed median homogenous reach length (ca. 400 m) gives some confidence in the ca. 1 km homogenous reach lengths assessed from widely available secondary sources by Cox et al. (2023) and suggests that the latter approach to defining reaches is probably adequate for operational assessments, where time is limiting. However, if an application requires greater precision, our more detailed combined walkover survey—DEM approach shows considerable potential.

Deeper analysis of reach characteristics, lengths and associations with physical habitats and sediments was not possible based on our data set, mainly because of the 100 m spacing of bed material estimates and the fairly small number of fixed sites for which we had physical habitat data. However, it is important to recognise the potential for more detailed data gathering and analysis techniques that could allow a deeper analysis of our results and especially of those from a larger study.

New technologies are rapidly advancing data gathering in the field, the delivery of high-resolution DEMs and advanced methods of data processing. In relation to observations of physical features, remote sensing techniques are transforming data capture and processing to support environmental investigations (e.g., Reichstein et al. 2019; Tomsett and Leyland 2019; Piégay et al. 2020). In particular, the use of unmanned aerial vehicles (UAVs) (e.g., Woodget et al. 2017; Helm et al. 2020) is showing enormous potential for detailed assessment of physical features and is advancing rapidly. However, processing of these high-resolution data sets requires considerable computational expertise and so the operational use of data captured by UAVs is currently fairly limited.

In relation to the quantification of channel slope, the processing of DEMs is rapidly advancing to assess this critical variable in the multi-scale analysis of river characteristics. Both broad slope-area relationships (i.e., steady downstream changes in channel gradient) and local 'noise' or 'bumps' in river long profiles have been identified at near-continental (e.g., Roberts et al. 2019) and more local scales (e.g., Schwanghart and Scherler 2017) through DEM analysis. While such local slope irregularities frequently emerge as a product of the scale and processing of the DEM (Smith et al. 2022), the present and related research has shown that these can also be genuine and important local elements of the river long profile. This is especially the case in steep mountain environments and along river profiles affected by changes in underlying rock type and/or subject to modification by past glaciations (e.g., Grant et al. 1990; Brardinoni and Hassan 2007; Addy et al. 2014; Livers and Wohl 2015). However, these steep mountain environments are also where sizeable errors can emerge in DEM analysis as a result of factors such as the nature of the radar data on which the DEM is based, the resolution and discretization of the DEM, and the impacts of natural 'noise' imposed by hillslope and river bed features (Schwanghart and Scherler 2017; Smith et al. 2022). As the precision and resolution of DEMs advances and methods of extracting channel slope from DEMs become more sophisticated, the automatic extraction of homogenous reaches and their gradients will become fundamental elements in reach definition and description. In addition, there may be many other ways to construct and automatically process walkover survey information, which could all be explored in a larger and more exhaustive study.

In the meantime, our simple processing and visual assessment of combined DEM-walkover information shows considerable potential for identifying homogenous reaches, quantifying indicators A1–A5, and partly validating homogenous reach and bed material boundaries using near-continuous recording of bedrock exposure. Once again, a choice needs to be made among secondary sources and field survey types to match the application being considered, and a larger study would go further in supporting such decision-making.

6.3 | Relevance of the Methodology and Outcomes to Other Environments

Taking advantage of several data sets, we have been able to explore stream types and habitat assemblages in detail within two small mountain catchments in Ireland. In other environments, a similar approach could be used on a test data set, to define an appropriate balance between data sources and desk/field surveys for other stream types, particularly for lower gradient streams but also for larger rivers. It is likely that lower gradient streams and rivers will display longer 'homogenous' reaches and that switching between stream types may be more influenced by human actions than natural processes, particularly as anthropogenic land use is more common in lowland settings (Allan 2004; Pedersen 2009; Downs and Piégay 2019). Furthermore, while analysis of habitat assemblages at a central site could be used to explore reach length-habitat assemblage associations, it is likely that several physical habitat survey sites may be needed within a long 'homogenous' reach to capture the full range of habitats that are present. This is particularly likely where there are marked longitudinal changes in riparian and/or aquatic vegetation (e.g., Gurnell, Corenblit, et al. 2016) or where human interventions affect local process-form interactions within the stream/river channel (e.g., channelisation and resectioning, Hohensinner et al. 2018; large wood removal, Montgomery et al. 2003; Wohl and Scott 2017; construction of dams and weirs, Grabowski et al. 2022) and channel margins (e.g., tree removal, Gurnell and Grabowski 2016; spread of invasive species, Colleran et al. 2020; O'Briain et al. 2023). Furthermore, land-use change at the catchment scale can result in far-reaching changes to local controls on river character (Downs and Gregory 2014; Dufour et al. 2015; Downs and Piégay 2019).

7 | Conclusions

In this article we have analysed field survey and desk study data sets for six headwater streams within two small headwater catchments in Ireland. We have found associations between the stream geomorphic type of 100 m long reaches and the physical habitat assemblage recorded at a central site within the reach. These associations identified within two headwater catchments appear to correspond with associations previously identified in mountain headwater streams across the Republic of Ireland (Cox et al. 2023).

We have compared the outcomes of our analysis with similar research conducted elsewhere and have found that our research findings are coherent with previous attempts to classify mountain stream types and arrange them along environmental gradients such as bed slope, channel sinuosity, and bed material grain size.

However, we have gone beyond the key physical habitats recognised in previous research to identify a range of additional physical habitats and vegetation structural components that are associated with these mountain headwater stream types and contribute to their physical habitat mosaic, at least in the studied Irish mountain headwater streams.

We have also proposed a new approach to identifying the extent of homogeneous reaches that can be assigned to different stream types. This involves complementing secondary data sets with walkover survey information captured in the field.

Lastly, we have defined homogeneous reaches based on a variety of sources and indicators and suggest that those based largely on widely available secondary sources are adequate for operational applications, where time is strictly limited, but that more detailed sources and methods including field measurements are likely to deliver more precise and reliable results.

As our research was only conducted in two small mountain headwater catchments, we stress that our methods should be seen as exploratory and our results as provisional. However, we have explored a number of perspectives that could underpin the design of a larger investigation of similar stream types or be used to focus on other (e.g., lower gradient, finer bed) stream types. While our specific outputs may not be applicable to other stream types and geographical settings, the analytical approach that we have presented is applicable elsewhere. Adopting such an approach at an early stage should lead to a cost-effective, two-scale methodology for characterising spatial variations in physical habitat assemblages for both operational and research investigations.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Box and whisker plots of the abundances of water surface flow types according to the stream type of the 42 100 m reaches analysed. Note the different scales of the vertical axes and that the maximum achievable abundance is 201 in all cases. Outliers are shown as diamonds. **Figure S2:** Box and whisker plots of the abundances of selected structural vegetation types on the bed (a–c, maximum possible abundance 201) and along the water margins (d–f, maximum possible abundance 402) according to the stream type of the 42 100 m reaches analysed. Note the different scales of the vertical axes. Outliers are shown as diamonds. **Figure S3:** The variance of the deviations in elevation of running means computed using a 5 m window and 10–300 m (in 10 m increments) windows from the 300 m window running mean values for (a) Bal_t1, (b) Bal_t2, (c) Dar_t1 and (d) Dar_t2. Note the same variance scale is shown for all tributaries with the exception of Bal_t2. **Figure S4:** The difference in elevation between the long profile computed using a 5 m window running mean and (from bottom to top) long profiles computed using 10, 30, 50, 100 and 300 m window running means for (a) Bal_t1, (b) Bal_t2, (c) Dar_t1 and (d) Dar_t2. **Figure S5:** Smoothed long profiles computed using 10, 30, 50, 100 and 300 m window running means (the profiles are offset by 4 m to allow visual comparison) for (a) Bal_t1, (b) Bal_t2, (c) Dar_t1 and (d) Dar_t2. **Table S1:** Categories of materials, physical features and vegetation properties, including human pressures and direct modifications, whose presence and abundance are captured by a MoRPh survey. **Table S2:** Summary statistics for stream channel dimensions measured at the mid-point of the 126 MoRPh surveys distributed along the six studied tributaries. **Table S3:** The abundance (mean and standard deviation) of river bed, bank and margin features according to River Type across the 42 100 m reaches. Note cascades, steps, and pools were recorded as a count, the maximum possible abundance for all other channel habitat types is 201, and 402 for bank and marginal features. **Table S4:** Summary statistics for lengths (estimated to nearest 50 m) of homogenous reaches of the studied tributaries.