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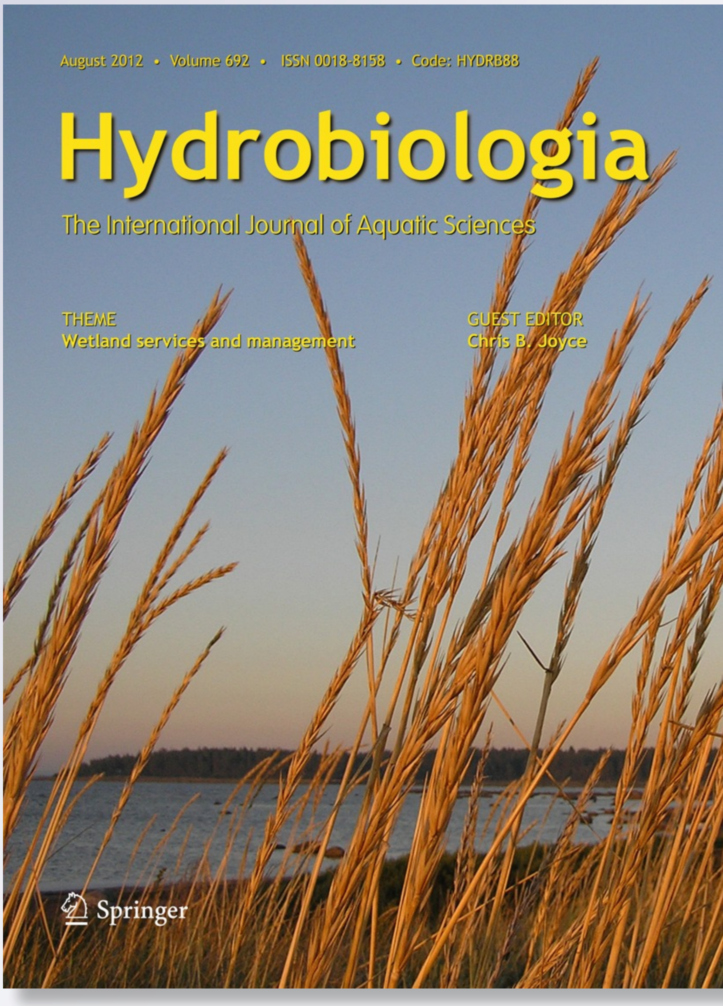

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PRIMARY RESEARCH PAPER

Characterization of hydraulic habitat and retention across different channel types; introducing a new field-based technique

V. S. Milner · D. J. Gilvear

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Abstract Understanding the interactions between physical habitat and aquatic biodiversity has become a key research objective in river management. River research and management practitioners are increasingly seeking new methodologies and techniques for characterizing physical habitat heterogeneity. The physical biotope has been widely employed as the standard mesoscale unit in river surveys. However, few surveys have quantified the combined physical heterogeneity at the meso- and microscale scale via a single technique. This paper describes a new field methodology for assessing variations in hydraulic habitat and retention across different channel types (e.g. step-pool, bedrock, plane-bed and pool-riffle). Hydraulic habitat and retention was measured by timing 100 flow tracers across a 100-m stream length, and recording the types of trapping structures. The pattern of flow tracers and retention varied significantly between channel types and structures. Rocks (boulders and cobbles) were more important retentive structures than eddies and snags (woody material and vegetation). The results indicate the importance of a diverse hydraulic environment, woody material and channel substrate character in increasing physical heterogeneity within a stream reach. The findings suggest that the field methodology may be an effective tool to assess differences in physical heterogeneity pre and post river restoration activities.

Keywords Hydraulic habitat · Retention · Channel type · Physical heterogeneity

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Introduction

Assessing the links between physical habitat and aquatic biodiversity has become an important research objective in river management (Vaughan et al., 2009) and is gaining increasing prominence in current legislation, such as the European Union Water Framework Directive (EU WFD; Council Directive 2000/60/EC, 2000). Physical habitat is created by the interactions between channel morphology and discharge, which form a diverse hydraulic environment that provides a range of in-stream habitats for aquatic biota (Maddock, 1999). In freshwater environments, the linkages between physical heterogeneity and biodiversity have been widely recognised (Harper et al., 1997; Rempel et al., 1999; Williams et al., 2005). Species diversity has been shown to increase with physical heterogeneity, particularly for benthic invertebrates and fish (e.g. Kaiser et al., 1999), provided other intra- and inter-specific interactions, such as food availability, regional species pool (McCabe & Gotelli, 2000; Ward & Tockner, 2001), colonization density, dispersal strategies and water quality are not limiting (Palmer et al., 2010). The rationale underpinning this theory is that physical heterogeneity provides more niches for species to occupy, a wider range of habitats for breeding and foraging and more refugia in highly variable flow environments (Townsend et al., 1997; Ward et al., 1999; Ward & Tockner, 2001). Many studies have noted this relationship at multiple hierarchical spatial scales (Garcia et al., 2012). At large scales, Brown (1997) reported the morphological diversity of wooded alluvial floodplains on the Lee River in south-west Ireland, increased benthic invertebrates within the river corridor. At the mesoscale, physical biotopes such as pools, riffles, runs and glides have been the basic unit to study physical heterogeneity and biodiversity interactions. These physical habitat features are formed from the combination of hydraulic and morphological processes that provide distinctive habitat for biota (Frissell et al., 1986; Maddock, 1999). At the microscale, the composition and characteristics of the channel substrate dictate habitat heterogeneity, which strongly influences the distribution and diversity of benthic invertebrates (Lamouroux et al., 2004; Merigoux & Doledec, 2004).

Traditionally, field-based mesoscale habitat surveys have been widely used within river and ecohydraulic science as a tool for assessing physical heterogeneity (Padmore, 1997; Harper et al., 1998). Physical biotopes (i.e. riffles, runs, pools and glides) are commonly employed as the standard mesoscale unit of physical habitat, particularly in the UK (Raven et al., 1997; Harvey & Clifford, 2009; Harvey & Clifford, 2010). Characteristic combinations of depth, mean velocity, bed shear stresses and substrate typify these features (Harrison et al., 2011). Riffles and runs for example, typically have high velocities, high bed shear stresses and coarse substrate, but vary in flow attributes as runs show three-dimensional flows (Garcia et al., 2012). Pools have lower velocities, finer sediments, deeper depths and often have recirculation zones (Brierley & Fryirs, 2005; Gordon et al., 2008). These hydraulic differences between physical biotopes can support relatively distinct biological communities, especially for benthic invertebrates (e.g. Brown & Brussock, 1991; Braaten & Berry, 1997; Thomson et al., 2004).

Whilst the majority of physical habitat assessments have focused on the reach scale, recent research is stressing the importance of including microscale habitats of approximately 1 m^2 within appraisals and protocols (Padmore, 1998). Small-scale bedforms described as pebble clusters (e.g. Brayshaw et al., 1983; Brayshaw, 1984; Billi, 1988) represent an important microhabitat and are the main type of microtopography in gravel-bed rivers (Brayshaw, 1985). These 'pebble clusters' represent a general term for bed obstacles (typically boulders and cobbles) that protrude above the water surface with a stoss-side accumulation of large pebbles and a wake deposit of finer particles (Robert, 2003). Pebble clusters can have multiple effects on flow intensities by creating transverse flow on the upstream side of the protrusion, and reducing lift and drag forces on the lee-side of the obstacle (Brayshaw et al., 1983; Best 1996). Eddy zones or pools may develop within the lee-side of obstacles and form shelters with low hydraulic stress (Crowder & Diplas, 2000). The hydraulic heterogeneity formed by such features is important through providing refugia from predation and cover for anadromous fish species at various life stages (Armstrong et al., 2003). The retention of leaf accumulations or woody material has also been shown to create microhabitats with distinctive macroinvertebrate fauna (Linklater, 1995; Sylvestre & Bailey, 1998). Undercut banks, tree roots, overhanging boughs and bankside vegetation can create unique microhabitats at stream margins. These marginal areas may be of ecological importance via the provision of refugia from flood events or predation (Harvey et al., 2008). Spatial heterogeneity and composition at this scale is considered to be directly related to ecosystem resilience and recovery response to disturbance resulting from high magnitude flood events (Lancaster & Hildrew, 1993; Townsend et al., 1997). Inclusion of this spatial scale should be incorporated into new field methodologies for river inventory, rehabilitation design and appraisal programmes (Harvey et al., 2008).

In this article, we discuss the findings of a novel field methodology and technique in assessing variations in hydraulic heterogeneity and retention in-stream reaches of different geomorphic type. The field methodology synthesises the effects of habitat heterogeneity at the meso- and microscale. In a wider context, the paper considers using the proposed approach as a rapid, low-cost field methodology for assessing river restoration schemes.

Materials and methods

Study area

The stream reaches were located in the upper River Dee (21) and adjacent Allt a'Ghlinne Bhig (3) catchments in the Cairngorm Mountains in north-east Scotland (Fig. 1). The River Dee and Allt a'Ghlinne Bhig catchments are located within the granite-dominated Cairngorm massifs. The geology of the catchment is mostly granite and quartzose-mica-schist with minor outcrops of limestone, graphitic schist and slate. The upper river drains a catchment area of approximately 289 km^2, but the adjacent Allt a'Ghlinne Bhig catchment possesses a smaller catchment area of 27.5 km^2. The catchments are principally upland in character with altitudes ranging from 274 to 615 m. Stream widths varied from 2.94 m (a step-pool channel) to 13 m (a plane-bed reach) with a mean stream width of 11.23 m. Fieldwork was conducted during May–August 2008. At Mar Lodge, situated in the centre of the study area, the Q95 was 2.182 m^3/s (Fig. 1), which was the discharge level when the fieldwork was conducted.

Geomorphic classification of stream reaches

Stream reaches were classified into step-pool (6), bedrock (5), plane-bed (6) and pool-riffle (7) channel types. Classification into channel type was based on the Montgomery & Buffington (1997, 1998) process-based typology developed for mountain streams in the northwest of North America. All stream reaches were in good condition (near to the inferred natural

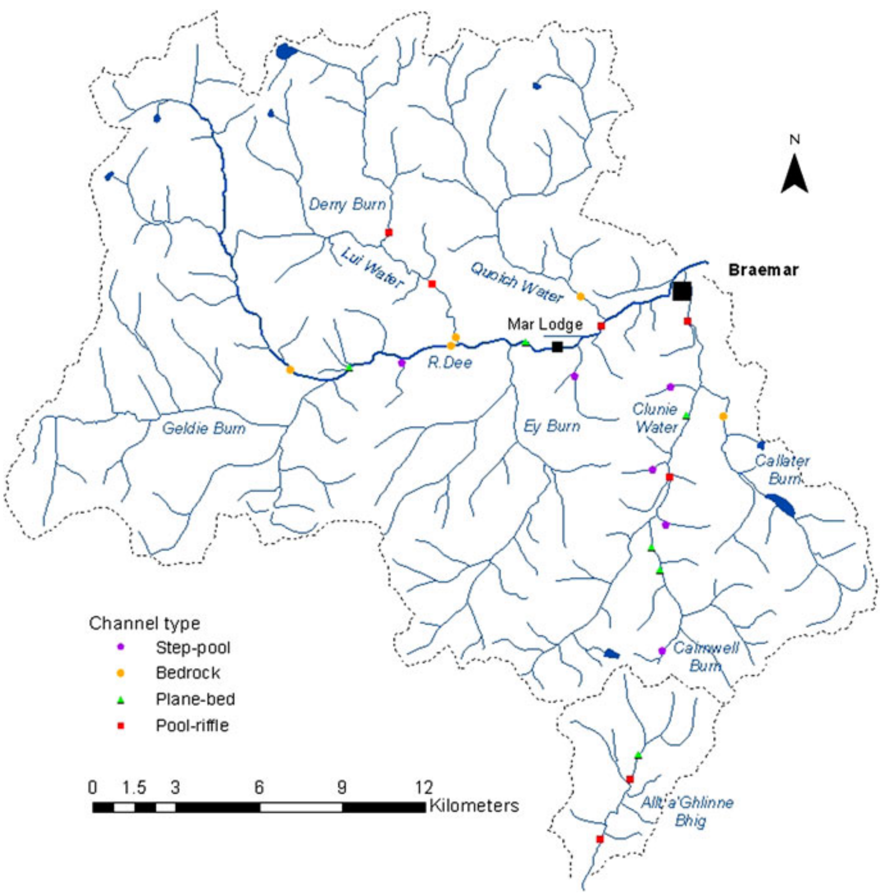

Fig. 1 Location of the study reaches in the River Dee and Allt a'Ghlinne Bhig catchments

reference condition). A reach was classified in good physical condition if the longitudinal and lateral connectivity was intact, a range of physical biotopes was present, and if the hydrological and sedimentological regime was unmodified. The study reaches were selected by a random stratified sampling procedure, whereby a 2 km × 2 km grid was imposed on the upper River Dee and Allt a'Ghlinne catchments, and random coordinates were plotted within the grid. Not all subcatchments with the upper River Dee could be sampled due to access issues relating to land ownership differences.

Physical habitat mapping of the study reaches comprised measurements of channel gradient, water depth, grain size and mean column velocity. Channel bed slope was measured using an Electronic Distance Meter (EDM). Water depth, grain size and mean column velocity (at 0.6 depth) were sampled at equidistant points along a reach in a zigzag fashion (as illustrated in Fig. 2). This sampling methodology provides a robust dataset suitable for quantitative analysis (Zavadil et al., 2012), and was first developed by Biggin & Stewardson (2004). Water depth and mean column velocity measurements were also conducted on four physical biotopes (i.e. a rapid, a riffle, a glide and a pool) at three sites on the Clunie Water (Fig. 1). At each cross section, point measurements of water depth and mean column velocity were collected at 0.5-m intervals across the channel. Velocity was measured with a propeller current meter (Flo-mate, model 2000) for 20 s.

Flow tracer type

Hydraulic habitat and retention was assessed through recording the time of travel of 100 artificial (i.e. polyethylene), near-neutral buoyancy, non-filled, perforated, spherical flow tracers (henceforth known as 'aqua-spheres'). The aqua-spheres were chosen because of their consistent size, shape, density (sphere

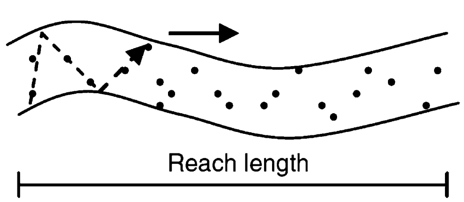

Fig. 2 Water depth, grain size and velocity sampling methodology across a reach (Zavadil et al., 2012)

surface area 78.5 cm^2, sphere volume 65.42 cm^3, sphere density 0.08 g/cm^3) and availability for commercial use (see Witzigs, 2012). The tracers were not intended to mimic the transport of leaves or wood, but to provide an inexpensive, semi-buoyant material that could be used globally to provide comparable and repeatable measures of reach-scale hydraulic habitat and hydraulic retention capacity.

Experimental procedure

The hydraulic habitat and retention field methodology was conducted across a 100-m stream length and on several physical biotopes. Field trialling on the Allan Water (catchment area of 210 km^2 and an average width of 10.5 m), a tributary of the River Forth in central Scotland suggested that a 100-m stream length was optimum for allowing sufficient time for tracer dispersal, but not too long for a length that traps structures retained too many tracers for recording the time of travel distribution. At each stream reach, a consistent release was located in a riffle and a stop net of 5 × 5 mm netting was installed downstream of the 100-m reach. A trial consisted of releasing 100 aqua-spheres uniformly across the width of the stream by hand. This technique aimed to ensure homogeneous distributions of aqua-spheres were released in marginal and central channel locations. A release in marginal, bankside areas would lead to high retention due to the trapping of aqua-spheres by bank irregularities, macrophyte patches and eddies. Additionally, the transfer time of aqua-spheres across the 100 m is likely to be of longer duration because of temporary retention in marginal habitats. In contrast, a release in the centre of the channel would result in the majority of aqua-spheres entering the thalweg, leading to shorter transfer times and less retention.

The field methodology was also conducted on individual physical biotopes: a rapid, a riffle, a glide and a pool on the Clunie Water (a tributary of the River Dee catchment; Fig. 1). Physical biotopes were identified visually based on descriptions in the Environment Agency's River Habitat Survey (RHS) methodology. The physical biotopes are assumed to be common to most channel types. Five releases were carried out over a 10-m length of each physical biotope (4 physical biotopes × 5 releases × 3 sites). The releases were undertaken to examine tracer response of individual physical biotopes to better interpret the pattern and retention of aqua-sphere response within the 100-m reach lengths. After all aqua-spheres ceased arriving at the net, a sweep up survey recorded any aqua-sphere trapped within the reach and the mechanism of retention. Trapping structures that physically retained aqua-spheres were classified into three categories: eddies, rocks and snags. Eddies were classified as areas where the water is deflected off an obstruction that causes upstream flow. They primarily occur at channel margins and from flow separation around bends (Brierley & Fryirs, 2005; James & Henderson, 2005). Embayments were also included in this category and comprised zones of deadwater located at channel margins, downstream of point bars and other obstructions. Rocks included boulders near or protruding from the water surface that trapped aqua-spheres. They are common in riffles where the water velocity tends to retain material firmly upstream or underneath boulders and cobbles (Environment Agency, 1997; James & Henderson, 2005). Snags comprised logs, woody material, bank and in-stream vegetation, including roots, overhanging branches and in-stream macrophytes (James & Henderson, 2005).

Data analysis

Hydraulic data for each stream reach (i.e. the transfer time across 100 m) was averaged according to channel type and plotted as a frequency distribution. A similar methodology was employed by Harvey & Clifford (2010) in assessing suspended sediment pathways for characterizing hydraulic habitat within physical biotopes on the River Tern, Shropshire, UK. Quantitative assessment of the hydraulic habitat involved derivation of a series of statistical summaries (Table 1 and Fig. 3a). The time of the first aqua-sphere to flow 100 m was assumed to indicate the minimum flow pathway/maximum reach-averaged velocity (akin to the thalweg). Time to rise denotes the dominant flow pathway with higher peaks representing conditions where one single flow pathway dominates the instream hydraulic habitat. The time to peak reveals whether aqua-spheres occupied a rapid or a moderately slow pathway through the reach. A long-time of travel may represent temporary retention, thus a diverse flow pathway. Subpeaks on the recessional limb represent a 'delayed' response due to slower flow/longer pathways or aqua-spheres temporarily retained in eddies or deadwater. Detailed interpretation of the frequency distributions in apportioning time of travel to flow rate, flow pathways and delays due to temporary storage is challenging. A frequency distribution is better visualised as a length averaged indicator incorporating the integrated effects of physical biotopes at the meso- and microscale. For example, a frequency distribution with a short time to rise, a singular high peak and a short recession limb would indicate a channel with hydraulic habitat comprising rapid flow rates, one dominant rapid flow pathway and a lack of slow flowing physical biotopes, large scale eddies and instream and marginal vegetation that can temporarily retain aqua-spheres and lengthen the time of travel (Fig. 3b). In contrast, a frequency distribution characterized by multiple, flatter peaks may denote a channel with pool-riffle morphology highlighting the effects of aqua-sphere transfer times through the slower and faster velocities of pools and riffles respectively (Fig. 3c).

Table 1 Variables derived from the aqua-sphere hydraulic releases and associated frequency distributions

Hydraulic indicator	Description
Time of first aqua-sphere	Time of the first aqua-sphere to flow 100 m
Time of last aqua-sphere	Time of the last aqua-sphere to flow 100 m
Time to rise	Time between the first aqua-sphere and the peak number of aqua-spheres
Time to recession	Time between the peak number of aqua-spheres and the last aqua-sphere
Time of peak	Time of the peak number of aqua-spheres
Peak magnitude	The number of aqua-spheres at the time of peak
Frequency distribution duration	The base width of the response curve
Flashiness	Ratio of peak to frequency distribution duration

A one-way Analysis of Similarity (ANOSIM) was used in PRIMER (Plymouth Routines in Multivariate Ecological Research, version 6.1.12; Clarke & Warwick, 1994) to examine the pattern of retention by different structures. ANOSIM is a non-parametric test for significant differences between two or more groups (or in this case channel types) based on any distance measure (Clarke, 1993). The test generates a

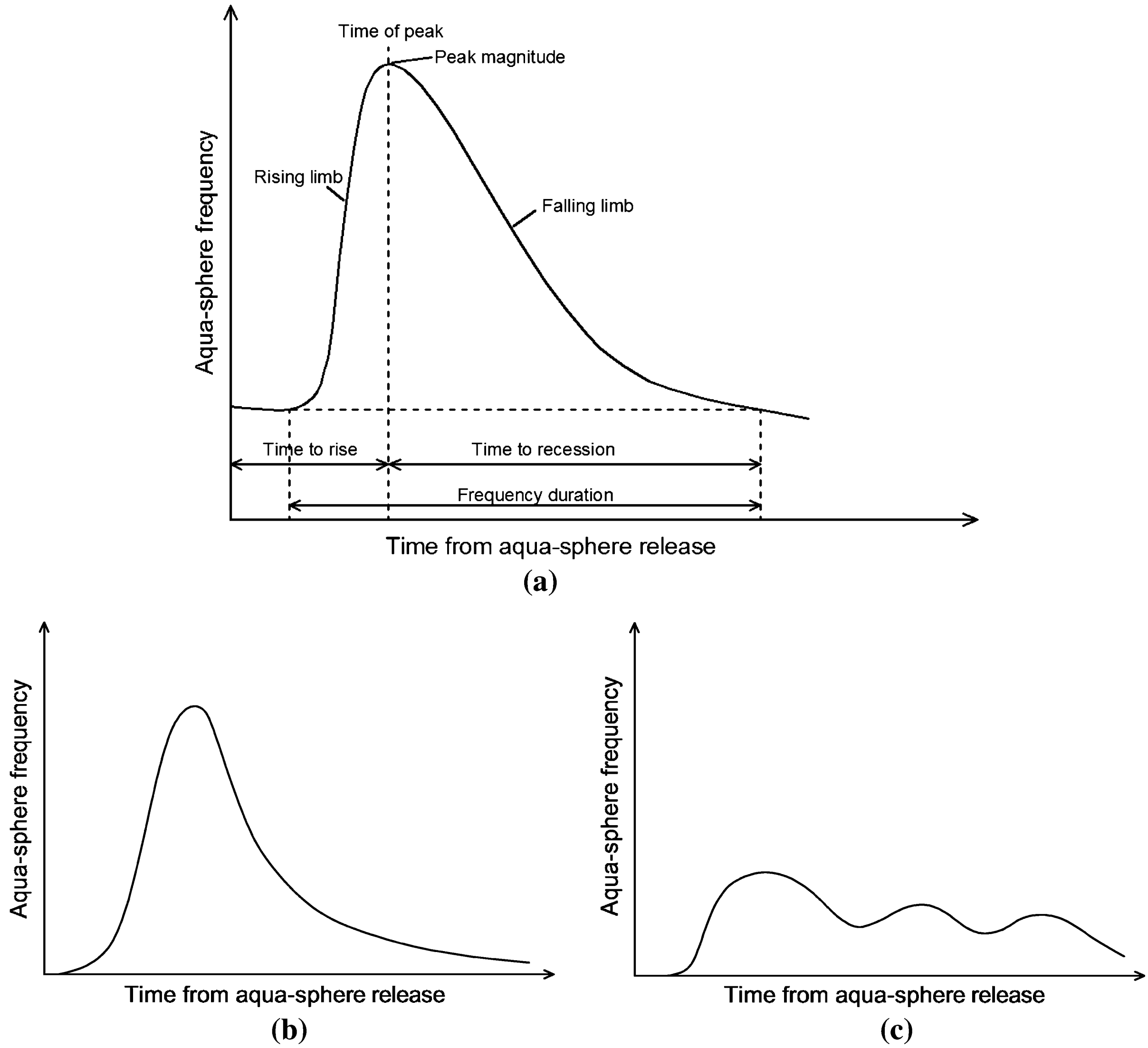

Fig. 3 **a** A hypothetical aqua-sphere frequency distribution to show the hydraulic statistics calculated for each aqua-sphere release (modified from Harvey & Clifford, 2010), and **b–c** hypothetical behaviour of aqua-spheres in-stream reaches with differing hydraulic and retention differences

Global-R value that ranges from 0 (no differences among groups) to 1 (dissimilarity between groups; Clarke & Warwick, 1994). Variables were log $(x + 1)$ transformed, normalised and a Euclidean distance measure was used. In one-way ANOSIM, reaches within a group (i.e. channel type) were classified as one sample and compared between different groups (i.e. between channel types; Clarke & Warwick, 1994). A total of 999 permutations were used in deriving the significance of tests ($P < 0.05$) for differences between channel types.

Results

Characterizing the hydraulic heterogeneity of channel types

The physical habitat characteristics of the physical biotopes and channel types were displayed by plotting the median and the range of values for velocity, depth, grain size and relative roughness (the ratio of the ninetieth percentile grain size to the bankfull flow depth [d_{90}/D]; Fig. 4). Comparisons can be derived

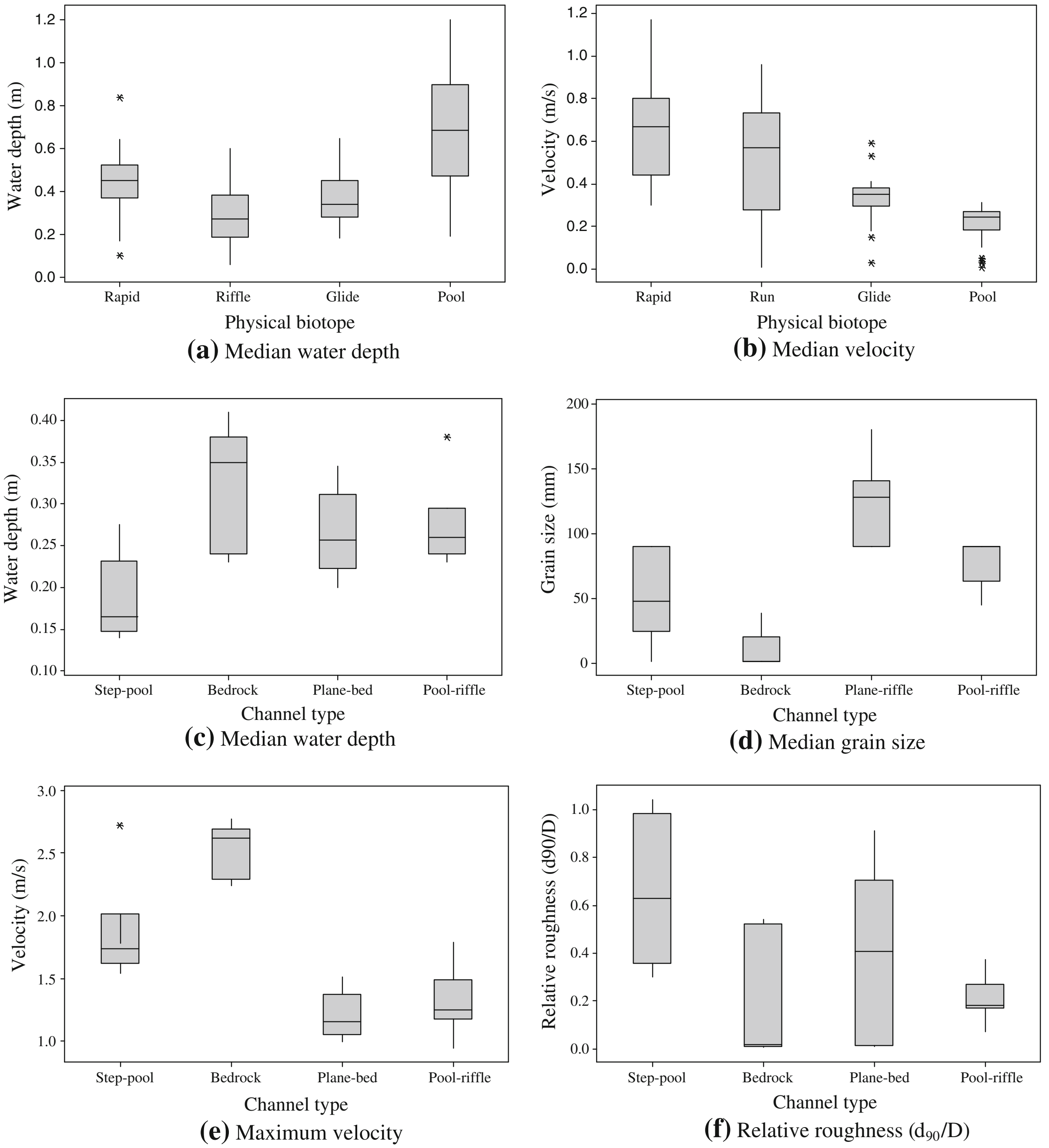

Fig. 4 Boxplots showing the median, range and interquartile range values for water depth, grain size, velocity and relative roughness according to physical biotope (**a** and **b**) and channel type (**c**–**f**). Data is derived from the physical habitat mapping of the study reaches

within and between physical biotopes, channel types and across physical habitat variables. Water depth and velocity show observable differences between physical biotopes. Pools have deeper depths and a distinct interquartile velocity with a large range of depths implying a heterogeneous environment. Glides tend to be more homogenous habitats, typified by a smaller range in depth and velocity values. The distribution of physical habitat values for the channel types clearly overlap with few geomorphic types possessing a discrete distribution based on any hydraulic variable. A notable exception are bedrock reaches, which are characterized by a unique inter-quartile velocity and grain size distribution, indicative of high velocities and small grain sizes. Step-pool reaches also have a distinct velocity profile and possess lower water depths. Much spatial hydraulic variability exists within as well as between types. Step-pool, bedrock and plane-riffle reaches, for instance, have a large range of relative roughness values, implying large spatial variability in roughness characteristics within these reaches. In contrast, the spatial variability in relative roughness within in pool-riffle reaches is less pronounced reflected by the smaller inter-quartile range.

Figure 5 and Table 2 reveal further detail in the hydraulic character within and between channel types. The mean frequency distribution for bedrock reaches (denoted by a solid line in Fig. 5b) was characterized by a tall peak, and a steep rising and recessional limb, which indicates the majority of aqua-spheres occupied a dominant flow pathway (i.e. the thalweg) through the stream reaches. However, both the frequency distribution with the maximum, mean and minimum peak for bedrock channels was characterized by subpeaks in the recession limb. This response implies that groups of aqua-spheres were temporarily retained in slower flows within bedrock reaches, such as in embayments or in re-circulatory flow characteristic of eddies. These fluvial features may only occupy microscale habitats at a scale of approximately 1 m^2, but increase hydraulically heterogeneity within a reach, and may also be ecologically important through providing refugia for aquatic biodiversity, particularly benthic invertebrates in a high energy environment.

The mean frequency distribution of plane-bed and pool-riffle reaches (in contrast to bedrock reaches) possessed a lower peak and several subpeaks in the recessional limb (Fig. 5c, d). A lower peak in these reaches signifies less aqua-spheres occupied the dominant flow pathway, and implies slower flows

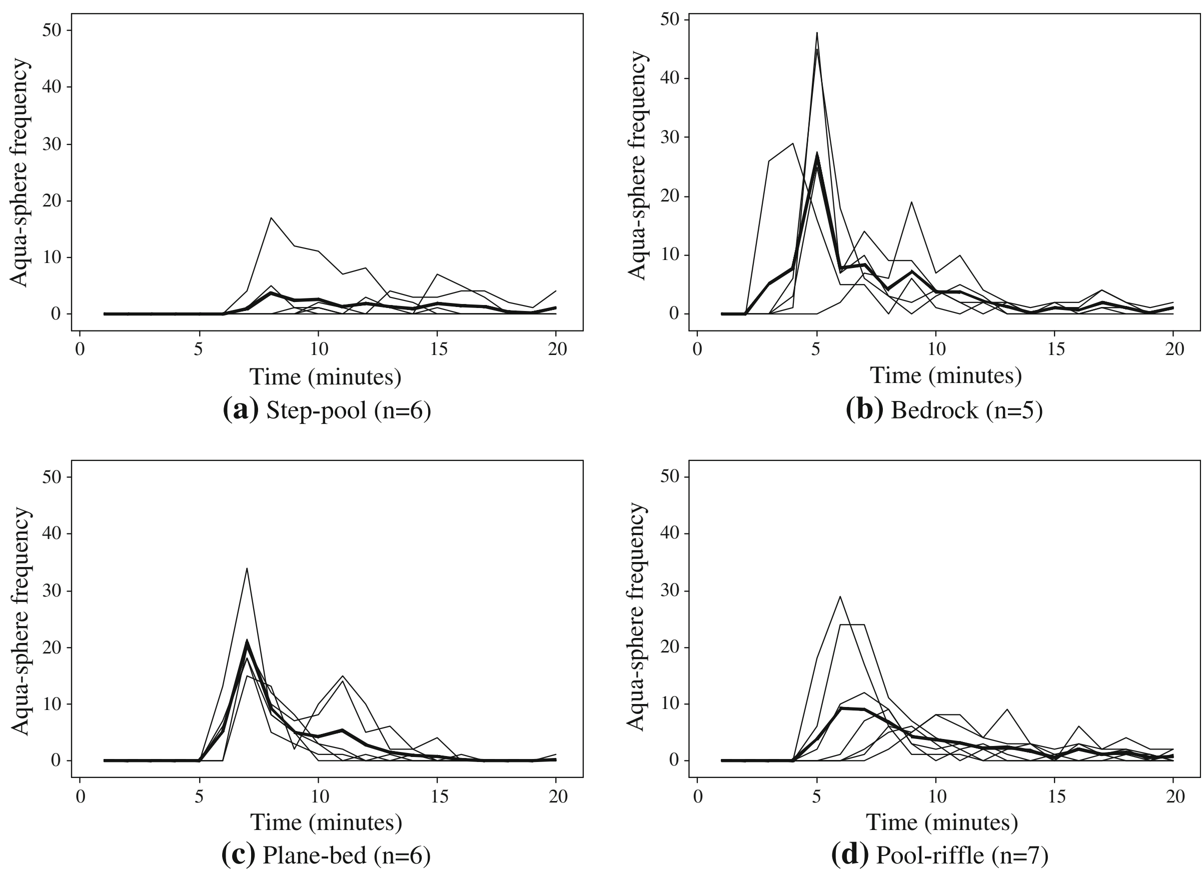

Fig. 5 Variability in aqua-sphere frequency distributions for stream reaches within each channel type. A *solid line* denotes the mean frequency distribution for reaches within a channel type

Table 2 Summary of hydraulic variables for the mean aqua-sphere frequency distribution within each channel type

Hydraulic variable	Channel type			
	Step-pool	Bedrock	Plane-bed	Pool-riffle
Time of first aqua-sphere (s)	105	75	105	135
Time of last aqua-sphere (s)	1635	1575	825	1635
Time to rise (s)	120	60	90	30
Time to recession (s)	180	270	210	270
Time of peak (s)	225	135	195	165
Peak magnitude	3.67	26.8	20.83	9.14
Frequency distribution duration (s)	210	330	240	300
Flashiness	0.01	0.08	0.07	0.03

and a diversity of flow pathways are present within the reaches. The mean frequency distribution of pool-riffle reaches possessed a relatively flat peak, which may indicate individual reaches peaked at similar times. A platykurtic distribution with no distinct peak characterized the mean frequency distribution of step-pool reaches (Fig. 5a), which denotes very high retention of aqua-spheres by trapping structures and no main flow pathway. Furthermore, a step-pool reach possessing a flat frequency distribution illustrates 100% retention of aqua-spheres. Both the mean and a flat frequency distribution reveal no dominant thalweg present in step-pool reaches, suggesting a large spatial coverage of retention-trapping structures and fluvial features such as embayments, eddies or marginal deadwater. These inferences imply that step-pool reaches possessed a different hydraulic environment compared to the other channel types.

The application of the field methodology on individual physical biotopes revealed that rapids possessed the fastest average time for an aqua-sphere to flow 10 m, followed by riffles, glides and pools (Table 3). The small range in the time of the first and last aqua-sphere to flow through a rapid, a riffle and a glide indicates low hydraulic variability within the physical biotopes at the Q95. In contrast, there is a large range in the time of the first and last aqua-sphere to flow through pools (range of 202 and 298 s respectively; Table 3), which reveals the effects of upstream and re-circulatory flow characteristic of eddies.

Retention structures

The pattern of retention varied significantly between channel types and structures (Fig. 6 and Table 4). ANOSIM showed that a significant channel type effect was present (Global $R = 0.415$, $P = 0.001$) with the greatest difference in retention being between step-pool and bedrock reaches ($R = 1$, $P = 0.001$; Table 4). The observed R statistic is the largest possible value, indicating completely different retention traits between the two channel types. Overall, 72% of aqua-spheres were retained in step-pool reaches with only 3.6% retained in bedrock reaches (Fig. 6). Step-pool reaches also retained a significantly higher proportion of aqua-spheres compared to plane-bed reaches (Table 4). In contrast, aqua-sphere retention was significantly lower in bedrock reaches compared to plane-bed and pool-riffle reaches (Table 4). Retention differences between the other channel types were not significant.

Table 3 Summary of hydraulic variables per physical biotope

Hydraulic variable	Physical biotope			
	Rapid	Riffle	Glide	Pool
Time of first aqua-sphere (s)	8 (5, 11)	11.7 (10, 13)	23 (18, 29)	90.7 (22, 224)
Time of last aqua-sphere (s)	15.3 (14, 17)	20 (19, 20)	35 (26, 49)	103.3 (37, 335)
Time of average aqua-sphere to Flow 10 m (s)	12	14.6	27.8	96.7

Data in brackets show the fastest and slowest aqua-sphere times per physical biotope

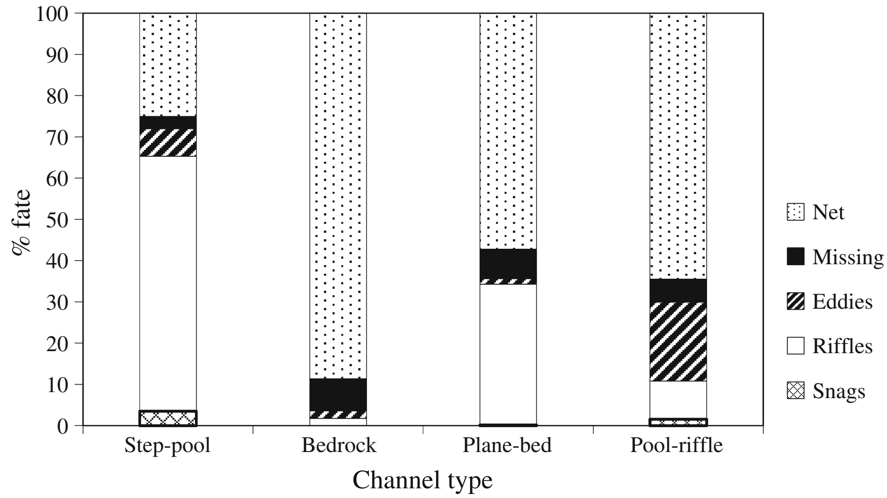

Fig. 6 Comparison of fates of aqua-spheres in each channel type

Table 4 ANOSIM results for the comparison of retention type (eddy, rocks and snags) among channel types

Fate	*R*	*P*	Channel type	Post hoc test group
Retention	0.415*	0.001		
	1	0.001	Step-pool	Bedrock
	0.25	0.05		Plane-bed
	0.936	0.001	Bedrock	Plane-bed
	0.572	0.001		Pool-riffle
Eddies	0.193*	0.05		
	0.387	0.05	Pool-riffle	Bedrock
	0.476	0.001		Plane-bed
Rocks	0.478*	0.001		
	0.824	0.001	Step-pool	Bedrock
	0.784	0.001		Pool-riffle
	0.669	0.001	Plane-bed	Bedrock
	0.439	0.001		Pool-riffle
Snags	0.145	NS		

NS not significant

* Indicates Global *R* statistic for all channel types

When eddies, rocks and snags were analysed separately, ANOSIM demonstrated the physical retention of aqua-spheres by trapping structures was not consistent among channel types. The Global *R* value revealed that eddies significantly retained aqua-spheres among geomorphic types (Global $R = 0.193$, $P = 0.05$) with the greatest differences been between pool-riffle and plane-bed reaches, and pool-riffle and bedrock reaches (Table 4). ANOSIM also tested the retention of aqua-spheres trapped in rocks between channel types and a significant effect was obtained (Global $R = 0.478$, $P = 0.001$). Step-pool reaches retained 61.83% of aqua-spheres within rocks compared to only 1.8% retained in bedrock sections (Fig. 6). Additionally, aqua-spheres retained by rocks between step-pool and pool-riffle reaches, plane-bed and bedrock reaches and plane-bed and pool-riffle reaches were also different (Table 4). Overall differences in the retention of aqua-spheres by snags among channel types was not significant (Global $R = 0.145$, NS).

Discussion

Hydraulic and retention differences between channel types

This paper summarises the findings from an experimental field methodology and technique aimed at characterizing hydraulic habitat and retention across a range of channel types. The approach has produced a complex dataset of hydraulic responses although some broad trends are evident. Three broad groups in hydraulic response have emerged from the field datasets, which may be viewed in terms of peak magnitude and time to rise (in Fig. 5). Firstly, step-pool reaches possess a distinctive frequency distribution in comparison to the other channel types, marked by a very low peak and high retention. These inferences imply that no single flow pathway dominates the instream hydraulic habitat in this stream environment at the Q95. A second key finding is that bedrock reaches are characterised by a steep rising limb and a high peak, implying that the dominance of one main flow pathway. Bedrock reaches are characterised by fully turbulent flow zones, which is important in determining food availability and oxygen concentrations for benthic organisms (McNair et al., 1997), filter feeding invertebrates and fish (Enders et al., 2003; Enders et al., 2005). The hydraulic character of bedrock reaches are markedly different compared to step-pool reaches. The third major finding is that plane-bed and pool-riffle reaches have similar response curves in terms of comparable peak magnitudes, time to rise, time to peak and time to recession. Plane-bed and pool-riffle reaches have differing morphological attributes; the former typically possesses a uniform structure with no distinct differences in depth and velocity and lacking rhythmical bedforms, whereas the latter is typified by topographic highs and lows representing pools and riffles (Richards, 1976; Keller & Melhorn, 1978). Data from the physical biotope releases show faster transfer times for riffles and slower transfer times for pools with glides having intermediate values (Table 3). The cumulative effects of high and slow velocities (characteristic of riffles and pools) may be minimised across a 100-m reach. For instance, the transfer time of aqua-spheres across pool-riffle morphology may be comparable to a plane-bed reach dominated by a glide habitat. This rationale may partly explain the similar response curves of plane-bed and pool-riffle reaches.

The presence and spatial distribution of physical biotopes within a stream reach is a key variable-controlling aqua-sphere response. Most reaches comprised a mixture of physical biotopes at the meso- and microscale. The type and spatial coverage of physical biotopes within a stream strongly influences time to rise, peak magnitude and time to recession. For instance, dominant physical biotopes within bedrock reaches are rapids, cascades and riffles (Newson et al., 1998; Kemp et al., 1999), which tend to be associated with fast velocities. Aqua-spheres flow quickly through these physical biotopes (Table 4). This combination of physical biotopes tends to produce frequency distributions with a steep rising limb, a high peak and a steep recession limb. Furthermore, the dominance of one habitat type within a reach, such as a rapid of cascade will generate a very peaked frequency distribution. Pool-riffle reaches in comparison are characterized by riffles, pools and glide morphologies with the latter two physical biotopes being associated with slower velocities (Gordon et al., 2008). Consequently, a stream reach dominated by pools and glides will generate a gentle rising and recession limb as material flows more slowly through the reach.

Significant retention differences were present between channel types and structures. High retention of aqua-spheres occurred in step-pool reaches, partly due to high relative roughness, low water velocities and shallow depths, particularly at stream margins. Bedrock reaches were relatively unretentive due to high velocities, lower relative roughness and less retention structures. Differences in the dominance of retention structures were also found. Rocks (i.e. boulders and cobbles) were the most common retentive structure, supporting the findings of Snaddon et al. (1992) who identified coarse substrate as the most effective retention structure for trapping leaves in two headwater streams. Eddies (pools, embayments and marginal deadwater) were the main retention structure in pool-riffle reaches. Some aqua-spheres rotated around an eddy for the duration of the experiment, whereas other aqua-spheres exited the eddy. However, we believe eddies are temporary forms of retention and will exhibit varying characteristics with changes in discharge. Snags trapped a low proportion of aqua-spheres within the stream reaches, which contrasts to the results of Speaker et al. (1984) who discovered sticks, roots and stems (i.e. snags) were the key physical mechanism of trapping plastic strips in several coastal Oregon streams. Similarly, Webster et al. (1994) concluded high retention of CPOM (Coarse Particulate Organic Matter) in streams in the southern Appalachian Mountains was due to high quantities of woody material (i.e. snags) trapping organic matter. In this study, logs and woody material were extremely localised, but their occurrence did increase the physical heterogeneity of a stream reach through increasing stream roughness, creating a forced pool via scouring processes, forming secondary currents and eddies near the structure. This study was conducted at low flows (i.e. the Q95); however, increases with discharge will alter dominant flow pathways within a reach, and the spatial and temporal pattern of retention structures (Wallace et al., 1982; Minshall et al., 1983; Snaddon et al., 1992; Webster et al., 1994). Work is underway to investigate patterns of hydraulic habitat and retention with higher discharges.

Flow refugia and invertebrate diversity

The findings from the field methodology indicate differences in hydraulic retention between channel types, which have implications for the availability of flow refugia and invertebrate drift. Flow refugia are habitats characterised by a stable substrate and low hydraulic stress during periods of increased discharge (Lancaster & Hildrew, 1993); and are important in providing organisms a refuge against harsh hydraulic environments (Winterbottom et al., 1997; Rempel et al., 1999). In this study, step-pool reaches are highly retentive of aqua-spheres (72%), particularly in rock microhabitats (i.e. boulders and cobbles). Pebbles clusters and individual substrate particles form an important microtopography in gravel-bed rivers (Brayshaw, 1985) and create substrate heterogeneity. The dominance of trapping structures in step-pool reaches suggests an abundance of available flow refugia for organisms during high flow events. Bedrock reaches in comparison, retained a lower proportion of aqua-spheres (3.65%), indicating a lower availability of flow refugia. Plane-bed and pool-riffle reaches retained comparable numbers of aqua-spheres (35.7 and 30%, respectively). In pool-riffle reaches, most hydraulic retention occurred in eddies (pools, embayments and marginal deadwater; Fig. 6). These hydraulic deadzones are important mesoscale flow refugia features, and can be reached by organisms by active or passive drift, subject to flow pathways and sedimentation (Garcia et al., 2012). These flow refugia features create a mosaic of habitat conditions and can possess high abundances of invertebrates with varying flow preferences (Growns & Davis, 1994). The findings have illustrated the range of available flow refugia present at the meso- and microscale between different channel types.

Perspectives

The use of the field methodology and technique is proposed here for application to river restoration. Natural channels are dynamic, energetically open and have a typical high degree of spatio-temporal variability (Ward, 1989; Thorp, 2009) in contrast to managed channels. Modified channels tend to be straightened, narrowed with a more uniform structure and often a trapezoidal cross section (Gregory et al., 1992). Banks are often stabilised through resectioning or reinforcements and channels are typically deepened through activities such as dredging (Wyrick & Klingeman, 2011). A range of restoration techniques are applied to channels aimed at restoring physical conditions that ‘mimic’ natural systems based on ‘reference’ conditions (Boon, 2004). Techniques include the reintroduction of meanders, removing obstacles to fish migration (Boon, 1998), the re-establishment of a natural flow regime (Puckeridge et al., 1998), the re-development of habitat complexity (i.e. introducing woody material, adding boulders to generate substrate heterogeneity and creating backwaters and secondary channels) (Ward & Tockner, 2001). Increasing habitat complexity is a common goal in river restoration efforts to improve aquatic biota within a stream reach (Garcia et al., 2012), but rarely quantified post-project. Indeed, high habitat complexity is associated with differences in hydraulic character, which strongly influences biotic communities (Stazner & Higler, 1986; Jowett, 1993). Benthic invertebrates are frequently defined by patches of differing habitat (Lancaster & Hildrew, 1993). So, stream reaches that are highly retentive and containing a mosaic of hydraulic habitats should be promoted within conservation strategies aimed at improving in-stream biodiversity. This rationale is proposed for use of the field methodology and technique for river restoration applications.

Aqua-spheres and other material (i.e. CPOM) should flow quickly through a uniform reach of low habitat heterogeneity and not be retained. Re-instatement of habitat complexity, such as the introduction of woody material and a diverse substrate aim to increase physical heterogeneity within a stream reach. Increases in habitat heterogeneity and retention structures would create a diversity of flow pathways and retain aqua-spheres. Differences in habitat heterogeneity pre- and post river restoration could be identified through by the field methodology and subsequently plotting and interpreting a frequency distribution. For example, pre-restoration a frequency distribution may have a steep rising and recessional limb. Post restoration, a frequency distribution may be characterized by a lower peak and subpeaks in the recessional limb indicating temporary retention of aqua-spheres. Differences in habitat heterogeneity could also be identified through identifying retention patterns by structures (i.e. eddies, rocks and snags) pre- and post-restoration.

In conclusion, this paper has presented a rapid, low-cost field methodology and technique to assess differences in meso- and microscale hydraulic habitat and retention across stream reaches of different morphologies. The findings of the study reveal that step-pool and bedrock reaches are characterized by a distinct hydraulic habitat. Step-pools have characteristically shallow depths and coarse substrate, whereas bedrock reaches are distinguished by fast velocities and a bedrock substrate. Plane-bed and pool-riffle reaches have similar response curves, reflected in the overlap of physical habitat variables. The field methodology also highlights retention differences between channel types and structures (i.e. eddies and rocks), which has implications on flow refugia and invertebrate drift. For instance, a hydraulic environment with an abundance of meso- and microscale habitat features is likely to be beneficial for organisms in providing flow refugia during high flow events. In this paper, the findings highlight the importance of a diverse hydraulic environment, woody material and channel substrate character in increasing physical heterogeneity within a stream reach and providing flow refugia for organisms, particularly benthic invertebrates.

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