Experimental field assessment of suspended sediment pathways for characterizing hydraulic habitat

Gemma L. Harvey[1]* and Nicholas J. Clifford[2]
[1] Department of Geography, Queen Mary, University of London, London, UK
[2] School of Geography, University of Nottingham, Nottingham, UK

*Correspondence to: Gemma L. Harvey, Department of Geography, Queen Mary, University of London, Mile End Road, London, E1 4NS, UK. Email: g.l.harvey@qmul.ac.uk

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ABSTRACT: The distribution of particulate matter within river channels, including sediments, nutrients and pollutants, is fundamental to the survival of aquatic organisms. However, the interactions between flow and sediment transport at the patch scale of river systems represents an under-researched component of physical habitat studies, particularly those concerning the characterization of 'physical biotopes' (riffles, runs, pools, glides). This paper describes a field methodology for exploring the transfer of particulate matter at small scales within river channels, which may be used to aid hydraulic habitat characterization. The field protocol combines field measurement of high frequency flow properties, to characterize hydraulic habitat units, and deployment of spatial arrays of turbidity probes, to detect the passage of artificially-induced sediment plumes through different biotope units. Sediment plumes recorded by the probes are analysed quantitatively in the manner of the flood hydrograph, and qualitative inferences are made on the dominant mixing processes operating within different parts of the channel. Relationships between the nature of spatio-temporal hydraulic variations within glide, riffle and pool biotopes, and the character and mixing behaviour of sediment plumes within these habitat units are identified. Results from these preliminary experiments suggest that investigating and characterizing the transfer and storage of sediments, nutrients and pollutants within and between different biotopes is a viable avenue for further research, with potential to contribute to improved physical habitat characterization for river management and habitat restoration. The experiments are also an illustration of the value of neglected synergies between process geomorphology, ecology and river hydraulics. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: physical biotope; in-stream habitats; ecohydraulics; habitat complexity; suspended sediment transport

Introduction

Explorations of physical habitat structure within small streams have, to date, focused principally on the spatial organization of flow velocities, water depths and bed sediments within the river channel. Together, these properties create 'physical biotopes' (riffles, runs, pools, glides); morpho-hydraulic river features which show some evidence of biological distinction in terms of the communities of aquatic invertebrates they support (Kemp *et al.*, 1999, 2000; Harper *et al.*, 2000; Harvey *et al.*, 2008) and which provide a practical focus for river habitat assessment, rehabilitation design and appraisal protocols (Newson and Newson, 2000). While commendable efforts have been made to characterize physical biotopes according to temporally- and spatially-averaged hydraulic parameters (Jowett, 1993; Wadeson, 1994; Padmore, 1997), most practical schemes using biotopes to classify flow and to inventorize physical habitat (e.g. the UK River Habitat Survey; Raven *et*

al., 1997) are based purely on visual recognition of *surface* flow characteristics (Environment Agency, 2003), without control for stage-dependent variation (Clifford *et al.*, 2006). In addition, interactions between flow properties and related sediment transport processes within these habitat units remain largely unexplored, so that the nature and robustness of the biotope concept as a true delimiter of physical habitat is unclear.

Recent studies have emphasized the significance of the microscale ecohydraulics of rivers, focusing, for instance, on the effects of individual obstructions on the velocity field (Crowder and Diplas, 2000; Shen and Diplas, 2008); the influence of microtopography and microscale hydraulics on the movement behaviour of aquatic invertebrates (McNair *et al.*, 1997; Lancaster *et al.*, 2006); and the relationships between turbulence and fish bioenergetics (Enders *et al.*, 2003, 2005). Previous work in geomorphology and hydraulics has emphasized the significance of variations in higher-order flow

(a) Pool-glide reach, Oakley Hall   (b) Pool-riffle reach, Napely Lodge Farm

Figure 1. Study reaches on the River Tern, Shropshire, where experiments were conducted during summer 2005: (a) pool-glide reach at Oakley Hall; (b) pool-riffle reach at Napely Lodge Farm.

parameters such as turbulence intensity and the size of flow structures between different river sub-environments (Clifford, 1996, 1997; Dyer and Thoms, 2006; Legleiter *et al.*, 2007; Thompson, 2007; Harvey and Clifford, 2009) and explored the routing of sediment through pools (Rathburn and Wohl, 2003); identifying implications for sedimentation and aquatic habitat provision. Such work provides a geomorphological justification for a more detailed experimental approach to the exploration of relationships between channel hydraulics, localized sediment transport and aquatic biota at the biotope scale of river systems.

Furthermore, a significant volume of research has identified the wide-ranging effects of local sediment transport processes on aquatic biota. Work has, for instance, highlighted the importance of channel hydraulics and sediment transport processes in the hydrochory of seeds and vegetative plant propagules, with implications for colonization (Gurnell *et al.*, 2006); and the spiralling of food and nutrients (Cummins, 1975; Newbold *et al*, 1983; Wotton, 1996). In contrast, negative impacts of sediment transport processes on aquatic organisms include abrasion, burial, psychological stress, impaired respiration and feeding, and changes to the structure of the aquatic community through longitudinal drift (Carling, 1995; Wood and Armitage, 1997; Argent and Flebbe, 1999; Shaw and Richardson, 2001; Soulsby *et al.*, 2001; Jowett, 2003; Sear *et al.*, 2004; Heywood and Walling, 2007). Furthermore, where contaminants are adsorbed to the surface of particulate matter, biota may be directly exposed to the toxic effects of chemicals from anthropogenic sources (Greenberg *et al.*, 2002; Hose *et al.*, 2002). Such work suggests that any variations in localized sediment transfer characteristics within physical biotopes are likely to have ecological significance.

There remains, however, a lack of studies attempting to link such microscale flow and sediment transport characteristics explicitly with the concept of physical biotopes, and hence, to exploit synergies between the disciplines of process geomorphology, ecology and river hydraulics. This reflects a significant gap in the understanding of, and approaches to the study of the nature of physical habitat within river channels, with implications for the successful management and restoration of, aquatic ecosystems. This paper describes a novel experimental field methodology developed to explore these characteristics using fine sediments as flow tracers. It offers some appropriate analytical techniques and discusses the implications of the preliminary findings for river habitat characterization.

Study Sites and Biotope Identification

The method was developed on two study reaches of the River Tern, Shropshire, located in the English Midlands approximately 50 miles north-west of Birmingham. The Tern catchment constitutes one of the three flagship catchments of the Natural Environment Research Council (NERC) Lowland Catchment Research (LOCAR) thematic programme developed to promote interdisciplinary hydro-environmental research within groundwater-dominated river systems (LOCAR, 2007). The Tern is a tributary of the River Severn, draining a catchment area of 852 km^2 within the North Shropshire Plain and is predominantly underlain by Permo-Triassic Sandstones. Two contrasting sites were selected for study, incorporating glide and pool biotopes (at the Oakley Hall reach; Figure 1a) and riffle and pool biotopes (at Napely Lodge Farm; Figure 1b) which were identified visually in the field according to the morpho-hydraulic characteristics outlined in the Bisson *et al.* (1981) classification and Environment Agency (2003) River Habitat Survey field guidance. Thus, riffles were identified as shallow, moderately fast-flowing zones with a disturbed water surface (unbroken standing waves) and gravel, pebble and cobble substrate; glides as moderately shallow areas with a lack of pronounced turbulence; and pools as deeper areas with fine substrate, backwater currents and no perceptible downstream flow across most of the wetted width. Oakley Hall (NGR SJ 704 377), an instrumented LOCAR site, is a relatively straight reach, ponded by debris dams and characterized by a glide-pool morphology. The bankfull width is approximately 5·6 m and sediment size (D_{50}) ranges from 0·18 mm in silted margins and pools to 45·00 mm in riffles and runs. The second site, Napely Lodge Farm, is located 0·5 km upstream (NGR SJ 707 384), exhibits a higher gradient and more tortuous channel and is characterized predominantly by a riffle-pool morphology. The bankfull width is approximately 4·5 m and D_{50} ranges from 0·06 mm to 49·00 mm. Gauging records from the Oakley Hall site for the 2005 study season report a minimum summer discharge of 0·14 m^3 s^{-1}, a maximum discharge of 0·76 m^3 s^{-1} and a mean annual flow of 0·33 m^3 s^{-1}.

Field Experiments

The field protocol combined high frequency flow measurement (used in order to characterize habitat hydraulics and

support visual identification of biotope units) with turbidity monitoring (used in order to trace sediment transfer pathways through different biotopes) following the release of artificially-induced sediment pulses.

Hydraulic characterization of biotope units

High frequency flow characteristics were sampled within glide and pool biotopes at Oakley Hall and riffle and pool biotopes at Napely Lodge Farm during a stable low flow period in June 2005 ($Q = 0.17$ m^3 s^{-1}/ 0.18 m^3 s^{-1}), and under intermediate flow conditions in July 2005 ($Q = 0.24$ m^3 s^{-1}/ 0.28 m^3 s^{-1}). Discharge conditions were constant during the sampling period. Streamwise (U) and vertical (W) velocities were measured along the channel centreline and along a channel cross-section at the centrepoint of each physical biotope unit. A spherical-headed two-dimensional Valeport 802 Electromagnetic Current Meter (EMCM) modified for 16 Hz analogue output was used in direct communications mode with a Campbell Scientific CR10X data logger to allow simultaneous high frequency (16 Hz) logging of U and W velocity components over a period of 30 seconds.

As a means of characterizing biotope hydraulics, the streamwise and vertical velocity (U and W) series were examined, and turbulent residuals (u' and w') were derived by fitting linear or low order polynomial regressions to velocity series following Gordon (1974) and Clifford and French (1993). Unfortunately, a logging error resulted in the loss of W series for the Napely Lodge Farm site under low flow conditions. Full analysis of turbulent properties of the flow series (including quadrant analysis, autoregressive modelling and spectral density analysis) is provided in Harvey and Clifford (2009).

Suspended sediment experiments

Suspended sediment experiments were conducted within the same biotope units as the hydraulic measurements, under the same discharge conditions. Within each physical biotope unit (glide, riffle, pool), two vertical arrays of three Partech IR40C infrared turbidity probes were deployed to monitor turbidity for the duration of artificially created sediment pulses. On each array, turbidity probes were positioned at 0.2, 0.6 and 0.8 of the water depth from the surface, and the two arrays were spaced 2 m apart along the channel centreline within each individual biotope unit. Figure 2 illustrates the experimental set-up. Then, 500 ml containers were filled with fine
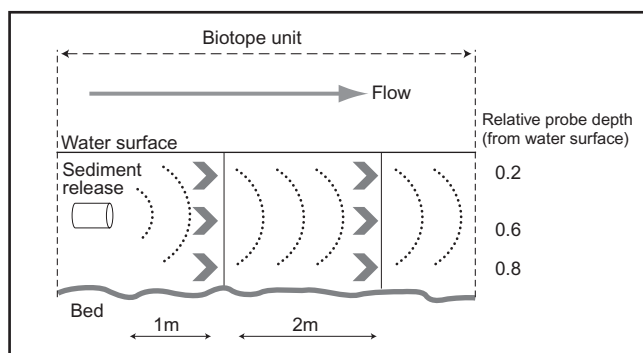
sediment (wet solid) collected from the channel margins at each respective study reach ($D_{50} = 0.06$ mm at Oakley Hall and $D_{50} = 0.18$ mm at Napely Lodge Farm) and released instantaneously into the flow 1 m upstream of the first probe array. Sediment pulses were released at three different relative flow depths (0.2, 0.6 and 0.8) during separate experiments within the glide and pool biotopes, but shallow depths within the riffle biotope limited the experiment to a single pulse release and detection at a relative depth of 0.6. Turbidity probes were connected to a Campbell Scientific CR10X data-logger, set to log at a frequency of 11 Hz for one minute prior to sediment release (in order to provide an indication of the ambient turbidity levels) and continuing for three minutes following each release (in order to ensure enough time for the sediment plume to pass both probes and a return to ambient turbidity levels).

IR40C turbidity probes measure the extent to which a beam of light of near-infrared frequency passing through the water is attenuated as a result of water turbidity. Attenuation is related to the surface area of particles and calibration is therefore necessary to relate probe output to the concentration of particles. IR40C probes produce typically near-linear calibration curves at low concentrations (Clifford et al., 1995), providing an accurate representation of increasing sediment concentration. This is demonstrated in Figure 3 for a selected probe calibrated using marginal channel silts from each study reach ($D_{50} = 0.06$ mm at Oakley Hall and $D_{50} = 0.18$ mm at Napely Lodge Farm) across the range of output values detected during the field experiments. Given this, and since for these experiments, the focus of interest is on suspended particles as flow tracers, rather than the actual particle concentrations, results are presented in turbidity output form (in mV); see Clifford and French (1996) for an earlier proof-of-concept field study.

Quantitative and Qualitative Approaches to Analysing Sediment Pulses

A threshold value of 1·5 times the ambient turbidity range was employed to delimit start and end points of the sediment plumes detected within the turbidity time series. The threshold value was selected following visual inspection of turbidity traces in order to exclude small infrequent fluctuations in
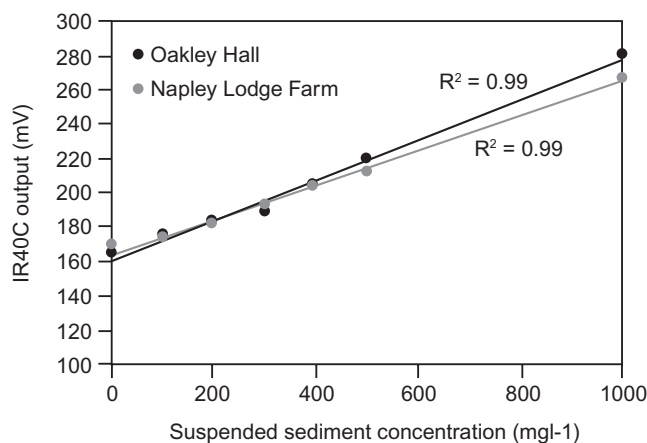
Figure 2. Instrumentation set-up for sediment transfer experiments conducted within different biotope units (cross-sectional view). Equipment was positioned around the centrepoint of each physical biotope unit as identified visually in the field at low flow stage.

Figure 3. IR40C turbidity probe calibration curve illustrating the linear relationship between probe output and suspended sediment concentration for the range of turbidity values identified in field experiments.
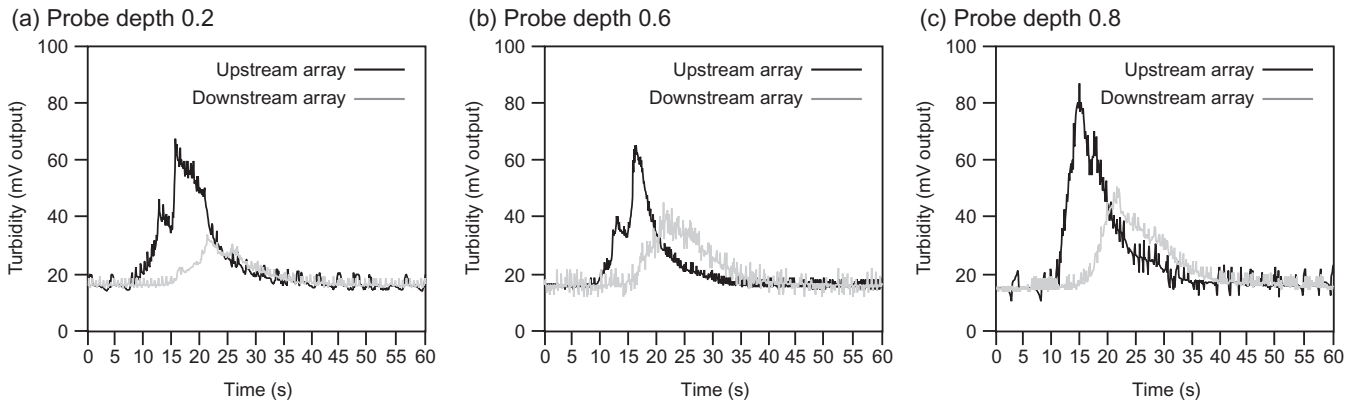
Figure 4. Examples of turbidity traces monitored within the glide biotope at Oakley Hall under low flow conditions for a suspended sediment pulse released at 0·6 of the water depth.
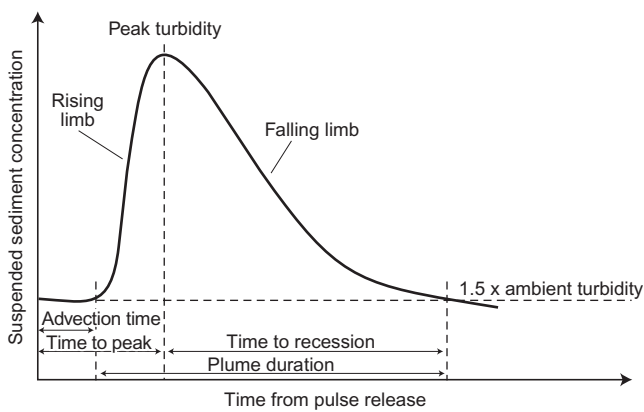

Figure 5. A hypothetical turbidity trace to demonstrate the various sediment plume statistics calculated for each turbidity trace.

turbidity associated with intermittent sediment suspension events (Lapointe, 1996) and unrelated to the passage of the artificially created sediment pulse. Turbidity traces were produced for each probe and visually inspected in order to: (i) calculate and compare various sediment pulse statistics (quantitative analysis); and (ii) determine dominant mixing processes (qualitative analysis). Figure 4 illustrates turbidity traces for the glide biotope at Oakley Hall as an example.

Quantitative analysis of sediment pulses

Quantitative assessment of the characteristics of detected sediment plumes involved calculation of a series of statistics as defined in Figure 5. This includes: the total plume duration; advection time; time to reach peak turbidity; maximum turbidity; and time to recession for each detected sediment pulse. The advection time represents the time period between sediment release and the first detection of the sediment plume at the upstream array (i.e. when turbidity levels increase beyond the 1·5 times ambient turbidity threshold level). Total pulse duration was calculated as the time from first detection of the sediment plume (above the threshold) to the return to the threshold level. The time to peak turbidity represents the period from first detection of the plume to the maximum recorded turbidity value for the plume; the time to recession represents the time period between maximum turbidity and the return to the threshold level.

Qualitative analysis of dominant mixing processes

During the quantitative analysis, it was noted that non-detection of pulses was relatively common within the data set, and appeared to be more common in certain biotope units (notably pools), perhaps indicating spatial variations in mixing mechanisms. By considering successful or failed detection of sediment pulses at various flow depths on both upstream and downstream probe arrays, it was possible to qualitatively explore the likely mixing mechanisms operating within each biotope, i.e. longitudinal advection; turbulent diffusion; vertical dispersion; and transverse dispersion. Advection refers to the process by which velocity currents move the sediment cloud in a downstream direction away from the release location. Pure advection moves the pulse downstream as a coherent body without change in concentration, while turbulent diffusion causes the pulse to spread out vertically within the water column and transversely towards the banks, transferring sediment from areas of high concentration to areas of low concentration and altering the size, shape and concentration of the sediment cloud (Allen, 1985; Rutherford, 1994). Since most river channels are characterized by widths many times greater than the water depth, complete diffusion is generally achieved more rapidly in the vertical dimension throughout the water column, than transverse diffusion across the channel (Rutherford, 1994). A further process, dispersion, may result in the movement of the sediment cloud bodily either towards the banks (transverse dispersion), or vertically within the water column (vertical dispersion).

Results

Hydraulic characterization of physical biotopes

Figure 6 plots the range, interquartile range and median values for streamwise and vertical velocity (U and W), and the detrended turbulent residuals (u' and w'). Comparisons may be drawn between biotope units, between sites and across flow stages. At Oakley Hall, the glide biotope is associated with slightly higher streamwise velocity values than the pool, but lower magnitude turbulent fluctuations (root mean square (RMS) values for u' and w' range between 0·01 and 0·02 for the glide and 0·03 to 0·08 for the pool). Furthermore, much greater spatial and temporal variation in hydraulics is noted

(a) Streamwise velocity

(c) Vertical velocity

(b) Streamwise velocity turbulent residuals

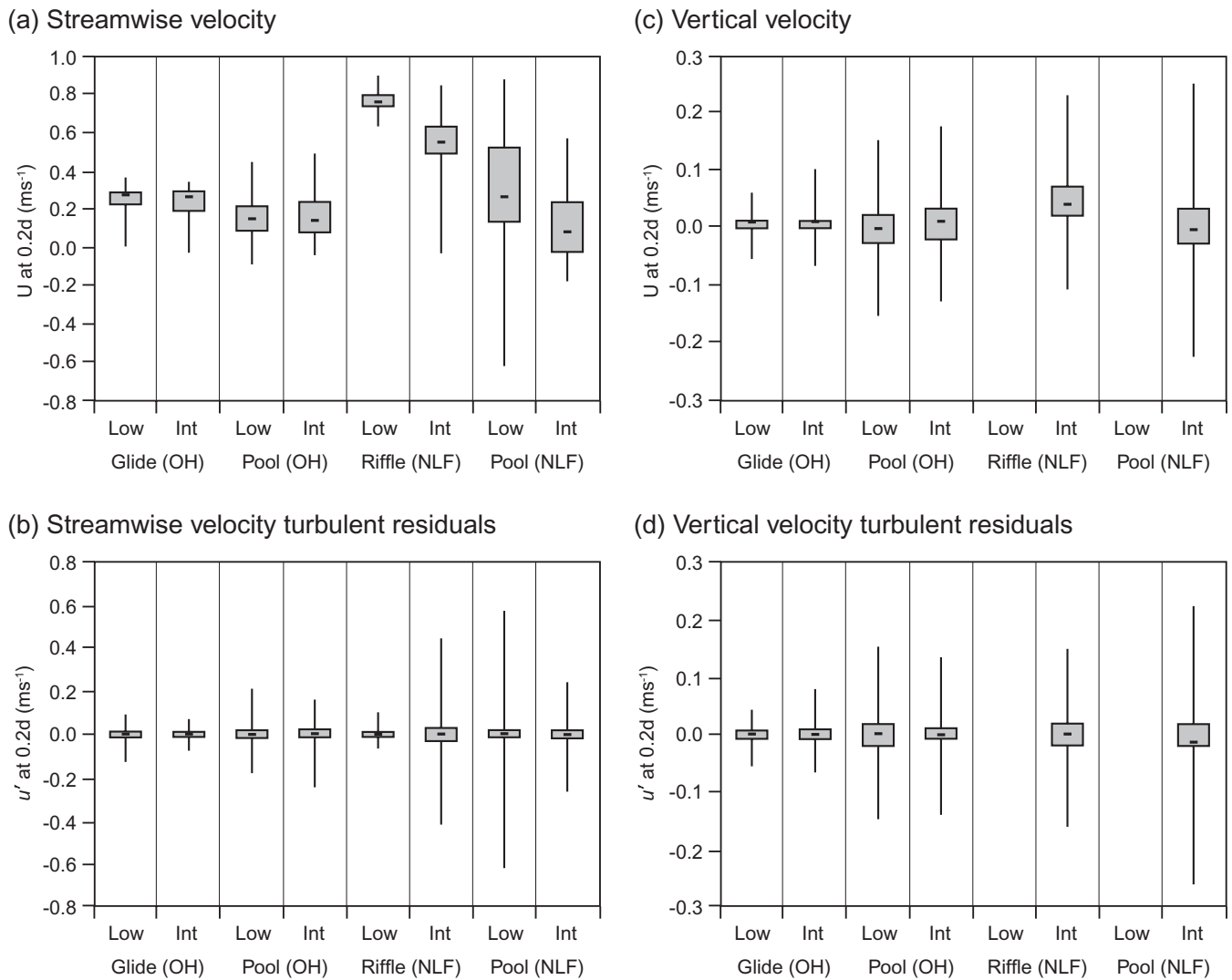## (d) Vertical velocity turbulent residuals

Figure 6. Boxplots displaying the median, range and interquartile range values derived from high frequency turbulent time series for streamwise and vertical velocity components and detrended turbulent residuals plotted for the different biotope units under low and intermediate discharge conditions at Oakley Hall (OH) and Napely Lodge Farm (NLF) field sites. The vertical velocity component for low flow surveys at NLF was lost due to a logging error. Data presented here were measured at 0·2 of the water depth (From the surface).

Table I. Summary of the hydraulic characteristics of the different biotope units studied as derived from examination of high frequency velocity series (see Figure 5; Harvey and Clifford, 2009)

Physical biotope	Flow properties	Spatio-temporal variation in hydraulics
Glide	– Intermediate flow velocities and water depths – Low turbulence intensities – Flow structures scaling on bed microtopography	– Spatially and temporally homogeneous flow environment
Riffle	– High flow velocities and low water depths – Intermediate turbulent intensities – Flow structures scaling on pebble clusters	– Spatial heterogeneity associated with marginal areas and localized flow intensification around bed microtopography – A systematic response to increasing discharge
Pool	– Wide range of flow velocities and water depths – Wide range of turbulence intensities – Range of coherent flow structures identified, scaling on roughness elements of varying sizes	– Hydraulically complex environment, with high spatial variability in turbulence properties – A spatially complex response to increasing discharge

for the pool biotope compared to the glide (see also Harvey and Clifford, 2009). Similar characteristics are observed for the pool at Napely Lodge Farm but spatial variability in hydraulics is more pronounced, reflecting the higher amplitude bedform structure at that site. The riffle biotope at Napely Lodge Farm is characterized by the highest flow velocities, and an intensification of turbulence at the higher flow stage (RMS values increase from 0·02–0·03, at low flow, to 0·03–

0·12 at intermediate flow). The full analysis of turbulent time series reported in Harvey and Clifford (2009), identified variations in turbulent properties and levels of spatial and temporal hydraulic variability within the biotopes studied which are of relevance to sediment transport processes at the local scale. The key characteristics identified are summarized in Table I to provide further context for the sediment transport experiments.

Table II. Detection and non-detection of sediment plumes by probes positioned at various depths on the upstream and downstream probe arrays for each experiment

Site	Biotope	Flow conditions	Release depth	Detection of sediment plume	
				Upstream array	Downstream array
Oakley Hall	Glide	Low flow	0·2	Detected (all probes)[a]	Detected (all probes)[a]
			0·6	Detected (all probes)[a]	Detected (all probes)[a]
			0·8	Logger error	Logger error
		Intermediate flow	0·2	Detected (all probes)[a]	Detected (all probes)[a]
			0·6	Detected (all probes)[a]	Detected (all probes)[a]
			0·8	Detected (all probes)[a]	Detected (all probes)[a]
	Pool	Low flow	0·2	Detected (0·2)[c]	Detected (all probes)[a]
			0·6	Detected (all probes)[a]	Detected (0·2; 0·8)[b]
			0·8	Detected (all probes)[a]	Detected (0·2; 0·8)[b]
		Intermediate flow	0·2	Detected (0·2; 0·6)[b]	Undetected[c]
			0·6	Detected (all probes)[a]	Undetected[c]
			0·8	Detected (all probes)[a]	Undetected[c]
Napely Lodge Farm	Riffle	Low flow	0·6*	Detected (0·6)*[a]	Detected (0·6)*[a]
		Intermediate flow	0·6*	Detected (0·6)*[a]	Detected (0·6)*[a]
	Pool	Low flow	0·2	Detected (all probes)[a]	Detected (0·2; 0·8)[b]
			0·6	Detected (all probes)[a]	Undetected[c]
			0·8	Detected (all probes)[a]	Undetected[c]
		Intermediate flow	0·2	Undetected[c]	Detected (0·8)[b]
			0·6	Undetected[c]	Detected (all probes)[a]
			0·8	Undetected[c]	Undetected[c]

Note: The same superscript letter distinguishes the number of probes on each array which successfully detected the passage of the sediment plume for each experiment

Characteristics of detected sediment pulses

Table II identifies the sediment plumes detected from turbidity traces for the various field experiments. In Table II, biotopes within which all probes detect the passage of the sediment plume are distinguished from those where only some of the probes detect the plume, or where the plume was undetected on all turbidity traces. Most notably, the detection of sediment plumes was successful for all probes within the glide, while pool records are more fragmentary. Analysis in this section focuses on the quantitative examination of turbidity traces where sediment plumes were detected; the subsequent section provides a qualitative analysis of mixing processes based on successful or failed detection of sediment plumes.

Figure 7 summarizes quantitative information on the various characteristics of detected sediment plumes within each biotope unit: advection time; plume duration; maximum instantaneous turbidity value; and the ratio of the time to peak, to the time to recession. Each bar in Figure 7 identifies the mean and range of values obtained for the range of experiments conducted within each biotope (combining traces from different plume release depths, probe position depths, and discharge conditions) in order to provide an overall indication of the ranges of values recorded for different biotopes and between the upstream and downstream probe arrays. The effects of varying discharge conditions, probe depths and release depths on plume detection is then explored in further detail for the glide biotope in Figure 8.

With the exception of duration at the riffle at Napely Lodge Farm, overall Figure 7 identifies a reduction in duration and maximum turbidity values between the upstream and downstream probe arrays reflecting the influence of diffusion of particles and, possibly, some settling-out of particles with distance from release (particularly at Napely Lodge Farm where the marginal fine sediment had a coarser particle size distribution). However, visual observation of the movement of sediment plumes during experiments confirmed that major settling-out of released particles over the short distances studied did not occur in any of four biotope units.

Some general differences in characteristics of detected sediment plumes can be observed between biotopes. Plumes within the riffle, for instance, are associated with longer durations, perhaps reflecting elongation of the sediment plume through velocity shear associated with the high streamwise velocities (Rutherford, 1994). The riffle also reveals some of the highest maximum turbidity values suggesting competent advection of the plume downstream as a coherent body, and the peak-to-recession ratio suggests that the length of rising and falling limbs of the passage of the plume are more similar within the riffle compared to the other biotopes studied. The maximum turbidity values decrease between the two arrays as a result of the natural turbulent diffusion of sediment within the flow.

The glide biotope is associated with plumes of intermediate duration and advection time, variable maximum turbidity values and a slightly longer rising limb. This may indicate a less efficient advection of the plume compared to the riffle biotope, consistent with the lower flow velocities and transport capacity associated with this biotope (see Figure 6 and Table I). The variable maximum turbidity value for the glide experiments indicates that concentrations at a particular probe depth are more closely related to the depth of the sediment release for this biotope compared to the pools, which may reflect a more regular logarithmic velocity profile consistent with the flume-like hydraulic properties identified in Harvey and Clifford (2009). Data available for quantitative examination are relatively fragmentary for the pool biotopes at both sites, since the passage of sediment plumes was not detected in a relatively large proportion of turbidity traces. The pools are generally characterized by shorter plume durations, intermediate to high advection times, lower maximum turbidity values and some of the highest peak/recession ratios,
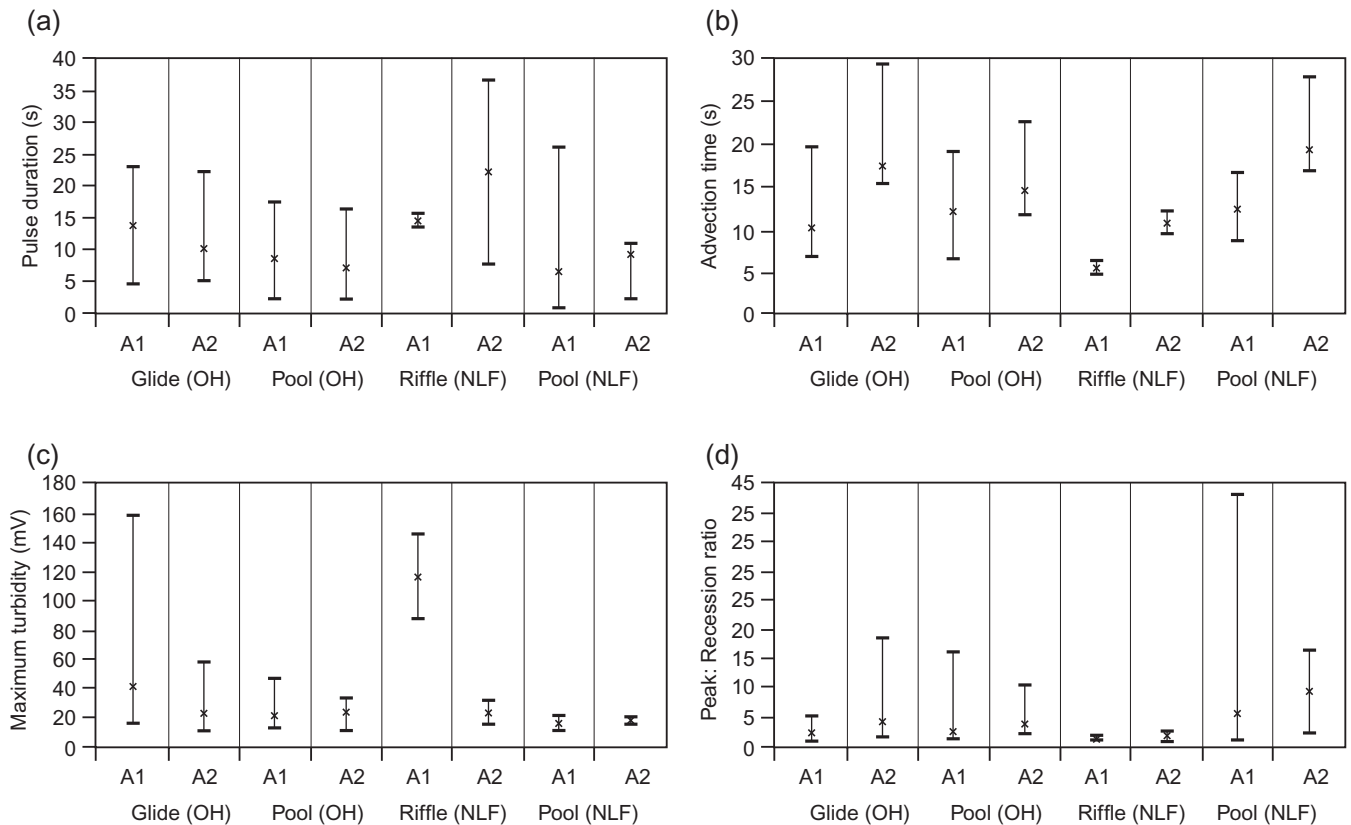
(a)

(b)

(c)

(d)

Figure 7. Mean and range of values associated with key pulse statistics for each array of probes within the four biotopes studied at Oakley Hall (OH) and Napely Lodge Farm (NLF): (a) pulse duration; (b) advection time; (c) maximum turbidity value; (d) peak/recession ratio. Data are amalgamated for the two experiments and for the three relative depths at which probes were positioned and show minimum, maximum and mean values. A1 represents the upstream array of turbidity probes and A2 represents the downstream array of turbidity probes within each biotope unit.

reflecting a complex and dynamic hydraulic environment (see Table I).

Vertical mixing behaviour

Positioning of turbidity probes at 0·2, 0·6 and 0·8 of the water depth permitted examination of the vertical mixing behaviour of suspended sediment plumes for the glide biotope (Figure 8). However, riffle depths were too shallow to permit positioning of more than one probe on each array, while pool records were too fragmentary to allow meaningful comparisons to be drawn (see earlier). Figure 8 thus plots statistics for plume duration, the maximum turbidity value and the peak/recession ratio for each detected plume within the glide biotope, according to the depth of both the sediment release and the detecting probe. Turbidity traces for the 0·8 release for the low flow experiment were lost due to a logging error.

Overall, trends become more complex for the intermediate discharge experiment, perhaps suggesting some localized flow intensification at the higher flow stage. At low flow, plume durations are consistently greatest at the water surface; but this is less apparent at intermediate flow where greater differentiation in values is noted for the various probe depths, possibly as a result of localized changes in hydraulics at the higher flow stage. The maximum turbidity values (Figures 8c and 8d) tend to increase towards the bed, which may reflect some settling out of particles, but again, this trend is less consistent at the intermediate discharge. The peak/recession ratios (Figures 8e and 8f) increase between the upstream and downstream arrays under both discharge conditions, supporting previous observations of lower ratios within the 'advection

zone' close to the release location (Rutherford, 1994). Once more, there is some suggestion of greater vertical complexity for the intermediate flow experiment.

Qualitative analysis of dominant mixing processes

As reported in Table II earlier, rates of successful detection of sediment plumes by turbidity probes varied between biotopes. This information was used qualitatively to infer the dominant mixing processes operating within the different biotope units. Dominant mixing processes were inferred by considering the successful or failed detection of sediment plumes by probes on upstream and downstream arrays for each sediment release experiment, according to the scheme shown in Figure 9. The dominant mixing processes operating within the various biotope units were identified as: turbulent diffusion and longitudinal advection; vertical dispersion; transverse dispersion; or a combination of vertical and transverse dispersion. Where all probes on each array detect the plume, the downstream advection of sediment within the flow must overcome (at least in part) depositional and diffusive processes over short distances. Furthermore, vertical diffusion of the plume must occur rapidly following release so that all probes positioned on the first array are able to detect the passage of the plume (although this cannot be assessed for the riffle). Given only partial sediment settling, where certain probes fail to detect the sediment plume it is likely that the plume has been moved bodily by dispersion processes associated with secondary current circulations
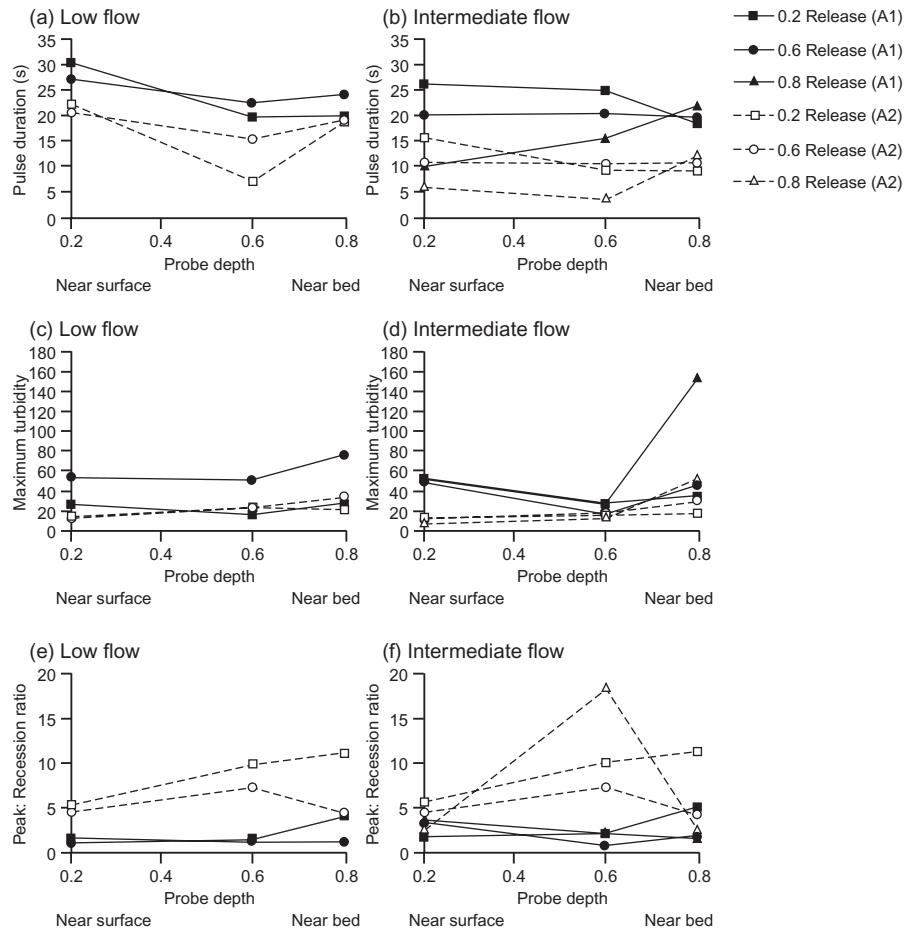
Figure 8. Key pulse statistics plotted according to relative depth of the release and relative depth of the detecting probe for the glide biotope at Oakley Hall. Results for low and intermediate discharges are plotted separately. Results are plotted for pulse duration (a and b), maximum turbidity (c and d) and peak/recession ratio (e and f).

(Rutherford, 1994). Vertical dispersion was considered to occur where the plume is detected at different probe depths on each array, associated with upwelling or downwelling currents operating between the two arrays. In cases where all of the probes on one or both of the arrays failed to detect the plume, transverse dispersion was considered to occur through deflection of the entire sediment plume by lateral secondary circulations towards either one of the banks. Settling-out of all particles, or diffusion of the sediment plume to ambient levels, was considered an unlikely explanation for non-detection of plumes, since visual observations confirmed the transfer of sediment plumes across the short distances studied within the various biotope units.

Based on this analytical scheme, Figure 10 summarizes the relative contribution of mixing processes identified within the different physical biotopes for the various experiments. Advective processes dominate in the glide biotope, supporting the idea of a more logarithmic velocity profile and homogeneous flow environment compared to the pools. It is not possible to make any reliable inferences on mixing processes within the riffle due to the limitations of the single release and probe depth at 0·6. In contrast to the glide, there are several instances where probes fail to detect sediment plumes released within the pools, suggesting that dispersion processes are significant. However, the nature of dispersion (transverse, vertical or a combination of the two) varies between the two pools, indicating variations in morpho-hydraulic characteristics associated with bedform amplitude (Harvey, 2006; Harvey and

Clifford, 2009), and with discharge, indicating a re-organization of flow with changing flow stage.

Discussion and Conclusions

This paper summarizes the preliminary findings from an experimental field method designed to explore the transfer of particulate matter at microscales within rivers. The approach represents a new direction in ecohydraulics research, which couples expertise and perspectives from process geomorphology, ecology and river hydraulics, and which may provide a means of exploring an under-researched aspect of physical habitat characterization with direct implications for aquatic biota.

The field experiments yield a complex dataset of sediment plume characteristics, from which some broad trends emerge. In particular, plume characteristics appear to reflect a more regular velocity profile and simpler and more spatially homogeneous flow environment within the glide unit compared to more complex and dynamic local hydraulics within the pools. These inferences are supported by the trends identified from high frequency streamwise and vertical velocity series summarized in this paper and explored more fully in Harvey and Clifford (2009). While the fragmentary nature of data sets for the pool biotopes limits a detailed quantitative analysis, the detection and non-detection of sediment plumes by turbidity probes is in itself an interesting feature, and this was used in a qualitative sense to infer the dominant sediment mixing
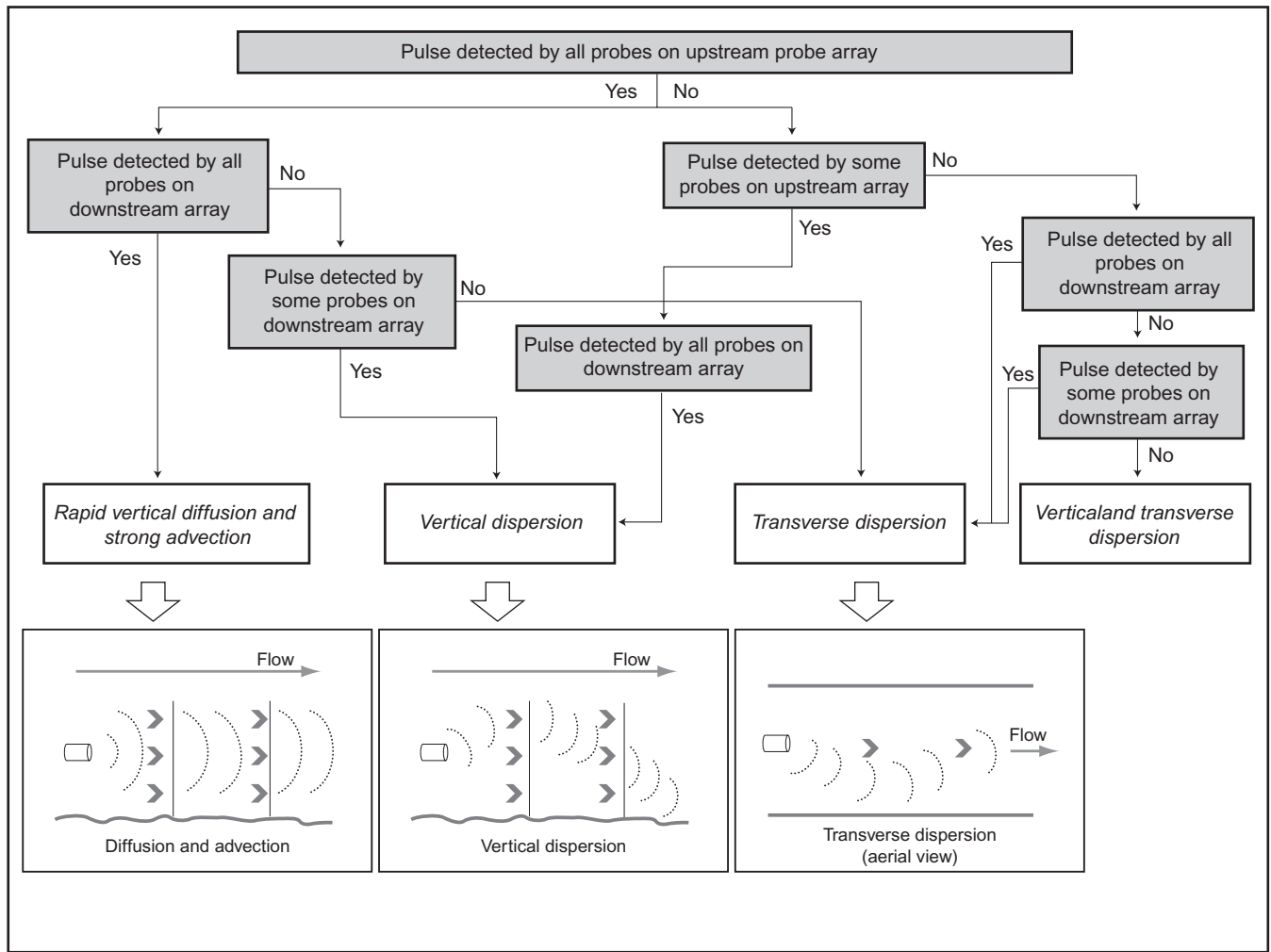
Figure 9. Qualitative approach to identification of the dominant mixing processes operating within different physical biotopes based on detection and non-detection of sediment plumes by turbidity probes positioned on upstream and downstream probe arrays.
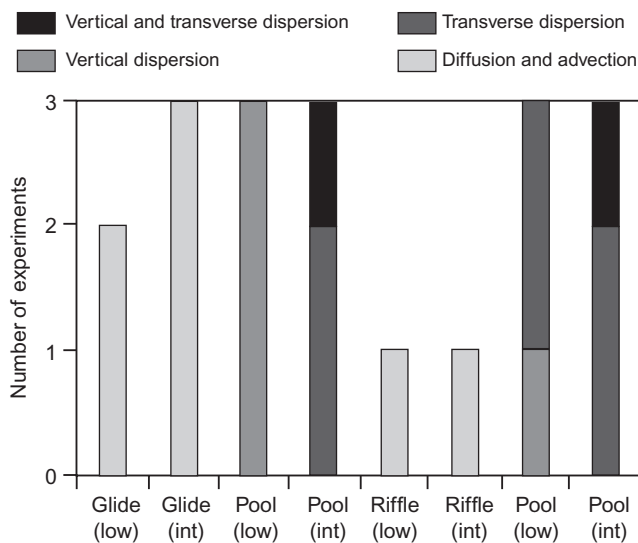

Figure 10. Inferred mixing mechanisms for sediment pulse experiments conducted under low and intermediate discharge conditions for maximum of three sediment releases (at 0·2, 0·6 and 0·8 of the water depth) within each biotope. The 0·8 trace was lost due to logging error for the glide at the low flow stage and shallow depths within the riffle biotope limited the experiment to a single release at 0·6.

processes operating within different biotope units. Results suggest that diffusion and advection processes may be common within hydraulically 'simpler' glide and riffle units, while the two pools are characterized by a combination of lateral and vertical dispersion of sediment plumes, emphasizing greater spatial and temporal hydraulic heterogeneity.

These observations suggest that variations in the processes of dispersal of sediments, nutrients and pollutants exist between different physical biotopes which are likely to reflect differing degrees of hydraulic complexity. Furthermore, these processes appear more strongly stage-dependent within certain biotopes compared to others. These observations complement the findings from previous work which has identified variations in the distribution of trace metal concentrations (Ladd *et al.*, 1998) and characteristics of high-frequency flow properties (Harvey and Clifford, 2009) between physical biotope units. Furthermore, these characteristics have implications for aquatic biota such as macro-invertebrates, through impacts on feeding and nutrient cycling, the nature and rate of downstream drift, provision of physical habitat, and disturbance. Thus, the findings potentially offer further ecological validation for biotope concept.

Improved understanding of such processes has the potential to strengthen the science underlying the ecological restoration of fluvial systems, and to help restore confidence in the geomorphological contribution to multi-disciplinary river restora-

tion efforts which has recently been questioned (Ormerod, 2004). However, these small-scale processes are inexorably linked to wider catchment scale sediment budgets and hydrological conditions, supporting the use of hierarchies of scale when considering river habitat features (Frissell *et al.*, 1986), and again, offering potential for deploying geomorphological expertise across the hierarchy (Harvey *et al.*, 2008).

In its present form, the research illustrates the value of process geomorphological investigations for applied river management, and their complementarity to other disciplines such as ecology and river hydraulics. The research also provides many opportunities for further exploration. Variation in biotope characteristics with stage, for example, is clearly evident, but is often not considered since the biotope is identified as a low flow feature. Similarly, work may explore how the results of experimental sediment plumes would transfer to real flow-event situations where the entire water prism is more turbid. Further, more intensive field deployments of turbidity probe arrays would potentially yield larger and more complete data sets to help to clarify observed patterns and identify any statistically significant differences among the full range of physical biotopes associated with UK rivers. Techniques such as videography, tracers, and floating surface markers in addition to detailed surveys of fine sediment deposits on the river bed may also provide further clarification.

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