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An assessment of temporal habitat availability in a gravel-bed river using a Lidar-derived CFD model

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Abstract Riffle-pool sequences in gravel-bed rivers provide the template for a number of fish and invertebrate habitats. Water flowing over these morphologies creates spatial hydraulic variations over a rivers flow regime that are logistically impossible to measure in the field. This paper utilises the FLUENT Computational Fluid Dynamics (CFD) model to construct a 0.2 m DEM for a 180 m reach of Kingsdale Beck, UK. CFD modelling allows spatial estimation of flow hydraulics for flows up to bankfull. With increasing discharge, complex patterns of hydraulic variation are revealed that exist within larger macroscale flow structures. During elevated flows these could act as biotic refugia. The spatial distribution and areal extent of habitat refugia for two commonly occurring macroinvertebrate species: *Gammarus pulex* (Amphipoda, Crustacea) and *Ephemerella ignita* (Ephemeroptera, Insecta), are explored for three discharges from baseflow up to bankfull. Temporal modelling permitted mapping of these refugia across the flow regime.

Key words Terrestrial Laser Scanning; CFD; gravel-bed shear stress; habitat availability

INTRODUCTION

It is well documented that during high flow conditions stream animals move into zones of lower energy (Borchatdt *et al.*, 1993; Winterbottom *et al.*, 1997; Lancaster, 2000; Lancaster *et al.*, 2006). Availability of adequate refugia during flood events are thought to be very important for macroinvertebrate community structure. Although some knowledge exists concerning the hydraulic requirements of certain fish and macroinvertebrate species (e.g. Borchatdt *et al.*, 1993; Barnodet & Helland, 1994), very little is known about the spatial changes in the availability of refugia with increasing discharge. Environmental flow prescription for river restoration schemes and regulated rivers should take into consideration the availability of flow refugia for target species, and requires an understanding of the influence of discharge changes upon the spatial distribution and areal availability of these refugia. Flow refugia vary in scale and take a variety of forms; e.g. the clast scale, microscale bedforms (particle clusters), and macroscale bedforms (pool-riffle-bar morphological units). The presence and absence of woody-debris or macrophytes also provide refugia, whilst some macroinvertebrates are also known to burrow down into the hyporheic zones, in between gravel interstices (Milan, 1994).

Pool-riffle bedforms are common quasi-stable features in moderate slope gravel-bed channels (Milan *et al.*, 2001). The interaction of discharge within this bedform provides a diverse range of hydraulic niches, the spatial pattern of which is dependent upon discharge (Milan *et al.*, 2001). The pool-riffle bedform is thus critical in sustaining habitats for both vertebrates and invertebrates (Greenwood & Richardot-Coulet, 1996; Montgomery *et al.*, 1999). Unfortunately, pool-riffle habitat has been lost by many channel management practices such as dredging; for example, Fox (in press) estimated that 174 000 riffles had been lost from 25 500 km of channel in the UK. Pools and riffles are now recognised as important features in restoration and rehabilitation projects, where their successful design relies on a thorough understanding of the fluvial processes responsible for their formation and maintenance (Brookes, 1992; Newbury, 1995; Sear & Newson, 2004; Caamaño *et al.*, 2009). Superimposed on this bedform is a mosaic of roughness elements, which influence microscale flow patterns close to the bed. Understanding hydraulic patterns within these microscale niches are also very important with respect to macroinvertebrate communities.

Clast size and imbrication is known to influence local bed hydraulics. Clustering of these particles is also known to occur (e.g. Wittenberg & Newson, 2005), further enhancing hydraulic complexity close to the bed and providing important refugia (Biggs *et al*., 1997).

This study explores the spatial distribution and areal extent of habitat refugia for two commonly occurring macroinvertebrate species: *Gammarus pulex* (the freshwater shrimp) and *Ephemerella ignita* (mayfly species), for three different discharges from low flow up to a bankfull flood. We use a Computational Fluid Dynamics Model to simulate shear stress patterns through a reach of gravel-bed river. Although other ecohydraulic studies have been able to present hydraulic maps of river reaches and relate this to instream ecology, for the first time this paper will present simulated hydraulic data at the sub-clast scale, which has significance to improving current understanding of the spatial pattern and extent of micro-hydraulic niches (e.g. downstream of clasts and pebble clusters). To permit this, a Terrestrial Laser Scan (TLS) was required to produce a clast-scale Digital Elevation Model (DEM) of the study reach.

STUDY SITE

Field data collection took place on Kingsdale beck, located 5 km north of Ingleton, North Yorkshire, UK (Fig. 1) (54°11′30.36N 2°27′33.83W). Kingsdale Beck drains a formerly glaciated valley. The underlying limestone geology results in numerous shake holes, pot holes and caves within the catchment. The key advantage of the selected study reach was the location of an upstream sink hole (Fig. 1). At base flow, the water descends through a series of bedding planes in the underlying geology before re-emerging 1 km downstream of the study reach. This presents an excellent opportunity for data capture using a Terrestrial Laser Scanner as the dry bed facilitates laser returns. The relatively small drainage basin (approximately 24 km^2) experiences a very flashy flow regime. The study reach has a Strahler stream order of 2 and is a single-thread, straight, gravel-bed channel, situated at 260 m AOD. Bankfull discharge occurs at 35 $m^3 s^{-1}$.

METHODOLOGY

There are a number of steps to allow the investigation to take place, firstly a digital terrain model is required to generate a hydraulic flow model, in this case TLS facilitates data collection. Secondly the model must be processed using CFD and a computational mesh of the model built which creates the domain in which the water will flow. Data on river flow is also required for both model input and validation; this is collected using an Acoustic Doppler Velocimeter (ADV) following the protocol described by Lane (1998).

Field data collection

A LMS-Z210 terrestrial laser scanner (TLS) manufactured by RIEGL was deployed in the field and is designed for the rapid acquisition of high-quality 3-D, x,y,z topographical data, providing a combination of high accuracy, wide field-of-view and fast data capture. Information on scanning principles and specifications can be found in Heritage & Hetherington (2007) and Heritage & Large (2009). An Acoustic Doppler Velocimeter (ADV) attains data using the Doppler shift principle, as such measurements are insensitive to water quality, therefore allowing for a wide range of different applications, capturing data in globally referenced East-North-Up (ENU) coordinates or as x,y,z coordinates relative to the probe. The use of a Topcon GTS-210 total station generates a standard baseline coordinate system in which both the TLS and the ADV are adjusted to, allowing direct comparisons to CFD model outputs. The x component of velocity was defined along the predominant flow, the y component of velocity orthogonal to the channel banks, and the z component of velocity in the vertical. The ADV functions by transmitting short pairs of sound pulses, listening to their echoes and, ultimately, measuring the change in pitch or frequency of the returned sound. The probe is submerged in the flow and three receivers are mounted on short arms slanted at 30° from the axis of the transmit transducer, the acoustic beams are oriented so that the receive beams intercept the transmit beam focusing on a common sample volume. The interception of these four beams, together with the width of the transmit pulse, define the sampling volume.

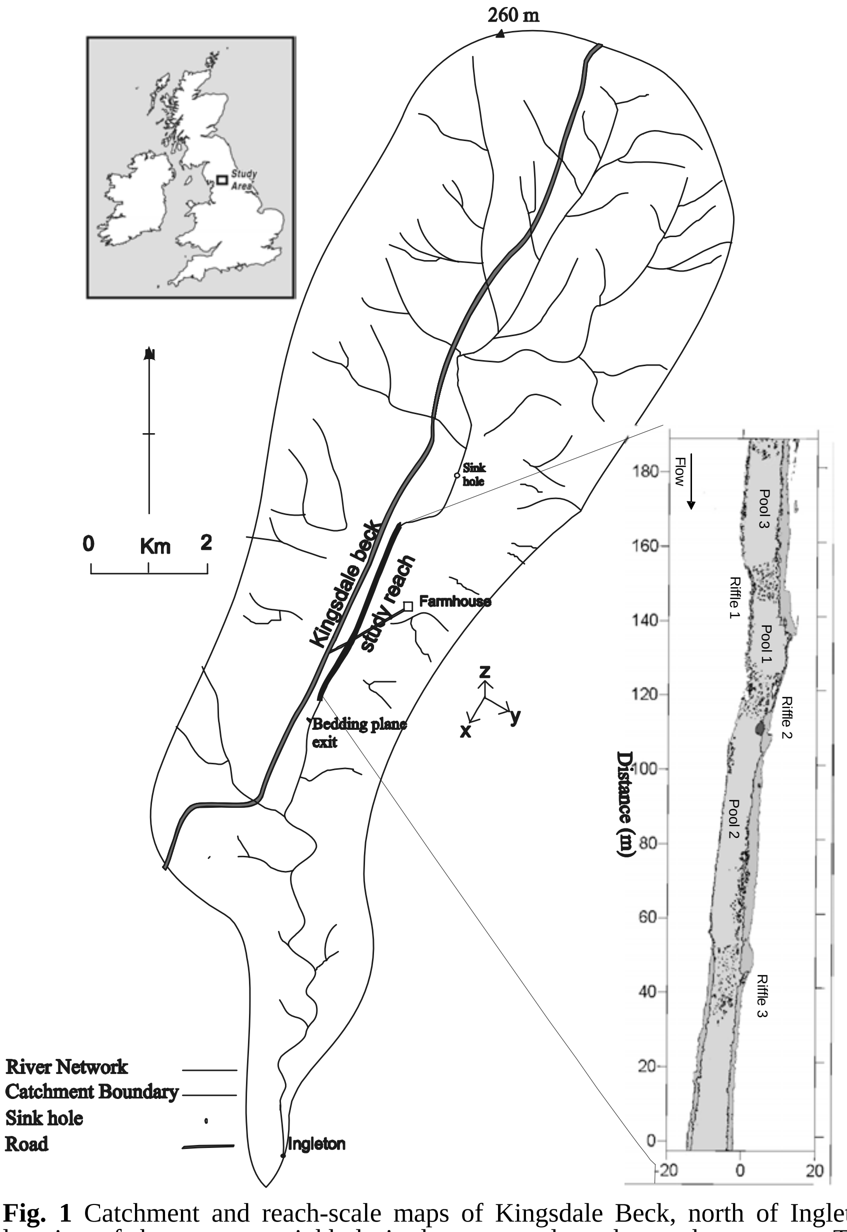

Fig. 1 Catchment and reach-scale maps of Kingsdale Beck, north of Ingleton Yorkshire, UK. The location of the upstream sinkhole is demonstrated on the catchment map. The reach-scale map was derived from TLS data captured during the present study, and identifies riffle and pool location.

CFD Model development

The CFD code used in this investigation is FLUENT. The software has been applied previously to flow dynamics of gravel bed rivers, in particular to address bed roughness (Nicholas, 2001; Carney *et al*., 2006), separating flow (Hodkinson, 1996; Hodkinson & Ferguson, 1998; Nicholas & Sambrook Smith, 1999; Dargahi, 2004), riffles and pools (Ma *et al*., 2002) and flood plains (Nicholas & McLelland, 2004). The model solves the full 3-D Navier Stokes equations with a $k - \varepsilon$

RNG turbulence closure model on a 3-D structured grid. Bradbrook *et al.* (1998) found that the RNG turbulence modification resulted in significant improvement in the correspondence between model predictions and laboratory observations due to improved representation of the effects of flow separation (further details of the RNG approach are provided in Bradbrook *et al.*, 1998). To create the computational domain FLUENT requires: (i) 3-D coordinates of the bed, imported from the TLS as structured x,y,z coordinates; (ii) discharge at the domain inlet, which was recorded at the field site; and (iii) boundary roughness (previously added to the code as a general roughness factor (e.g. Manning's *n*). Model solution is carried out by using the SIMPLE algorithm of Patankar & Spalding (1972) which first determines the pressure field required to conserve mass. The momentum equations, including the turbulence model, are then solved using the resulting pressure field. The ensuing velocities then satisfy momentum, but not continuity, therefore the FLUENT code recalculates the continuity errors. These are subsequently used to adjust the pressure and velocity fields to satisfy continuity. The velocities will now no longer satisfy momentum as this process iteratively repeats until both continuity and momentum errors are acceptably small. The computational domain extracted from the TLS output consisted of a 190-m reach, with a channel width of approximately 12 m and an approximate 1.25 m bankfull depth. The TLS generated in excess of 10 000 xyz data points per m^2, the data was post-processed and subsampled to produce a 0.2 m DEM which was considered to be sufficient to define bed roughness without the necessity for a correction parameter, and could be directly used with the CFD software given the computational resources available.

CFD model validation

For this investigation, model validation was conducted for three separate flows (2.02, 13.37 and 28.97 $m^3 s^{-1}$) where independently measured ADV data was available for 69 point locations throughout the study reach. At each of these points velocity was measured with the location mapped with the total station. Observed *vs* simulated x (streamwise) velocities are shown in Fig. 2(a), where r^2 values of 0.83, 0.75 and 0.78 are comparable to previous modelling studies conducted using field studies (e.g. Hodkinson, 1996; Bradbrook *et al.*, 1998; Hodkinson & Ferguson, 1998; Nicholas & Sambrook Smith, 1999; Booker *et al.*, 2001; Ma *et al.*, 2002; Dargahi, 2004; Nicholas & McLelland, 2004; Milan, 2009). Similarly Fig. 2(b) shows observed and simulated velocities for y with an r^2 of 0.52. Data returns for the z axis were very low and as such resulted in a poorer 0.1 r^2. However, there were no velocities recorded higher in the z than 0.1 m s^{-1}.

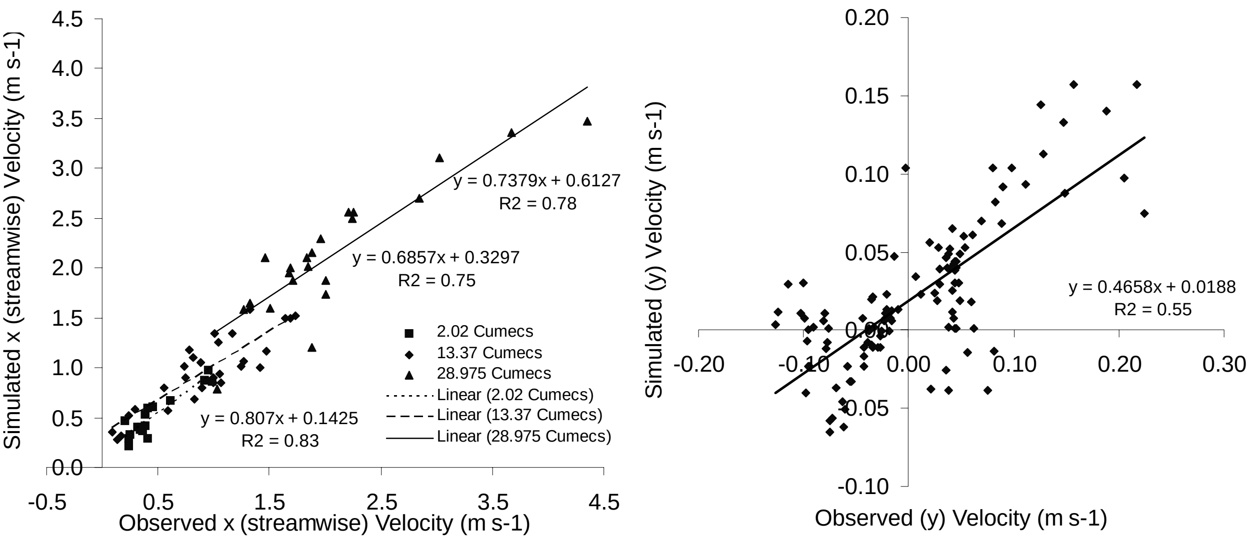

Fig. 2 Observed against simulated velocities in: (a) x, streamwise direction and (b) y, bank orthogonal direction for Kingsdale.

RESULTS AND DISCUSSION

Output from CFD flow simulations are shown in Fig. 3, which details contour plots of shear stress over the study reach for three discharges, 2.02, 13.37 and 28.98 $m^3\ s^{-1}$. During the low flow events the levels of shear stress are higher over riffles than pools. The contour maps in Fig. 3 illustrate that with increasing discharge the more complex patterns of shear stress as riffles extend both upstream and downstream of riffle crests. Figure 4 illustrates the frequencies of shear stress as dyne values for the pool units (a) and the riffle units (b). There are noticeable differences between riffles and pools with the former having predominantly higher energy. Pools show a dominance of low energy even with increasing discharge. As discharge increases, the pools show a resilience to maintain their low shear regime. In contrast, riffles are progressively more energetic with approximately 40% of the bed in the higher 30–40 dyne range.

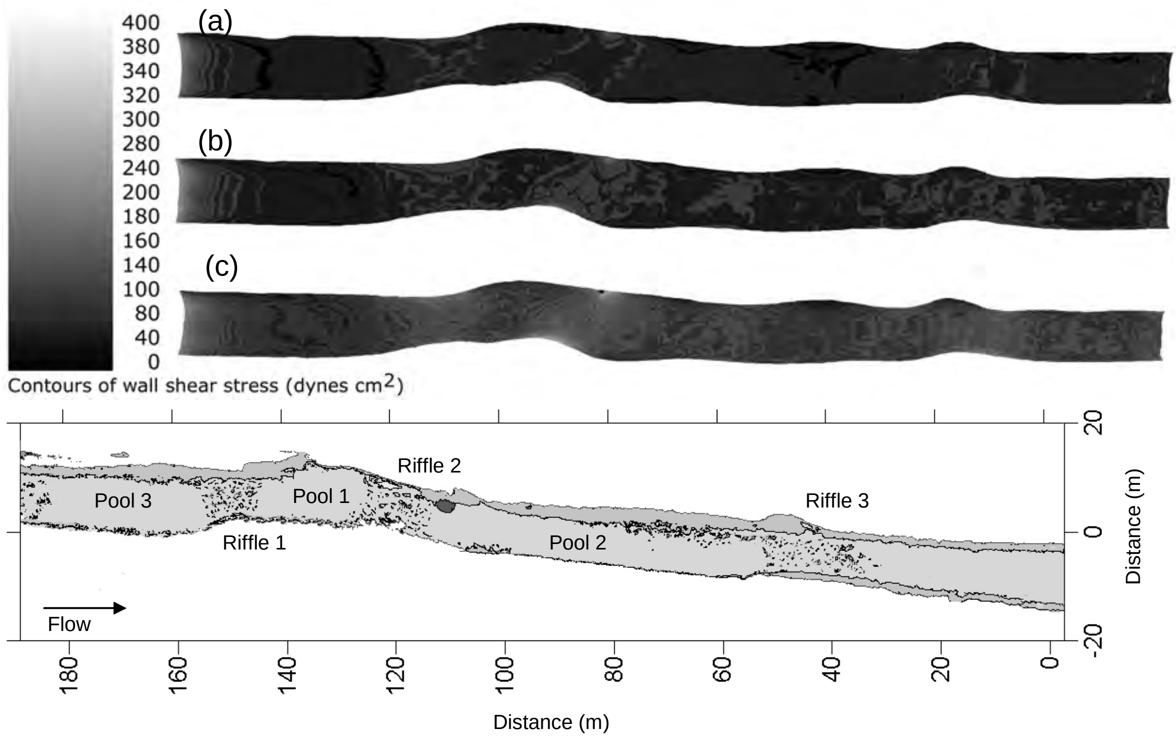

Fig. 3 FLUENT shear stress outputs (dynes cm^{-2}), for the reach at three different discharge rates, (a) 2.02 $m^3\ s^{-1}$, (b) 13.37 $m^3\ s^{-1}$ and (c) 28.98 $m^3\ s^{-1}$. A morphological map of Kingsdale beck map derived from terrestrial laser scanner obtained during the survey, highlighting location of riffles and pools within the study reach.

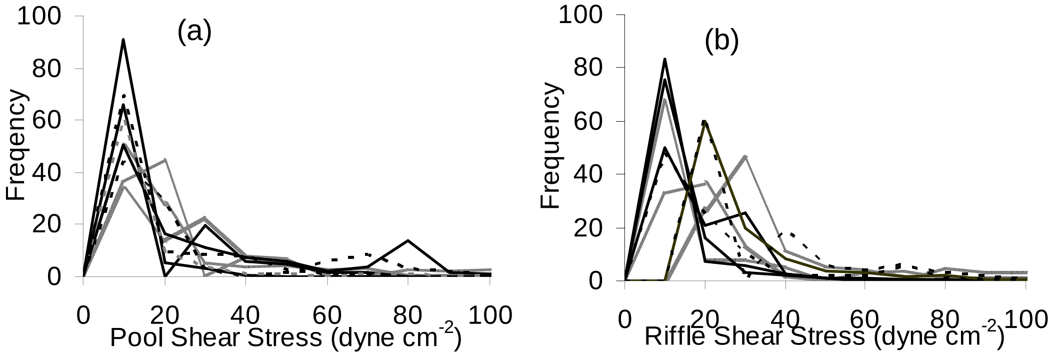

Fig. 4 Shear stress frequencies for each of three pool units (a), and three riffle units (b), for three different discharge levels, i.e. 2.02 m^3s^{-1}(solid), 13.37 m^3s^{-1} (dashed) and 28.98 m^3s^{-1} (dotted).

With increasing discharges there are significant changes between shear stress for both pools and riffles. Significantly riffles have the greatest changes with high frequency concentrations in the lower ranges falling from 90% at baseflow to 50% near bankfull. Pools, however, maintain a predominantly low energy unit throughout the regime. However, there are some smaller areas within pools that exert higher shear stresses values, which are evident in Fig. 4(a). Figure 5 increases the clarity of unit change behaviour across the low shear stress range with each pool and riffle illustrated separately for the three discharges. At baseflow, riffles and pools show similar frequencies of shear stress values with between 50 and 80% characterised by <20 dyne cm^{-2}. As discharge increases it can be the 13.37 m^3 s^{-1} discharge riffles have increased shear stress levels to frequencies with approximately 60% in the 20–30 dyne cm^{-2} range. In contrast to the three pools which have 40–60% shear stress characterised by <20 dyne cm^{-2}. At near bankfull discharge 28.98 m^3 s^{-1}, with the exception of riffle 3, riffles have higher shear stress with 70% characterised by >20 dyne cm^{-2}, which is much greater than for pools at the equivalent discharge. The relationship between shear stress and surface particle size has important ecological implications. Shear stress magnitude can influence the ability of benthic organisms to safely occupy a site, because it relates the local hydraulic environment (e.g. near-bed velocity and turbulent fluctuations) to dimensions of microhabitat that are controlled by particle size (e.g. substrate interstices and wake zones). At low shear stress, organisms would not likely be displaced, conversely at higher shear, organisms would more likely be displaced by high bottom velocities, although shear stress can influence different species in different ways as some macroinvertebrates are adapted in terms of body shape and size to cope with high shears stress, e.g. a mayfly (Statzner & Holm, 1982), compared e.g. with a freshwater snail that can only cope with slow moving water. The wide

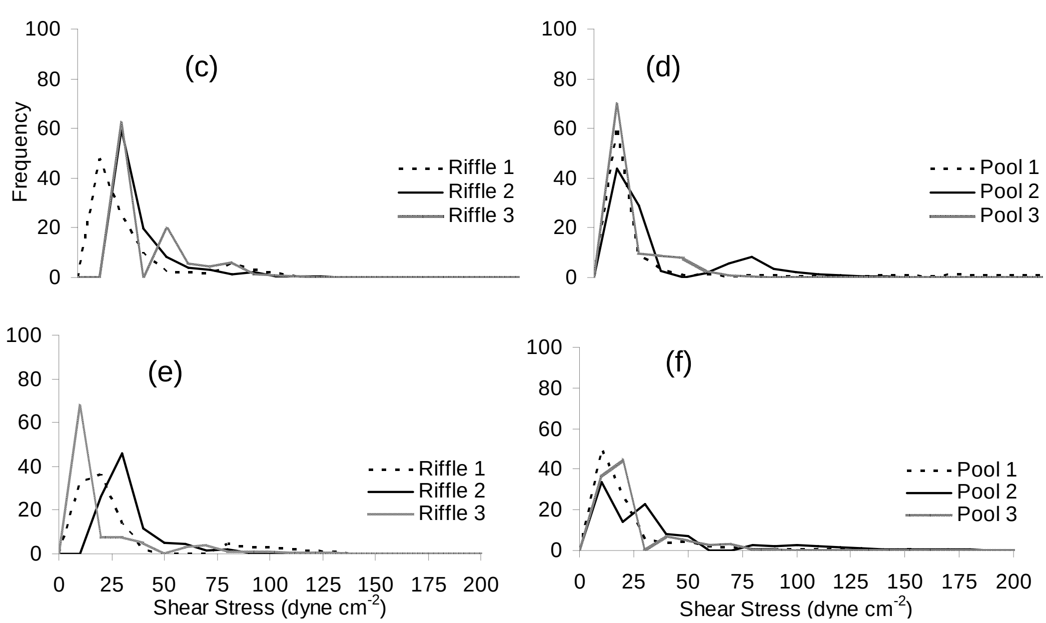

Fig. 5 Separated shear stress frequencies for riffles (left) and pools (right) at 3 distinct flow rates, i.e. (a)–(b) 2.02 m^3 s^{-1}, (c)–(d) 13.37 m^3 s^{-1}, (e)–(f) 28.98 m^3 s^{-1}.

range in values of shear stress observed at Kingsdale Beck, a relatively straight gravel-bed channel, indicates a tendency toward complexity in the association between benthic substrates and hydraulic conditions. The frequency distributions suggest that at bankfull flow, high-velocity sites are somewhat limited and that low-velocity sites provide enough refugia to maintain populations of organisms adapted to stable substrates.

Stage-dependent refugia

The shear stress exerted on macroinvertebrates at the bed can cause dislodgement and subsequent downstream transport of individuals. Controlled laboratory investigations conducted by Borchardt (1993) identified critical shear stresses of 11 and 31 dyne cm^{-2} for *E. ignita* and *G. pulex*, respectively. If it is assumed that areas of refugia are represented by shear stress zones below these critical values, then it is possible to plot the spatial pattern of refugia for these two species for the three simulated discharges at Kingsdale. The resultant refugia maps for *E. ignita* are presented in Fig. 6, and for *G. pulex* in Fig. 7. It can be seen from the maps and from the summary in Table 1 that there is a general decline in available refugia with increasing discharge. The area of available refuge for *G. pulex* is consistently greater compared with *E. ignita* as this species can withstand higher shear stresses before going in to drift. Pools appear to provide the most extensive areas of potential refugia at low flow; however, refuge zones are not necessarily critical at this flow stage.

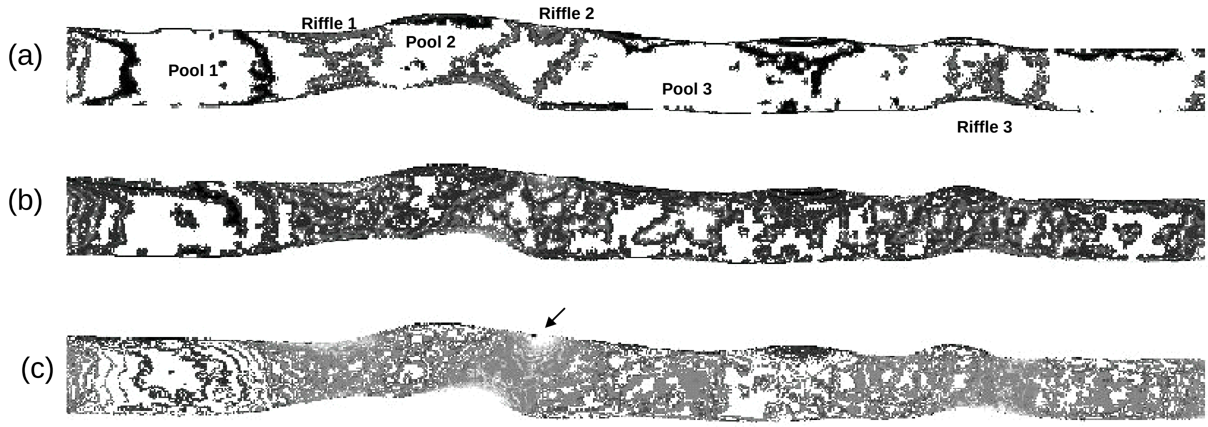

Fig. 6 Refugia map for *E. ignita*, indicating zones below 11 dynes ($dyne/cm^2$) as white areas, with shear stress levels increasing with greyscale for three discharges: (a) baseflow of 2 $m^3 s^{-1}$; (b) an intermediate flow of 14 $m^3 s^{-1}$; and (c) a near bankfull flow of 32 $m^3 s^{-1}$.

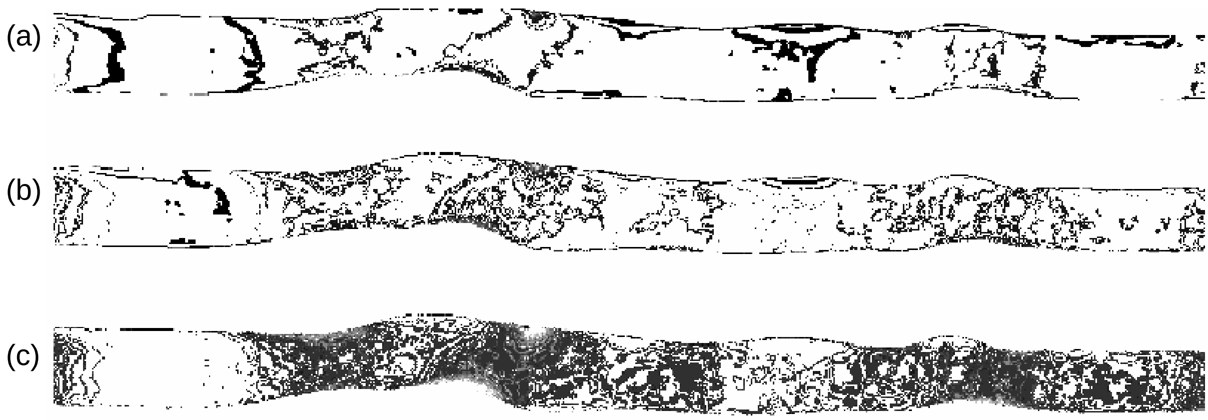

Fig. 7 Refugia map for *G. pulex*, indicating zones below 30 dynes ($dyne/cm^2$) as white areas with shear stress levels increasing with greyscale, for three discharges: (a) baseflow of 2 $m^3 s^{-1}$; (b) an intermediate flow of 14 $m^3 s^{-1}$; and a near (c) bankfull flow of 32 $m^3 s^{-1}$.

Table 1 Stage dependent refugia availability for *G. pulex* and *E. ignita*.

Discharge	*E. ignita* refugia (% reach < 11 dyne/cm^2)	*G. pulex* refugia (% reach <30 dyne/cm^2)
2 m^3 s^{-1}	89.94	84.84
14 m^3 s^{-1}	64.67	75.56
32 m^3 s^{-1}	33.64	45.92

Pool 3 at the upstream end of the reach appears critical in sustaining refugia even at bankfull flow. There is a substantial reduction in refuge availability for *E. ignita* at 14 m^3 s^{-1}, and less of a reduction between 2 m^3 s^{-1} and bankfull discharge. This may suggest that this species is more susceptible to the impacts of disturbance. A greater proportion of the reach still satisfies refugia conditions for *G. pulex* even at bankfull discharge, suggesting that this species is likely to have greater tolerance to disturbance. The maps in Figs 6 and 7 also suggest limited connectivity between refuge zones, even at the lowest discharge. The implication here is that for animals to migrate along the river corridor by crawling, the animal would have to crawl to the channel margin first, instead of crawling directly upstream or downstream along the bed.

There is also evidence of small patches of refugia (e.g. around pool 2). These may relate to local zones of low shear stress on the lee side of pebble clusters and are most evident during the near bankfull discharge maps. Furthermore on the left bank of riffle 2, there is an area of refugia for both *E. ignita* and *G. pulex* on the lee of a larger sediment clast that is not apparent on both the base and intermediate discharge map (highlighted with an arrow on Fig. 6).

CONCLUSION

CFD modelling in conjunction with a subclast scale DEM of the study reach, derived from Terrestrial Laser Scanning, has permitted detailed mapping of shear stress patterns across the flow regime. With increasing discharge, a complex pattern of hydraulic variation is revealed. Extensive grain to grain interaction promotes sediment sorting within small-scale gravel bedforms possibly forming pebble clusters which allow areas of local reduced energy refugia during elevated flows, and also affect sediment transport pathways over the bed of the river channel. At low flows, hydraulic diversity is maximised with greatest diversity over riffle areas. As discharge increases, refugia space is reduced as shear stress levels across the bed in both pools and riffles increase.

The role of bed shear stress upon benthic habitat availability has been far less studied in comparison to the role of other flow parameters such as velocity or Froude number. This study utilised existing laboratory data on the known shear stress thresholds for two species of macroinvertebrate, and mapped out areas of the study reach below these thresholds for three different discharges. It is acknowledged that limitations exist in the transferability of laboratory results to the field, and field verification of the results presented herein are needed. However, the approach presented in this paper clearly demonstrates the potential of CFD modelling for river management, facilitating simulation of different flow stages and investigation of the effects upon the spatial availability of habitat for different species. Further work with other hydraulic variables is underway that may provide more direct links to the hydraulic requirements of differing habitats, with the aim that the results may be linked to hydraulic preferences determined for the local biota so providing a management tool for sustaining a diverse fish and invertebrate community within riffle-pool ecosystems.

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