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Virtual velocity of tracers in a gravel-bed river using size-based competence duration

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ABSTRACT

Virtual velocity (V_i) of river gravels is commonly used to determine sediment transport rates and gravel dispersion dynamics. Virtual velocity is calculated from tracer gravel step-length data as the distance travelled divided by the duration of competence. However, no allowance is usually made for differences in competence duration according to grain size. In this investigation, V_i of gravel tracer clasts for the River Rede, Northumberland, UK, is calculated using a method that takes into consideration an approximation of size-based competence duration. Although scaled transport distance data compared favourably to past studies, it was the comparatively smaller clasts that tended to have lower V_i in comparison to coarser clasts, because of their longer competence duration, contrasting with previously published research. The key findings of the study serve as proof of concept and should be adopted in future studies that focus upon V_i estimation.

1. Introduction

Virtual velocity of river gravels is commonly used to determine sediment transport rates, knowing the depth and width of the active layer (Haschenburger and Church, 1998) and to investigate gravel dispersion dynamics over time (Haschenburger, 2011). Virtual velocity is calculated as the distance travelled divided by the duration of competence, rather than calendar time, as this is composed mainly of inactive periods. Grain size and tractive force are known to affect grain velocity (Drake et al., 1988; Wilcock, 1997) as (i) the displacement length of a tracer clast is known to increase absolutely and relatively for a given particle size for a given flow (Ferguson and Wathen, 1998; Lenzi, 2004), and (ii) displacement length and frequency increase with tractive force (Lenzi, 2004; Lammare et al., 2005). Past studies have demonstrated the dependence of virtual velocity upon excess stream power (Hassan and Church, 1992; Hassan et al., 1992; Haschenburger and Church, 1998; Haschenburger, 2011), relative grain size, and Shields stress (Ferguson and Wathen, 1998; Ferguson et al., 2002). Ferguson and Wathen (1998) also demonstrated that finer clasts have higher virtual velocity and that virtual velocity has a tendency to increase with grain Shields stress.

A key limitation with all previous studies that have estimated virtual velocity is that no allowance is made for possible differences in duration of competent flow for different grain sizes. In heterogeneous sediment mixtures, as found in gravel-bed rivers, the shear stress required for initial motion of particles may vary according to grain size. In streams that show evidence of size-selective transport (e.g., Ashworth and Ferguson, 1989; Lisle, 1995), progressively coarser sediments require a progressively greater shear stress for mobilisation. However, in some gravel-bed rivers, finer clasts can be sheltered from the flow in the lee of coarser clasts and can require the coarser clasts to be mobilised prior to the finer clasts. Grain protrusion of coarser clasts into the flow can also increase their likelihood of mobilisation in comparison to smaller clasts. This phenomenon is collectively known as 'equal mobility' (e.g., Klingeman and Emmett, 1982; Parker et al., 1982a,b; Andrews and Parker, 1987). In both situations, once clasts are mobilised, the finer clasts are likely to be transported for longer durations and hence farther than the coarser clasts. With this in mind, it is therefore surprising that size-based competence duration has not previously been considered in the calculation of virtual velocity.

This paper addresses this issue and presents an approach that considers variations in competence duration for different grain sizes of tracers. The approach is one-dimensional, considering longitudinal dispersion of tracer clasts and reach-average hydraulic and sedimentological properties. Data are presented on travel distance and tracer virtual velocity for a range of tracer size fractions seeded in a gravel-bed river, monitored on five occasions over a 13-month period.

2. Study site and methods

The field study was performed on the River Rede, a tributary of the River North Tyne, rising at 490 m A.O.D. in the Cheviot Hills in Northumberland, UK (Fig. 1A). The 200-m reach was 4.5 km from the source (55° 19.942′ N., 2° 26.457′ W.), where the river had a Strahler stream order of 4 and comprised a single-thread, gravel-bed channel with pool–riffle morphology, with a sinuosity of 1.82 (Fig. 1B). The bed gradient for the reach is 0.006. The grain size

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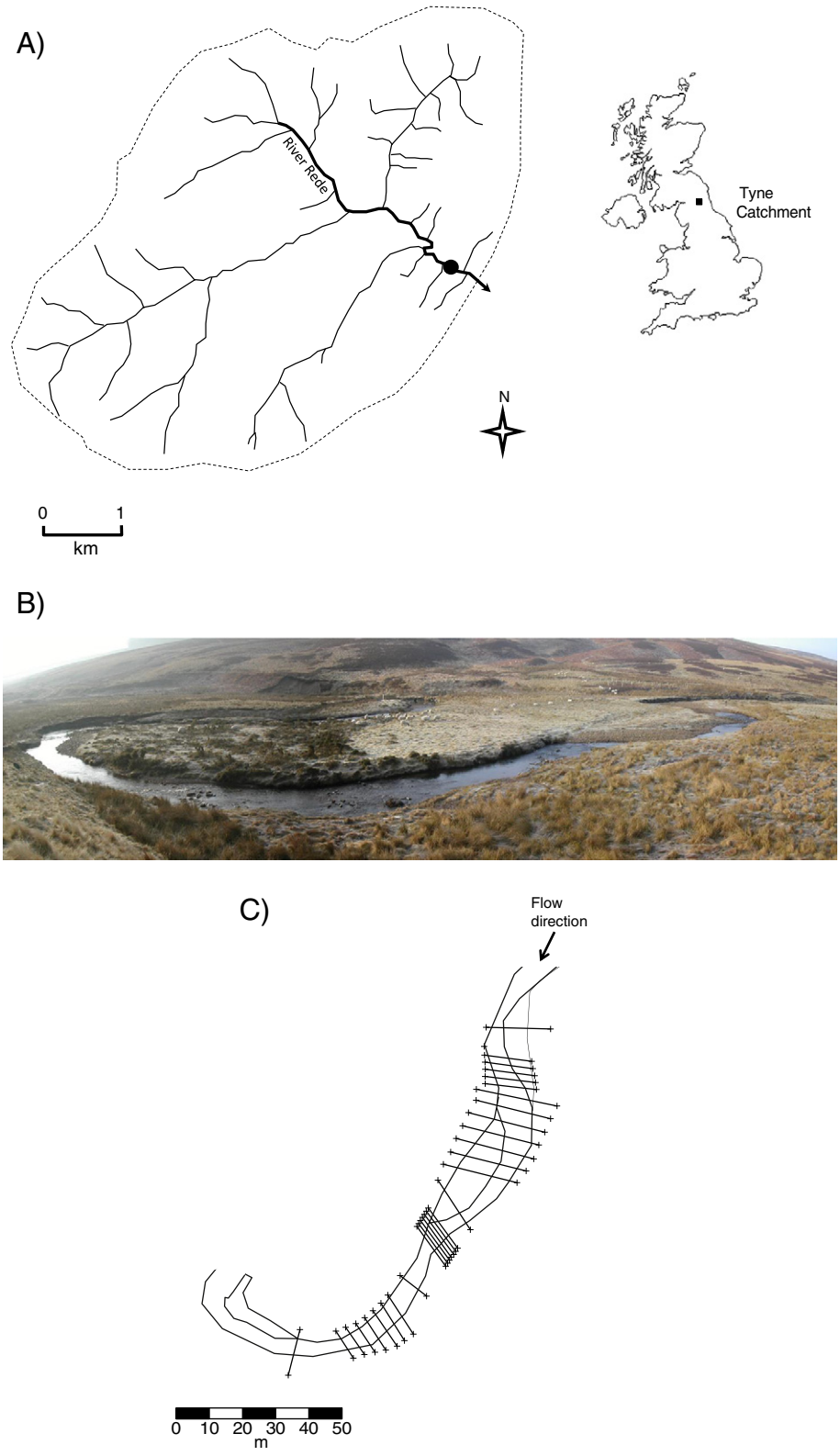

Fig. 1. Study site location. (A) Catchment map, (B) reach photograph, and (C) reach map indicating cross section positions.

distribution of the surface and subsurface sediments is presented in Fig. 2 and indicates surface and sub surface D_{50} values of 86 and 60 mm, respectively. The Rede drains a catchment of 18 km^2 in an area upstream of the site, with an impermeable geology of Carboniferous sandstones and shales overlain by peat and till. Flow within the Rede shows a strong seasonal signal with more numerous flood peaks between the months of October and April, driven by cyclonic rainfall, and occasional summer convective events. Mean monthly rainfall recorded nearby at Catcleugh Nursery since 1963 is 91.2 mm. Flow at the Rede study site responds rapidly to rainfall inputs