Controls on spatial and temporal variations in sand delivery to salmonid spawning riffles

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ABSTRACT

Fine sediment infiltration into gravel interstices is known to be detrimental to incubating salmonid embryos. Infiltration into spawning riffles can show large spatial variations at the scale of a morphological unit and over time, with significant implications for embryo survival. Furthermore some process-based infiltration studies, and incubation-to-emergence models assume that fines are delivered to redds via suspension rather than bedload. This process-based twelve-month study examined spatial patterns of predominantly sand infiltration into gravels in an upland trout stream, using infiltration baskets. An assessment of Rouse numbers for infiltrated sand indicated that it was transported predominantly as bedload at flow peaks. Clear temporal and spatial patterns existed; with highest rates of infiltration strongly associated with higher discharges (r^2=0.7, p<0.05). Seasonal variations in the delivery of different grain-sizes were also a feature; with enhanced contributions of 0.5-2 mm sediment, during elevated winter flows, and 0.125-0.5 mm sediment during spring and summer; the latter potentially harmful to the later stages of embryo incubation. Clear spatial patterns were also evident across riffles; with highest rates of infiltration tending to occur in areas of lower relative roughness; the areas competent to transport sand for longer periods. Incubation-to-emergence models should take into consideration spatial patterns of fine sediment dynamics at the pool-riffle scale, to improve prediction.

INTRODUCTION

The detrimental biological impacts of fine-grained sediment (<2 mm) infiltration into gravel interstitial voids are well documented (Wood and Armitage, 1997), where particular emphasis has been placed upon the impacts to salmonid embryos (Soulsby *et al*., 2001; Jensen *et al*., 2009; Kemp *et al*., 2011), and macroinvertebrate communities (Extence *et al*., 2013; Jones *et al*., 2011; Mathers *et al*., 2014). A variety of metrics have been used to describe fine sediment, ranging from clay (<0.004 mm) through to sands and granules up to 12.7 mm (Tappel and Bjornn, 1983; Greig *et al*., 2005). Different size classes are known to impact different stages of the embryonic part of the salmonid life-cycle. Ingress of silts and fine sands can block interstitial flow pathways, reducing permeability and intragravel velocity, starving embryos of dissolved oxygen, and failing to remove metabolic waste products; effectively poisoning the embryos (Chapman, 1988; Acornley and Sear, 1999; Greig *et al*., 2005; Kondolf *et al*., 2008). As finer grades (<0.063 mm) are known to preferentially infiltrate deeper through gravel voids (Einstein, 1968), this effect is most pronounced in the early stages of embryo survival when the embryos are immobile and are positioned deeper in the redd. In addition to reduced permeability and intragravel velocity, Greig *et al*. (2005a,b) have shown that clay-sized sediment can reduce dissolved oxygen diffusion across embryo membranes. In addition to the physical effects of the interstitial fine sediment, the organic component has also been shown to reduce dissolved oxygen availability to embryos through its decomposition (Greig *et al*., 2005a,b, Sear *et al*., 2014), and block interstitial pathways through biofilm formation (Petticrew and Arocena, 2003). The later mobile stage of embryonic development, when the embryo develops into an alevin, is susceptible to coarser sands and granules, that have a tendency to block the near surface voids (Beschta and Jackson, 1979); creating a physical blockage to alevin escape from the redd.

Several studies have developed models to predict spawning habitat quality, some of which rely on developing predictive relationships between fine sediment concentrations (<2 mm, or <1 mm; Jensen *et al*., 2009; Julien and Bergeron, 2006; Heywood and Walling, 2007; Kemp *et al.,* 2011, Sear *et al*., 2014) and embryo survival. However, survival can also be predicted from infiltration rates (Lisle and Lewis, 1992). Improved understanding of the controls on infiltration of interstitial fines may potentially offer improvements to such models.

Fine sediment management issues

Fine sediment delivery to salmonid spawning habitat is known to be influenced by catchment-scale processes and management. For example, a number of studies in the US dating back to the 1960s have shown the deleterious impacts of timber harvesting upon increased fine sediment loadings in fish spawning gravels (Hall and Lantz, 1969; Duncan and Ward, 1985). In the UK fine sediments have been recognized as a contaminant due to their association with heavy metals (Petts *et al*., 1989), nutrients such as phosphorous, pesticides and persistant organic pollutants (Walling and Collins, 2016). Changes in gravel quality (Kondolf *et al*., 2008) have also been associated with flow regulation (Petts, 1984; Sear, 1992; Milan, 1994), and low flows (Milan and Petts, 1998). Many upland catchments in the UK are dominated by moorland-peatland areas, often with modified drainage (grips). Gripping has the effect of lowering the water table, has been shown to increase flood peaks (Gunn and Walker, 2000), and can also be dominant sources of fine sediment (Holden *et al*., 2007). Rotational patch burning, can also increase sediment and organic matter delivery to streams (Tallis, 1987), with consequences for instream biota (Brown *et al*., 2014). Furthermore, over the last 20 years in the UK there have been particular concerns regarding agricultural diffuse pollution, related to intensification and changes in farming practice (Theurer *et al*., 1998; Collins and Anthony, 2008; Stopps *et al.,* 2012). The problem of fine sediment pollution in river catchments in Europe is currently being addressed through the Water Framework and Freshwater Fish and Habitats Directives (European Parliament, 2000).

Infiltration controls

Infiltration of fines into gravel-beds has been demonstrated by a number of laboratory (Einstein, 1968; Beschta and Jackson, 1979; Carling, 1984; Schälchli, 1992; 1995; Allan and Frostick, 1999) and field studies (Frostick *et al*., 1984; Sear, 1993; Acornley and Sear, 1999; Zimmerman and Lapointe, 2005; Mather and Wood, 2016). Two different mechanisms of infiltration have been reported, governed by the size of the infiltrating fines and the size and shape of the receiving gravel framework voids (Meehan and Swanston, 1977; Frostick *et al*., 1984), and hydraulic conditions (Beschta and Jackson, 1979; Allan and Frostick, 1999). Over stable openwork gravel it appears that finer grades (<0.063 mm) infiltrate deeper and fill voids the base upwards (Einstein, 1968). Conversely, coarser grades (sands and fine gravel) may form near-surface seals, bridging the framework voids and preventing further ingress (Beschta and Jackson, 1979).

A number of flume-based investigations have drawn links between hydraulics and infiltration dynamics (Beschta and Jackson, 1979; Schälchli, 1992; 1995; Allan and Frostick, 1999). Over stable beds, Beschta and Jackson (1979) found greater depths of fine sediment intrusion at higher shear stresses (τ_o). At τ_o around the threshold for gravel framework mobilisation, dilation of framework particles can occur; opening up previously blocked void spaces. Dilation causes a change in pressure differentials between the void spaces and induces the 'Venturi' effect, encouraging deeper penetration of fines (Allan and Frostick, 1999). At even greater τ_o, total flushing or desiltation of interstitial framework voids may occur (Schächli 1992; 1995).

Spatial patterns of infiltration

A number of field studies have also shown spatial variability in infiltration across morphological units (Table 1), and have linked this to velocity patterns. Knowledge of the spatial patterns of fine sediment infiltration are important because salmonids have been reported either to favour riffle heads or tails for spawning sites, as these areas have been reported to have enhanced downwelling or upwelling flow respectively (Briggs, 1953; Hoopes, 1972, Hunter, 1973; Crisp and Carling, 1989; Tonina and Buffington, 2009). Carling and McCahon's (1987) experiments on the upland Great Eggleshope Beck, UK, demonstrated that the infiltration rate of fines increased linearly from the outside of a river bend toward the inside. Maturana *et al's* (2014) modelling study also suggests that fine sediment can be steered away from pools; tending to infiltrate point bars and shielding downstream riffle spawning habitat from sedimentation. Variations in fine sediment infiltration between pool-riffle units has also been documented (Carling and McCahon, 1987); for a 10% increment in stream width, the infiltration rate increased by $0.017\,\mathrm{kgm^{-2}day^{-1}}$ in the pool and $0.015\,\mathrm{kgm^{-2}day^{-1}}$ over the riffle. The 2-4 mm fraction was found to show enhanced infiltration rates in high velocity zones in the pool and a number of other high velocity threads across shallower areas. Welton (1980) has also shown spatial variation for Tadnoll Brook, UK, a lowland chalk stream, with $5\,\mathrm{kgm^{-2}day^{-1}}$ deposited along the thalweg and up to $70\,\mathrm{kgm^{-2}day^{-1}}$ deposited along the channel margins. Fines deposited in this low-energy stream were probably dominated by grades transported in suspension rather than bedload, showing enhanced deposition along the low velocity channel margins.

Study goals

This study seeks to further quantify the effects of hydraulics and local morphology upon fine sediment infiltration dynamics, with particular emphasis given to the sand load. Improved information is needed concerning the physical controls on infiltration rate, to improve the predictive capabilities of salmonid embryo incubation-to-emergence models. Furthermore, knowledge of hydraulic controls on fine sediment infiltration may aid environmental flow design in regulated rivers (Kondolf and Wilcock, 1996), and a better understanding of the morphological controls on infiltration may assist future design of spawning riffles in river restoration projects (Pasternack and Brown, 2013; Schwartz *et al.*, 2015). This study aims to identify

a) spatial variations in the quantity and grain-size of sand infiltrating salmonid spawning habitat over a full hydrological year,

b) the effect of local hydraulics and morphology on fine sediment infiltration.

STUDY SITE

The study was conducted on a 250 m reach of the River Rede, a headwater tributary to the river North Tyne in Northumberland, UK (Figure 1). The River Rede at this location, is unregulated and provides habitat for brown trout (*Salmo trutta L.*), and supports populations of two species that are of international conservation significance; brook lamprey (*Lampetra planeri L.*) and bullhead (*Cottus Gobbio L.*). Both species are listed under Annex II of the Habitats and Species Directive (92/43/EEC). Sea trout (migratory form of *Salmo trutta L.*) and Atlantic salmon (*Salmo salar L.*) are supported downstream of the study site, in the regulated Rede below Catcleugh reservoir, however their migration to what would have been their natural spawning sites is impeded. The study site has a Strahler stream order of 4 and is a single-thread, sinuous gravel-bed channel with well developed pool-riffle morphology (Milan *et al.,* 2001; Heritage and Milan, 2004). Brown trout select riffles for spawning on the Rede, with redds tending to be located in patches of finer, movable, gravel. Although small-scale redd morphology was evident, there was no evidence of larger-scale changes to bed morphology (*sensu* Hassan *et al.*, 2008). The Rede drains a moorland catchment of 18 km^2 upstream of the site, devoid of trees, with an impermeable geology of Carboniferous sandstones and shales overlain by peat and till. The mean annual runoff is 1026 mm and the flow regime is flashy. Bankfull discharge recorded at the study reach (GS, Figure 1b), and supported by post-flood trash line observations, is approximately 9 m^{3}s^{-1}. Bankfull channel width is between 9 and 18 m and the average bankfull channel depth is 0.7 m. The mean

gradient of the bed throughout the reach is 0.006 m/m. Suspended sediment concentrations are typically below 50 mgl^{-1} for flood peaks (Milan, 2000), low in comparison to other UK rivers (Walling and Webb, 1987). Fine sediments are largely sourced from till at eroding bluffs in slope-channel coupling zones and from remobilized bed material; mainly from point bars (Milan and Large, 2014). Some modification to land drainage is evident in the headwaters, in the form of grips cut into the peat, however their sparse distribution is unlikely to play a significant role in altering catchment hydrology or sediment delivery.   In addition, there was no evidence of moorland burning, a common form of upland management, during the period if the investigation. Sheep grazing is the dominant land-use in the catchment upstream of the study site. Results presented in this paper focus upon a single 110 m length pool-riffle unit towards the head of the reach (Figure 1b, c).

METHODS

Baseline sediment characteristics

Surface sediments were sampled using a modified grid-by-number method (Wolman, 1954), whereby the intermediate axis of 450 clasts were sampled from each riffle and 100 clasts from each of the pools. In order to characterise the proportion and grain-size characteristics of <2 mm sediment material held within the sub-surface, sediments were sampled using freeze-coring (McNeil and Ahnell, 1960; Petts *et al*., 1989; Milan, 1996). Freeze-coring has the advantage over other sub-aqueous sediment sampling techniques in that all size fractions can be retrieved *in situ*, without washout of the finer fractions, and frozen cores also permit variations in vertical structure to be assessed (Thoms, 1992; Milan *et al*., 1999). A stainless steel tube, closed at one end was inserted into the substrate up to a depth of 60 cm, using a sledge hammer. Between 5 and 10 litres of liquid Nitrogen was then poured down the tube over a 15-20 minute period, freezing the interstitial water. The sediment freezes to the outside of the pipe, and a columnar core of frozen sediment may be removed from the bed using winching apparatus. Nine 60 cm cores per riffle and 5 were taken from each pool, satisfying Thoms's (1992) freeze-core sampling protocol, with a total dry sample weight of 47 kg (mean core weight = 15 kg, standard deviation = 7.2 kg). Cores were then split into 15 cm sections, with data for the near surface 15 cm (that comparable with the basket trap depths) being presented in this study, and more detailed data presented elsewhere (Milan *et al*., 1999; Milan 2000). The total dry sample weight for the near surface 15 cm of sediment was 132 kg,

sufficient to represent grain-sizes up to 170 mm using Church *et al.*'s (1987) most relaxed 5% bulk sampling criterion.

Basket trapping

A novel cell-based sampling strategy was employed to capture spatial variability in processes operating within riffles, specifically to identify differences in fine sediment infiltration between riffle heads, crests and tails, and right, mid and left sides of the channel, and differences between riffles and pools. Three riffles were each split up into nine cells, and the intervening pools treated as a single cell (Figure 1b, c). Basket traps similar to those used by Lisle and Eads (1992) and Sear (1993) were emplaced in the center of each cell, during low flow conditions. Each basket was constructed from a galvanised zinc wire 1cm mesh, and permitted intragravel flow. At the base of each basket a collapsible bag with a wire collar was inserted (Figure 2). Each basket was filled with a locally-derived matrix-free gravel framework and armour particles were placed on top of the trap. In effect this simulates the initial redd condition immediately after construction by the female fish, which has been reported to reduce the fine sediment content (Kondolf *et al.*, 1993). Traps located on the riffles were operational for the full duration of the study and were emptied on fourteen occasions following flood events of varying magnitudes over a year from (18th January 1996 to 11th March 1997). Traps located in the pools were not operational until December 1996. Unfortunately, no samples could be retrieved from the trap situated in the deepest of the pools in the study reach (pool 1). This was initially due to difficulty in accessing the trap during high winter flow conditions, and the subsequent loss of the trap during a flood. Following removal of the armour layer, leads attached to the collar permitted the mixture of infiltrated fines and gravel framework to be removed, leaving the wire basket in the river bed. The fines were separated from the framework material whilst in the field, by washing the fines through <2 mm sieve into a bucket. The collapsible bag was replaced at the bottom of each trap, and then the clean framework gravel and armour layer replaced, ready for the next flood event. The baskets did not provide information on vertical patterns of infiltration.

Grain-size analysis

Sediment samples were oven dried at 40 °C prior to sieve analysis. Freeze-core samples were dry sieved through 63, 37.5, 20, 6.3 and 2 mm aperture sieves, following other freeze-core sampling work undertaken on upland streams in the UK by the author (Milan *et al.*, 2000). For the <2 mm material retrieved from freeze-coring and basket sampling, 100 g sub-samples of the were wet sieved down to 0.063 mm. Sub 0.063 mm from freeze-cores were analysed using laser diffraction. This paper focuses upon spatial and temporal infiltration rates of the sand fraction based upon the weight of infiltration material per unit area, per epoch (time period between sampling), and the association between infiltration rate and shear stress.

Derivation of trap-specific boundary shear stress

Boundary shear stress τ_o was derived from the St Venant equation,

$$\tau_o = \rho g R_h \left(s - \frac{\partial d}{\partial x} - \frac{u}{g}\frac{\partial u}{\partial x} - \frac{1}{g}\frac{\partial u}{\partial t} \right)$$

(1)

where ρ is the fluid density, g is gravitational acceleration, R_h is the hydraulic radius, s is the energy gradient derived from water surface slope, x is longitudinal distance, t is time and u is cross-section average velocity $\left(\frac{Q}{A} \right)$, where Q is discharge and A is the wetted cross-section area. Water depth (d) is commonly substituted for R_h and is an appropriate approximation in channels with high width:depth ratios. This data was obtained from a tachometric survey of the bed morphology at cross-sections running across the line of each trap and from rating curves of the water surface relative to each section for flows between 0.1 and 8.6 m^3s^{-1} (Milan, 2000). Discharge was recorded at a gauging station located at the study location (see GS, Figure 1b). Subtraction of water surface elevation from the local bed elevation at each trap location gave d.

The unsteady term $\left(\frac{1}{g}\frac{\partial u}{\partial t} \right)$ in Eq. (1) can be neglected as steady-state shear stress, rather than time-varying shear stress over the range of the natural hydrograph, is being estimated.

Milan (2001) have demonstrated the non-uniform flow term $\left(\dfrac{\partial d}{\partial x} - \dfrac{u}{g}\dfrac{\partial u}{\partial x} \right)$ to be negligible

over the reach for the full range of flows considered. Their analysis established the ratio between propulsive and resistive forces (β) over the flow regime, at length scales equivalent to those of the riffles and pools in the reach (between 6 and 36 m). Strongest non-uniform effects were found at a discharge of $2\,\mathrm{m^3s^{-1}}$. At this flow, strong accelerative effects were shown between pool 2 and riffle 2, and pool 3 and riffle 3, where β deviations from unity of 0.19 and 0.49 were found. Less strong decelerative effects were shown between riffle 2 and pool 3 where there was a deviation of 0.2 from unity. The only other notable deviation is shown at a discharge of $7.26\,\mathrm{m^3s^{-1}}$ between pool 2 and riffle 2 where flow deceleration results in a β value of 0.31. Although Milan *et al.* (2001) conclude that it appeared reasonable to approximate the flow as being uniform, it is recognized that some uncertainty must still exist in the application of the slope-depth product to produce local τ_o values.

Sediment transport mechanism

The Rouse number P (Rouse, 1937) for sediments entering the traps over the entire study period was ascertained to identify the predominant mode of transport of sand delivered to the basket traps, derived from

$$P = \frac{\omega_s}{\kappa u_*}$$

(2)

where is ω_s settling velocity, κ is the von Karman constant, $\kappa = 0.4$, and u_* is the shear velocity, calculated as

$$u_* = \sqrt{\frac{\tau_o}{\rho}}$$

(3)

Trap-specific τ_o for hydrograph peaks in between sampling are used in Eq. (3) above. Settling velocity was calculated using the drag law based on Dietrich (1982) and Ferguson and Church (2006). Their equation is

$$\omega_s = \frac{RgD^2}{C_1\nu + \left(0.75C_2RgD^3\right)^{0.5}}$$

(4)

where R is submerged specific gravity $\left(\frac{\rho_s - \rho}{\rho}\right)$, where ρ_s is sediment density, D is the median sediment diameter, ν is kinematic viscosity of water, and C_1 and C_2 are constants related to the shape and smoothness of natural grains (C_1=18; C_2 1.0). The results of this analysis are shown for each of the riffles in Figure 3, where the mode of transport at flood peaks mainly appears to be split between bedload and the suspended load/bedload transition. It is likely that much of the sediment transported as suspended load and some of the washload enters the traps on the falling limb of the hydrograph when trap-specific τ_o is lower.

Local morphological control

Relative roughness was used to assess the influence of local bed morphology upon fine sediment infiltration, and was calculated by fitting a 'datum' line that passed through the lowest pool troughs (pool 1 and 4) in the study reach (Figure 4), with a slope equivalent to that of a regression line fitted to the bed long-profile. The elevation difference between the bed and the datum line at the position of each trap (k_f) was then divided by local flow depth (d) estimated for each flow peak in each of the 14-epochs, derived from rating curves (Milan, 2000). Assuming that morphological change was negligible over the period of a single flood event, this provided a measure of the protrusion of the bed morphology into the flow at each trap location, over the flow regime; with greater relative roughness exhibited at lower discharges (Sargent, 1979). In general terms bars and riffles have greater relative roughness in comparison to pools and glides.

RESULTS

Boundary shear stress

Boundary shear stress for riffle heads, crests, tails and for pools for a range of discharges from baseflow up to bankfull discharge are shown in the box and whisker plots in Figure 5. Overall there was a gradual increase in overall τ_o with discharge for all morphological units.

Boundary shear stress data suggests greater sediment transport potential towards riffle tails and in pools; a) there was a clear tendency for a gradual increase in τ_o from the riffle head towards the riffle tail (at flows of 0.1 m^{3}s^{-1}, 2 m^{3}s^{-1}, and 7.26 m^{3}s^{-1}), although this effect was less evident at the highest discharge, and b) pools show higher τ_o compared with riffle heads at lower discharges (0.1 m^{3}s^{-1}, 2 m^{3}s^{-1}, and 5.44 m^{3}s^{-1}).

Baseline sediment character

Summary statistics for the armour layer median grain-size (D_{50}) are shown in Table 2. A notable feature was the coarse nature of the pools (D_{50}=109 mm) in comparison to the riffles (D_{50}=83 mm), thought to be due to the hydraulic characteristics experienced over the flow regime (Milan *et al.,* 2001), and the relative pathways of both coarse (Milan *et al*., 2002; Milan, 2013) and fine sediment (Milan and Large, 2014). Riffle C was the coarsest riffle, possibly reflecting greater hydraulic energy compared to the other two riffles.

Summary statistics for the sub-surface sediments are shown in Table 3. There was less difference in the sub-surface grain-size characteristics between riffles and pools overall, with riffles slightly finer (D_{50}=45 mm) than the pools (D_{50}=48 mm). Although <2 mm concentrations were similar between pools and riffles, with just over 11%, this is likely to be influenced by an outlier (pool 1). There was more variability between the four pools sampled, compared to the riffles; pool 1 was much coarser and held much lower concentrations of fines in comparison to the other three pools.

Temporal patterns of infiltration

The time series for overall infiltration rates are demonstrated in Figure 6b, alongside the discharge information (Figure 6a) for the same period (15th March 1996 to 11th March 1997). Overall individual basket infiltration rates (for riffles) ranged between 0.0013 and 1.527 kgm^{-2}day^{-1}. The limited data for pools suggested a much lower infiltration rate on average in comparison to riffles, with the exception of Pool 3. The highest rate of infiltration was found in traps at Riffle B after a flow of 7.12 m^{3}s^{-1}. The mean temporal rate of infiltration showed a similar pattern between riffles however slight variations were encountered. During the first

half of the investigation (pre-October 1996) traps at Riffle B appeared to collect greater concentrations of fines coinciding with floods of a lower magnitude ($<5\,m^3s^{-1}$) than those recorded later on in the study. During the later period it is the traps located at Riffle C which appear to collect slightly more fines than the other two riffles, a factor particularly evident after discharges greater than $5m^3s^{-1}$. In the early part of the study when flows recorded were $<5\,m^3s^{-1}$ (pre-October 1996) these traps had collected the lowest concentrations of fines. Overall, concentrations of fines collected in the traps during the later part of the study pre-October 1996) are generally greater than those during the earlier part, which appears to be a response to the higher flows experienced during the same period.

Cross-riffle variation

Cross-riffle data showed a similar temporal pattern for the between-riffle data (Figure 6c), with low rates generally below $0.1\,kgm^{-2}day^{-1}$, in the early part of the study, and with peaks of up to $0.5\,kgm^{-2}day^{-1}$, shown later. Although all locations (lb, mid, rb) showed similar patterns in infiltration rates over the study period, significant differences in rates were observed over the study period (one-way ANOVA: $F_{2,\,278}=6.71$, $p<0.01$). Traps located towards the left side of the channel consistently recorded the lowest concentrations of fines, indicating that this area was not a major zone for fine bedload routing (Tukey multiple comparisons test: lb versus mid, $p<0.05$, lb versus rb, $p<0.05$). Traps located on the right and middle of the channel showed very similar values between October 1996 and January 1997 (Tukey multiple comparisons test: rb versus mid, $p>0.05$).

Down-riffle variation

The time-series for down-riffle variation is demonstrated in Figure 6d. Lowest infiltration rates once again featured in the early part of the study, whilst highest rates occurred during the series of floods between October 1996 and January 1997, with the peak occurring after a flood of $7.12\,m^3s^{-1}$. Although differences between infiltration rates between riffle heads, crests and tails were not found to be statistically significant (one-way ANOVA: $F_{2,\,278}=1.47$, $p>0.05$), spatial patterns were evident; during the early part of the study (pre-October 1996) the head and crest of the riffles appeared to collect similar amounts of fines. The tail of the riffles consistently had the highest infiltration rates, possibly reflecting increased delivery to this area related to high τ_o at low flow, relative to other parts of the riffle (Figure 5). This

pattern appeared to be lost after higher magnitude flows between October 1996 and January 1997, only to re-appear once more after two lower flows (February 1997). It was the traps located at the crest of the riffle, that exhibited the highest infiltration rates after larger floods, whereas the head of the riffle had a tendency to record the lowest rates at these flows. Intermediate and low discharges however appeared to encourage high infiltration at the tail of a riffle.

Pool-riffle variation

Pools 2 and 4 (see Figure 6b) consistently showed less infiltration of fines in comparison to the riffles up- and downstream. Pool 2 tended to exhibit the lowest infiltration rates, whilst Pool 3 exhibited the highest, and on two occasions this pool collected more fines than the adjacent riffles. Notably, Pool 3 was not as deep as the other two pools, and was situated on a straight section of channel. Fines had to be fed through this pool, whereas on meandering sections, fines could be fed over bar surfaces instead of through the pool trough.

Overall there was a tendency for greatest rates of infiltration to be associated with the higher flow events; particularly during the 1996/97 winter. Conversely, lowest infiltration rates were associated with the summer low flow period. This association is shown more clearly in Figure 7, where infiltration rate is plotted against discharge. When the mean data is considered, a strong dependence between total deposition and discharge was shown (r^2 =0.7, p<0.01); a finding also noted by Maturana *et al*. (2014). Extrapolation of the regression equation suggested that fine bedload movement was initiated at discharges in excess of 0.7 m^3s^{-1}. Error bars, showing 25th and 75th percentiles, were indicative of significant variability; with the greatest variability evident at the highest discharges. The variability indicated that local controls on fine sediment infiltration were important.

Grain-size character of infiltrating fines

The grain size distribution for fine sediments infiltrating the traps is shown in the histogram in Figure 8. Ninety percent of the material infiltrating the traps was sand (>0.063 mm), with dominant modes in the 0.063-0.125 mm, and 0.25-0.5 mm size range.

Temporal variations in down-riffle median grain size for sand (0.063-2 mm) are shown in Figure 9b. Coarser sediments were found to infiltrate traps in response to the higher magnitude flood events experienced in the later half of the study. Significant differences were found in the grain-sizes of material entering riffle head, crest and tail traps over the study period (one-way ANOVA: $F_{2, 225}$=4.27, p<0.05). There was a tendency for either the crest (and less frequently the tail) of the riffles to collect coarser sediments (Tukey multiple comparisons test: head versus tail, p<0.05), with the head of the riffle consistently collected the finest sediments.

Temporal variations in cross-channel grain-size characteristics for sand infiltrating right-bank (rb), channel center (mid) and left-bank (lb) traps are shown in Figure 9c. There was a trend for retrieval of coarser material in the later part of the study (post-October 1996), which appeared to reflect higher magnitude flows experienced during this period. Overall there was a significant difference in the grain-size of material infiltration traps across the channel (one-way ANOVA: $F_{2, 243}$=14.32, p<0.01; Tukey multiple comparisons test: lb versus mid, p<0.01, rb versus mid, p<0.01), with significantly coarser material accumulating in traps located in the center of the channel. Left-bank traps tended to collect the finest material up until October 1996, whereas the right-bank traps collected the finest material from late November 1996 through until mid January 1997.

Temporal enrichment

The ratio of each grain-size class in the bedload (0.125-2 mm) deposited into the traps, compared with the background levels present in the substrate, retrieved from freeze-cores, is shown as a time-series plot alongside the discharge hydrograph for the study period (Figure 10). The enrichment index (p_i/f_i), where p_i and f_i are the proportions of each size fraction in the sub-surface and infiltrating fines respectively, showed clear temporal and size-dependent patterns. Coarser sands (both the 1-2 mm and 0.5-1 mm categories) had a tendency to be enriched during periods of higher discharge. Conversely, lowest concentrations of these size classes were found during low flow periods, particularly over the summer months. The finer sand-size categories considered (0.25-0.5 and 0.125-0.25 mm), showed the opposite pattern; tending to be enriched during low flow periods and depleted during winter peaks flows.

Dependence of infiltration upon shear stress

The overall relationship between infiltration of <2 mm material and local τ_o for riffles A, B, and C, and the pools are shown in Figures 11. Sub-2 mm loadings tended to show a clear association with τ_o, although there was considerable scatter caused by a number of factors. Firstly, variable local hydraulic conditions in the vicinity of each trap could result in local variation in sediment transport. Secondly, variation in local sedimentary structure within and between riffles may also be responsible for limiting supply and may alter local hydraulic conditions. Thirdly, the permeable nature of the traps may have allowed some post-depositional intragravel modification of material before it was sampled. The range of τ_o which mobilised fine bedload was wider for the Riffle A and C traps in comparison to those situated on Riffle B, where τ_o ranged between 20-70 Nm^{-2}. Infiltration of fine bedload in Riffle A traps appeared to show the strongest dependence upon τ_o, whereas the dependence of infiltration rate upon τ_o is not as strong for Riffle B and C (Table IV). The poor relationship shown for Riffle C data is partly a reflection of small quantities of infiltration of fine bedload below 10 $N\,m^{-2}$, which is not a feature shown at traps on the other riffles. Although fewer data were available, a clear dependence of infiltration rate upon shear stress was also exhibited for the pools, over a shear stress range of 20-200 Nm^{-2}.

Rating relations for individual riffle traps for <2 mm material are shown in Table IV and for riffle A traps only in Figure 12. Less scatter was evident for individual traps, as fewer data are being considered (14 data points; one for each epoch). For the traps situated at the head of Riffle A (Figure 12a) low rates of infiltration were found at τ_o below 50 Nm^{-2}, whereas much greater rates were found for τ_o >50 Nm^{-2}. At the riffle head, trap A3 had a tendency to collect higher concentrations of fines for a given τ_o. This may have been due to the proximity of the trap to the left-bank, immediately below a point bar; on the Rede bars appeared to act as sources of fines rather than pools, which are clean of fines at base-flow. Data for the crest of Riffle A are shown in Figure 12b, where highest infiltration rates were found at $\tau_o > 60\,Nm^{-2}$, and rating relations were all very similar (Table IV). The channel center trap A5 tended to show the greatest infiltration particularly at higher τ_o. Data for the tail of Riffle A, shown in Figure 12c, demonstrated that most transport was triggered at slightly greater τ_o than those

experienced further up-riffle, at around $100 \, \mathrm{Nm^{-2}}$. The highest infiltration rates for a given τ_o tended to be located at trap A8 in the channel center. Conversely trap A9 recorded the lowest rates of infiltration for a given τ_o. Trap A9 was situated in an area of high τ_o in the order of $90 \, \mathrm{Nm^{-2}}$. It is possible that some of the finest fractions, which had been deposited in the trap, may have been subsequently flushed out by lower magnitude flows before the trap was sampled. For most traps there was a strong relationship between τ_o and infiltration of fines. However some traps, particularly those located on Riffle C, did not display a strong relationship between these two variables (Table IV). Infiltration in these traps must therefore depend upon other variables such as relative roughness.

Dependence of infiltration upon relative roughness

Riffle heads, margins and bar tops had higher relative roughness than riffle tails, centres and pools. Areas of low relative roughness are likely to be the preferred zones of sediment routing as these areas are competent for longer periods of time and experience greater tractive force compared to zones of high relative roughness. Therefore it may be expected that riffle heads and margins, with greater relative roughness, would tend to have lower infiltration rates in comparison to riffle centres and tails, with lower relative roughness (Figures 6c and d). The plot of relative roughness versus infiltration in Figure 13 provides the expected pattern, with a negative exponential relationship between relative roughness and infiltration; with least infiltration in traps situated on the higher relative roughness elements, and highest infiltration on the low relative roughness areas. The higher rates of infiltration in these areas reflect enhanced delivery of material; greater length of time where flows are competent enough to transport material to the trap, and may also reflect enhanced downward hydraulic forces. The bed surface in lower elevation areas always appeared clear of fines at low flow, indicating the efficient flushing of material on the falling limb of the hydrograph. This flush-out of fines however did not appear to influence the quantity of material stored in the traps, although there was a suggestion that it may influence its grain-size.

DISCUSSION

The infiltration rates of fine sediments measured for the River Rede are comparable to some previous investigations (Table I), for example those measured by Sear (1992a) in the adjacent North Tyne catchment. Infiltration rates tended to be higher than some studies on chalk streams (Acornley and Sear, 1999; Welton, 1980), and other lowland streams (Thoms, 1987), where most infiltrated fines are derived from suspended sediments rather than bedload. Conversely, infiltration was not as high as those reported on some other high energy streams (Zimmerman and Lapointe, 2005; Schindler Wildhaber *et al.*, 2012)

Seasonal trends

The clear association between infiltration rates and discharge, with greatest rates of infiltration being associated with high winter flows is a feature supported by other investigations (Maturana *et al.*, 2014). Higher winter discharges have the competence to transport greater quantities of bedload, however the supply of sand is also a key factor. The main sources of fines on the Rede are from erosion scars/bluffs in slope-channel coupling zones, in-channel supply, and run-off from surrounding moorland. Low and intermediate magnitude ($<3\,m^3s^{-1}$) events are likely to be responsible for re-working in-channel sources, such as those deposited on bar surfaces, or on the lee of large clasts, and introducing finer grades from run-off into the channel. Larger events are more likely to introduce coarser fines derived from slope-channel coupling zones. During the winter months these areas become much more active as erosion bluffs become saturated with rainwater, and experience the effects of freeze-thaw action. In addition, flood-driven disturbance of the bed structure (armour) results in more frequent release of sand held in gravel voids during this period. The main in-channel source area for fine bedload on the Rede is likely to be point bars, where fines are either stored as interstitial deposits or as fine sediment drapes on the lee side of the bars. Point bars tend not to be armoured, and thus the sediment mixture is easily entrained during floods. This finding is supported by the modelling work of Maturana *et al.* (2014) and sand tracing work (Milan and Large, 2014) conducted at the Rede site that showed surficial deposits of sand were found on bars and riffle margins, but not pool troughs, contrasting with other studies that have shown pools to act as fine sediment stores during low flow (Lisle and Hilton, 1999).

Clear seasonal trends appeared to exist in the proportions of different size classes delivered to basket traps. The enrichment effect of coarser material at high flow may be explained through a number of factors including exhaustion of finer grades, enhanced transport and delivery of coarser grades in areas of higher τ_o, post-depositional flush-out of finer grades (Schächli, 1992; 1995), and dilution effects. In addition, some of the finer grades may become washload during elevated flows and pass through the reach without infiltrating traps. A seasonal change in sediment source within the catchment may also explain the change in grain-size of sediments accumulating in traps. Similar enrichment and exhaustion effects have also been reported previously for a nival discharge regime (Church *et al.*, 1991).

The finest fractions of the sand bedload (<0.5 mm), harmful to the early embryonic stages of the salmonid life-cycle, are more prevalent following lower energy discharge events and reduced flood frequency (during the summer), whereas coarser sand (0.5-2 mm), that can prevent alevin escape through blockage of interstitial voids, have a tendency to be delivered in response to higher magnitude and frequency flows during the winter. The timing of embryo incubation, October-February for brown trout in upland streams in the UK (Crisp and LeCren, 1970), relative to the nature of the hydrograph and sediment supply is therefore a critical determinant in the success of embryo incubation.

Spatial patterns of infiltration

Spatial variations in τ_o over the flow regime result in significant spatial variability in fine sediment infiltration at the scale of a single riffle, implying significant variability in potential survival rates for developing salmonid embryos. Highest infiltration tended to occur in the traps situated on areas of low relative roughness on the riffles (Figure 13), although one pool situated on a straight section of channel registered higher values occasionally (Figure 6). Although median shear stresses appeared to equalize between morphological units at high flow, some of the lower elevation areas exhibited the highest tractive force during periods of high flow, indicated by the whiskers on Figure 5e; hence the high infiltration reflected the high rates of delivery to traps located in these areas.

Maximum rates of infiltration tended to be found in the channel center along the line of the thalweg (Figure 6c), supporting the findings of Frostick *et al.* (1984) and Thoms (1987). There were significant differences in the amount of fine sediment which infiltrated the

channel margin traps; the right-bank sometimes showed greatest infiltration and left-bank consistently showed the lowest rate of infiltration. Fines avoided settling in pools situated on channel bends (Pools 2 and 4, Figure 6), however Pool 3, situated on a straight section of channel recorded greater infiltration in comparison to the adjacent riffles, indicating that fines were routed through this pool.

Considering down-riffle variation, lowest rates of infiltration were found at riffle heads, with a gradual increase towards the riffle tail (Figure 6d). Similar findings were found by Mathers and Wood (2016), however in contrast, Thoms (1987) report greatest infiltration at riffle heads. Riffle tails also collected the coarsest material on the Rede, further contrasting with Thoms (1987). Greater infiltration at the riffle tails suggests that these zones are competent for longer durations. Preferential infiltration of coarser sands at riffle tails indicates that this zone is more susceptible to near-surface void blockage, detrimental to the later stages of embryo development. Riffle tail τ_o values are greater than head and crest τ_o for most of the flow range apart from peak flows (Figure 13), resulting in these areas maintaining high transport rates and sediment delivery. Greater τ_o at riffle tails and centers at all but the highest flows (Figure 13) may transport coarser sand for longer durations compared with other areas of the riffle. Post-depositional modification of infiltrated fines may also occur in zones of high τ_o, flushing out silt and fine sand from near-surface interstices within traps prior to sampling (Schächli, 1995).

Over a stable bed, pool-riffle morphology drives flow structure, with converging downwelling helical flow at pool entrances (Thompson, 1986; Rodríguez *et al*. 2013), associated with high velocity cores, and divergent upwelling over riffles. Near-bed downwelling found in areas of low relative roughness such as where the riffle tail merges into the next pool entrance, may promote infiltration of fine bedload into gravel interstices. Work on pool-riffle intragravel flow, however has shown riffle tails to exhibit upwelling hyporheic flow (Tonina and Buffington, 2009), which should potentially discourage fine sediment infiltration. For the Rede, hyporheic upwelling at riffle tails may either prevent the finer grades (<0.5 mm) from infiltrating gravel voids, or alternatively flush them out post-deposition. However, hyporheic flows are insufficient to prevent coarse sand (0.5-2 mm) from infiltrating gravel voids, and incapable of flushing it. This could further explain the coarser nature of fines found in traps situated in areas of low relative roughness.

Catchment-scale fine sediment delivery

In the UK over the last 20 years there has been particular attention drawn to the impacts of agriculturally-derived fine sediment (<0.063 mm) on salmonid spawning grounds, delivered to the channel as suspended load (Theurer *et al.*, 1998; Collins and Anthony, 2008). Significant advances have been made in both the sampling and monitoring of this fraction (Phillips *et al.*, 2000), and identifying the sources of the material through fingerprint modelling (Walling *et al.*, 2003; Collins *et al.*, 2010; Stopps *et al.*, 2012). Attention has also focused upon modelling the impacts of this fraction upon salmonid embryo survival (Sear *et al.*, 2014). However it is clear from this and other studies (Lisle and Lewis, 1992) that in many rivers the dominant fine sediment fractions delivered to gravel voids in salmonid redds are sands and granules (>0.063 mm), delivered via bedload rather than suspended load. These coarser grades are known to be particularly harmful to the emergence phase of the salmonid life-cycle, through the creation of sand seals, and it is important that the processes responsible for delivery and infiltration of this material into spawning redds are better understood and included in future embryo incubation-to-emergence modelling. A key limitation with models such as SIDO-UK, is the assumption that all infiltration is derived from suspended sediment (Sear *et al.*, 2014). This model has the potential to be modified to include equations that predict fine bedload infiltration based upon its' relationship with τ_o and relative roughness, as demonstrated in this paper.

CONCLUSIONS

Zones of low relative roughness such as the riffle centers and tails act as preferential routing zones for fine sediment and also tend to transport coarser material in comparison to areas of high relative roughness. Low relative roughness zones are competent to transport fines for longer periods, resulting in longer transport and interstitial flushing periods (removing silt and fine sand). Higher τ_o at riffle tails are also capable of mobilising coarser grades of sand, in comparison to riffle heads. Clear associations exist between 1) local τ_o and infiltration rate, and 2) relative roughness and infiltration rate. Where knowledge exists of the relationship between embryo survival and infiltration rate (Lisle and Lewis, 1992), these associations have to potential to be used to predict the spatial variability in embryo incubation-to-emergence. The next generation of incubation-to-emergence models should consider sand delivered as bedload to the redd environment, and will need to consider redd and reach

sediment transport processes, as well as catchment-scale drivers for hydrograph character and sediment supply over the period of embryo incubation. Restoration of pool-riffle habitat should also consider fine sediment dynamics in their design, and hence may also benefit from simulating the hydraulic and morphological controls on the spatial patterns of infiltration. Such procedures could aid pool-riffle restoration that targets enhancement of salmonid habitat.

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Table I Documented field studies describing accumulation rates of fines in gravel-bed rivers.

River	Reference	D_{50} (Framework) (mm)	Rate of accumulation Kg m^{-2} day^{-1})	Discharge conditions
Rede UK	This study	53	*0.0013-1.527*	Variable
Enziwiger, Switzerland	Schindler Wildhaber et al. (2012)	-	*0.1-10.36*	Variable
-	Seydell et al. (2009)	-	*0.16 ± 0.07*	Variable
Cascapedia River, Canada	Zimmerman & Lapointe (2005)	-	*0.006-6.8*	Variable
Wallop Brook, UK	Acornley & Sear (1999)	36.5	*0.0428-0.4071*	Variable
River Test, UK	Acornley & Sear (1999)	21.6	*0.0143-1.0*	Variable
River Piddle, UK	Walling and Amos (1994)	22.6	0.0143-0.6429	Variable
North Tyne UK	Sear (1992a)	54	*0.005-0.086* *0.004-0.064* *0.013-1.574*	Compensation Hydropower Flood
Caspar, Jacoby, & Prairie Creeks, US	Lisle (1989)	21-25	*9-133*	Flood
Black Brook UK	Thoms (1987)	13	0.614 *0.26-2.49*	Variable
River Blythe UK	Thoms (1987)	15	0.644 *0.312-0.861*	Variable
River Tame UK	Thoms (1987)	22	0.399 *0.008-0.779*	Variable
Turkey Brook UK	Frostick *et al.* (1984)	27	0.24 4.43	Baseflow Flood
Tadnoll Brook UK	Welton (1980)	22	*0.37-0.93* *5.00-10.00*	Baseflow Flood
Great Eggleshope Beck UK	Carling and McCahon (1987)	20	0.008 *0.29-2.5*	Baseflow Flood
Harris Creek Canada	Church *et al.* (1991)	20	0.03 25.9	Baseflow Nival Flood
River Sanno Japan	Ebise *et al.* (1983)	-	0.401 *0.03-1.469*	Variable
Thompson River Australia	Davey *et al.* (1987)	<45	*0.056-0.307* *0.073-0.506*	Upstream dam Downstream dam
Strawberry Creek California	Reiser *et al.* (1985)	-	1.20 *0.876-4.56*	Variable
East Creek Alaska	Meehan and Swanston (1977)	-	0.497 *0.320-0.670*	Variable
Centennial Creek	Slaney *et al.* (1977)	45	25.0	Flood

Table II Summary surface layer characteristics of individual geomorphic units

Site	D_{16}	D_{50}	D_{84}
Riffles			
A	41	75	133
B	44	84	150
C	56	96	150
Mean	**47**	**85**	**144**
Pools			
1	82	120	190
2	72	120	195
3	86	115	170
4	43	82	120
Mean	**71**	**109**	**169**

Table III   Summary substrate grain-size characteristics

Site	D_{16}	D_{50}	D_{84}	Matrix (%)
Riffles				
A	5	44	127	12.18
B	7	53	136	10.13
C	3	35	115	12.58
Mean	**5**	**45**	**129**	**11.55**
Pools				
1	18	52	130	2.53
2	0.5	8	22	22.35
3	0.25	14	49	25.24
4	7	62	142	10.92
Mean	**7**	**48**	**133**	**11.36**

Table IV   Log-log regressions for infiltration rate (I) versus shear stress (τ_o) for < 2 mm material. *p<0.01, †p<0.05. NS: Not Significant

Trap number	Riffle A	Riffle B	Riffle C
1	$I = 2\text{E-}04\tau^{1.47}$ $r^2 = 0.803*$	$I = 5\text{E-}09\tau^{4.84}$ $r^2 = 0.949*$	$I = 3\text{E-}06\tau^{3.20}$ $r^2 = 0.658†$
2	$I = 0.001\tau^{1.21}$ $r^2 = 0.449†$	$I = 1\text{E-}09\tau^{4.87}$ $r^2 = 0.837*$	$I = 0.001\tau^{1.70}$ $r^2 = 0.604†$
3	$I = 1\text{E-}04\tau^{1.83}$ $r^2 = 0.705*$	$I = 7\text{E-}12\tau^{5.99}$ $r^2 = 0.628†$	$I = 6\text{E-}05\tau^{2.09}$ $r^2 = 0.08\text{NS}$
4	$I = 3\text{E-}04\tau^{1.49}$ $r^2 = 0.841*$	$I = 4\text{E-}15\tau^{7.86}$ $r^2 = 0.722†$	$I = 0.001\tau^{1.07}$ $r^2 = 0.474\text{NS}$
5	$I = 1\text{E-}04\tau^{1.69}$ $r^2 = 0.546*$	$I = 8\text{E-}09\tau^{4.51}$ $r^2 = 0.810*$	$I = 0.001\tau^{1.76}$ $r^2 = 0.580†$
6	$I = 2\text{E-}04\tau^{1.51}$ $r^2 = 0.668*$	$I = 5\text{E-}07\tau^{3.62}$ $r^2 = 0.469†$	$I = 0.003\tau^{1.26}$ $r^2 = 0.374\text{NS}$
7	$I = 2\text{E-}05\tau^{1.85}$ $r^2 = 0.790*$	$I = 3\text{E-}08\tau^{3.89}$ $r^2 = 0.953*$	$I = 0.002\tau^{1.16}$ $r^2 = 0.522†$
8	$I = 1\text{E-}06\tau^{2.61}$ $r^2 = 0.528*$	$I = 1\text{E-}05\tau^{2.81}$ $r^2 = 0.892†$	$I = 3\text{E-}05\tau^{2.53}$ $r^2 = 0.397\text{NS}$
9	$I = 8\text{E-}08\tau^{2.91}$ $r^2 = 0.719†$	$I = 3\text{E-}08\tau^{4.14}$ $r^2 = 0.611†$	$I = 9\text{E-}05\tau^{1.66}$ $r^2 = 0.044\text{NS}$
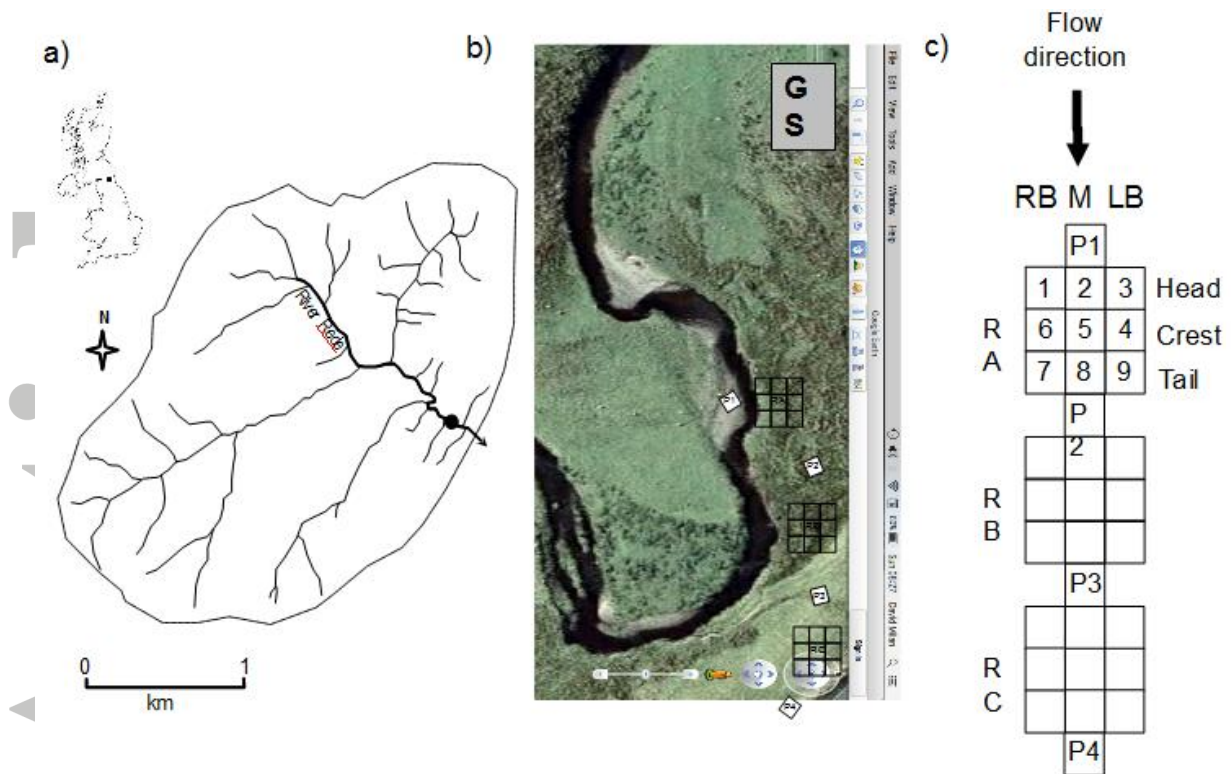
Figure 1 Study Location, a) River Rede catchment, b) aerial photograph of study reach, showing location of sampling cells (Google Earth, 2016), and the location of the gauging station (GS), c) representation of cell-based strategy used to sample pools (P) and riffles (R), right-bank (rb), channel mid line (b), and left-bank (lb), and riffle head, crests and tails.
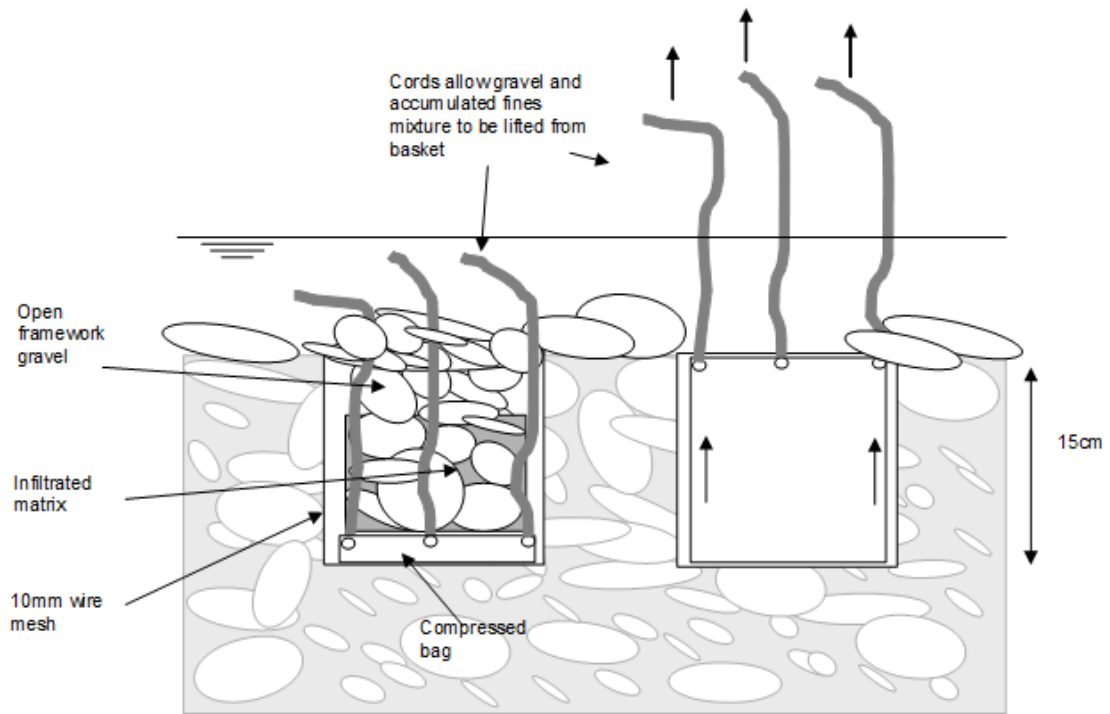
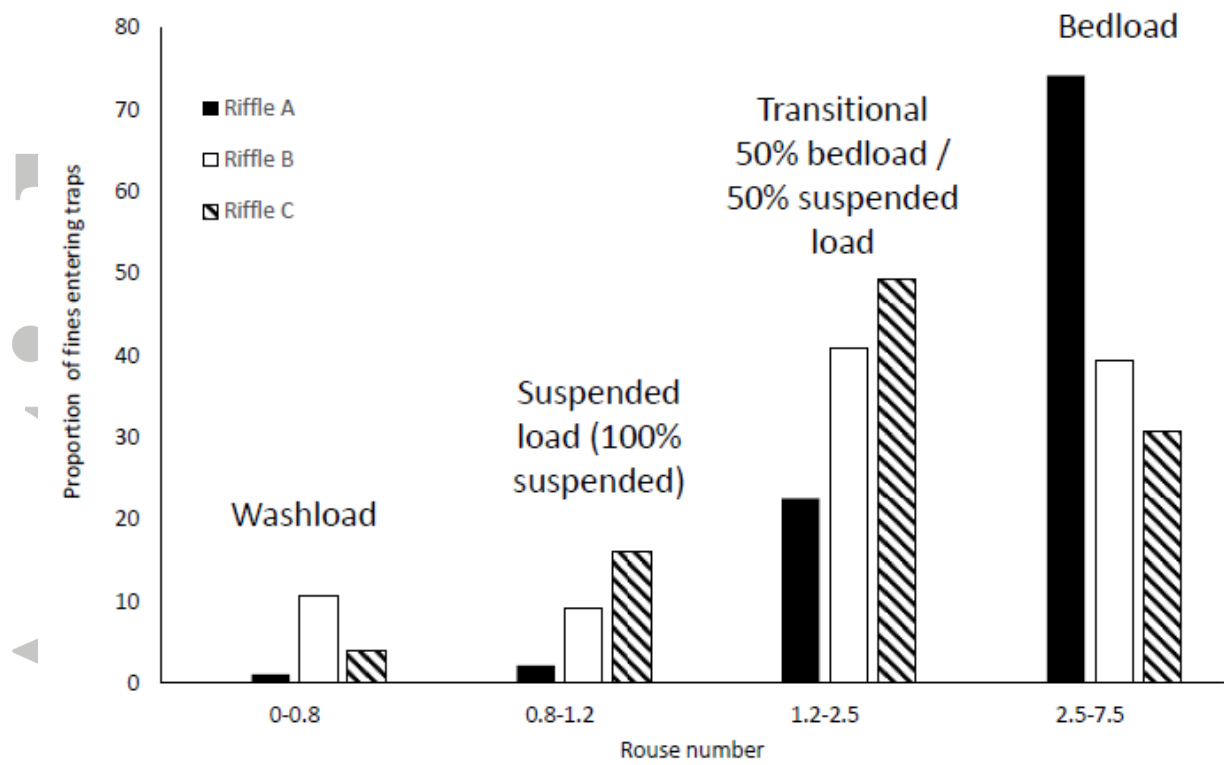Figure 2 Basket traps used to sample fine bedload sediments.

Figure 3 Average Rouse number calculated for basket traps over the study period.
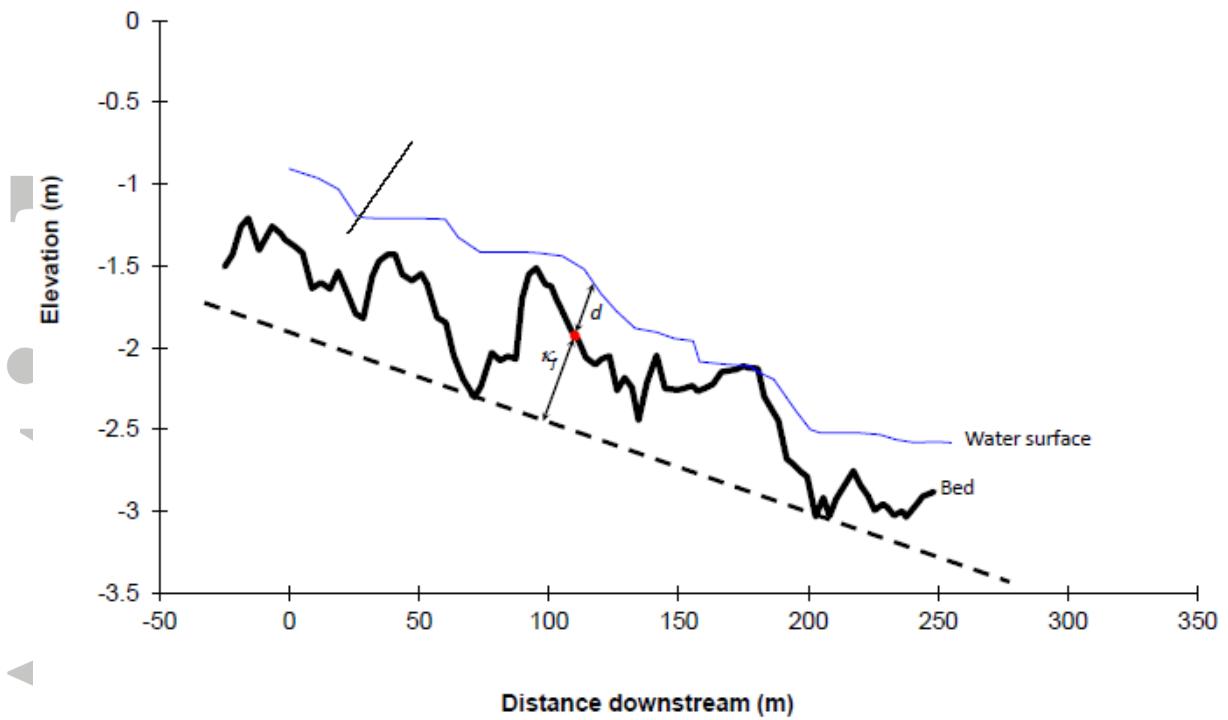
Figure 4 Derivation of relative roughness. Long profile and low flow water surface are indicated. Roughness height (k_f) is the elevation above the regression line fitted to the long profile of the bed, and passing through the lowest pool troughs (pool 1 and pool 4), as indicated by the stippled line. Relative roughness is derived through the ratio of k_f to flow depth (d).
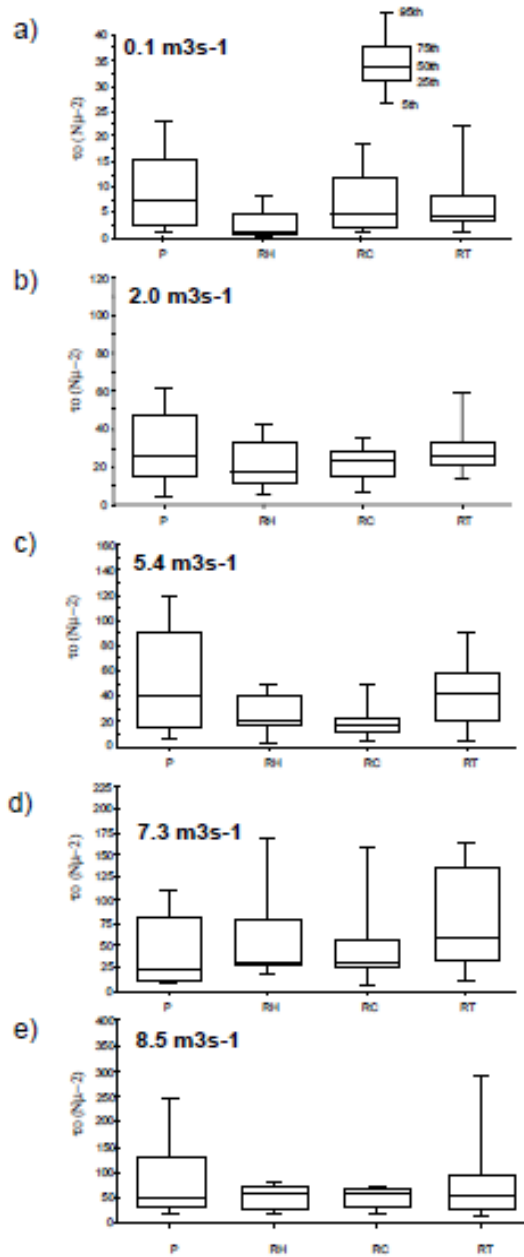
Figure 5 Shear stress variations for different morphology units (P-pools; RH – riffle heads; RC-riffle crests; RT-riffle tails), for different discharges, a) $0.1 \text{m}^3\text{s}^{-1}$, b) $2 \text{ m}^3\text{s}^{-1}$, c) $5.44 \text{ m}^3\text{s}^{-1}$ d) $7.26 \text{m}^3\text{s}^{-1}$, e) $8.52 \text{m}^3\text{s}^{-1}$. Note that the y-axis scale is not uniform.
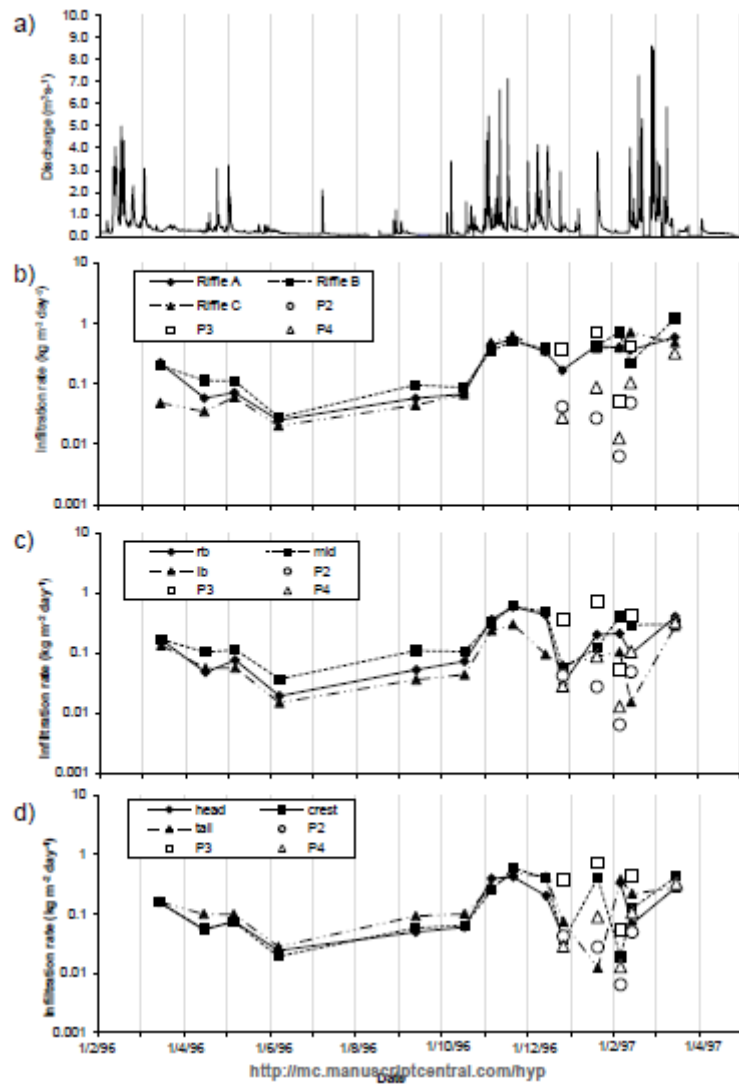
Figure 6 Temporal and spatial variability in infiltration rates, a) Discharge, b) between riffle, c) cross-channel variability using an ensemble of data from all the riffles, d) longitudinal variability using an ensemble of data from all the riffles. Rb- right-bank, lb- left-bank, mid-mid channel, P – pool.
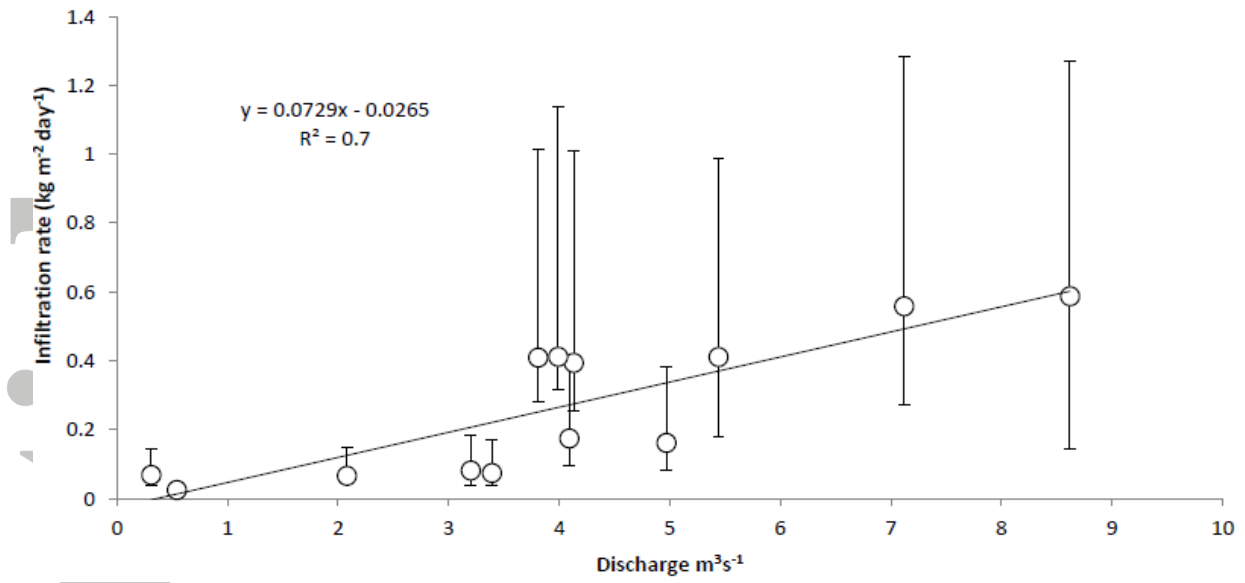
Figure 7 Relationship between mean infiltration rate and peak discharge. Error bars are 25th and 75th percentiles.
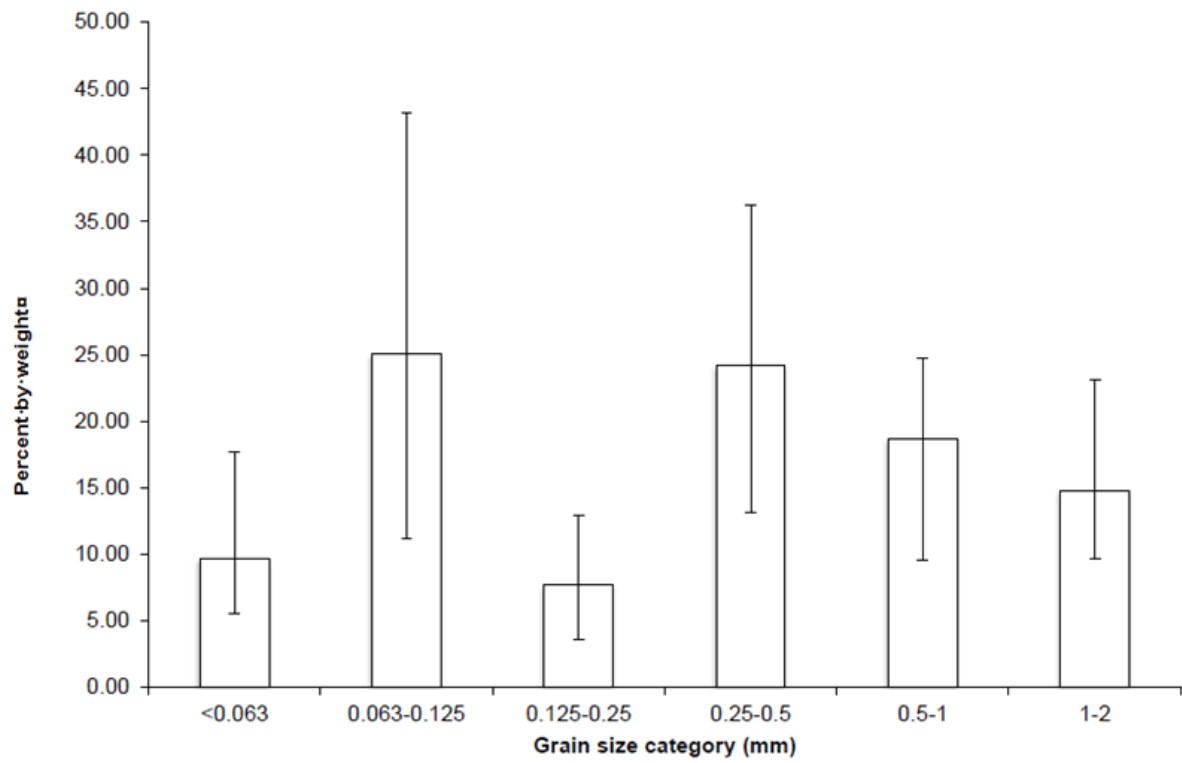
Figure 8 Grain size characteristics of infiltrating fines. Error bars show 5th and 95th percentiles.
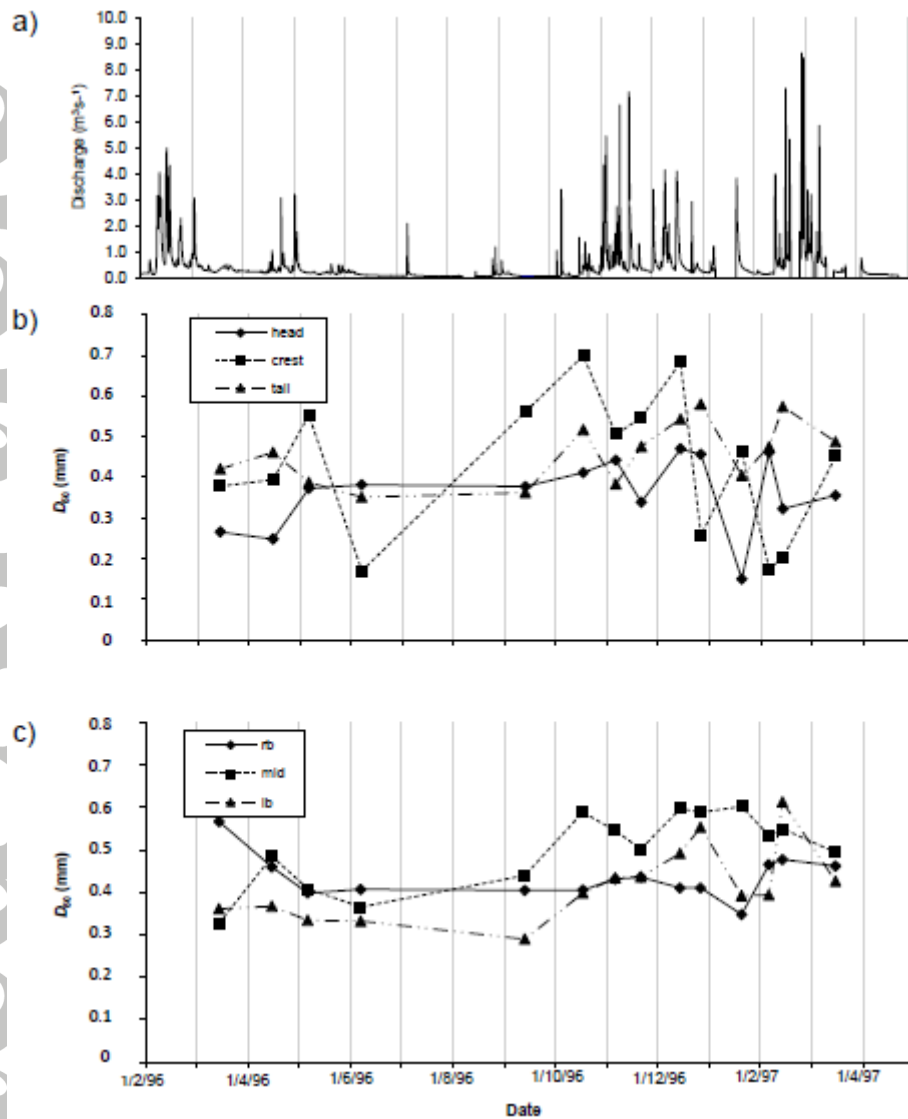
Figure 9 Temporal variations in median grain size characteristics for infiltrated sediments (0.063-2 mm) over the study period, a) discharge time series, b) Longitudinal variability for the head, crest and tail, c) Cross-channel variability (Rb – right-bank- looking downstream, lb - left-bank, mid-mid-channel)
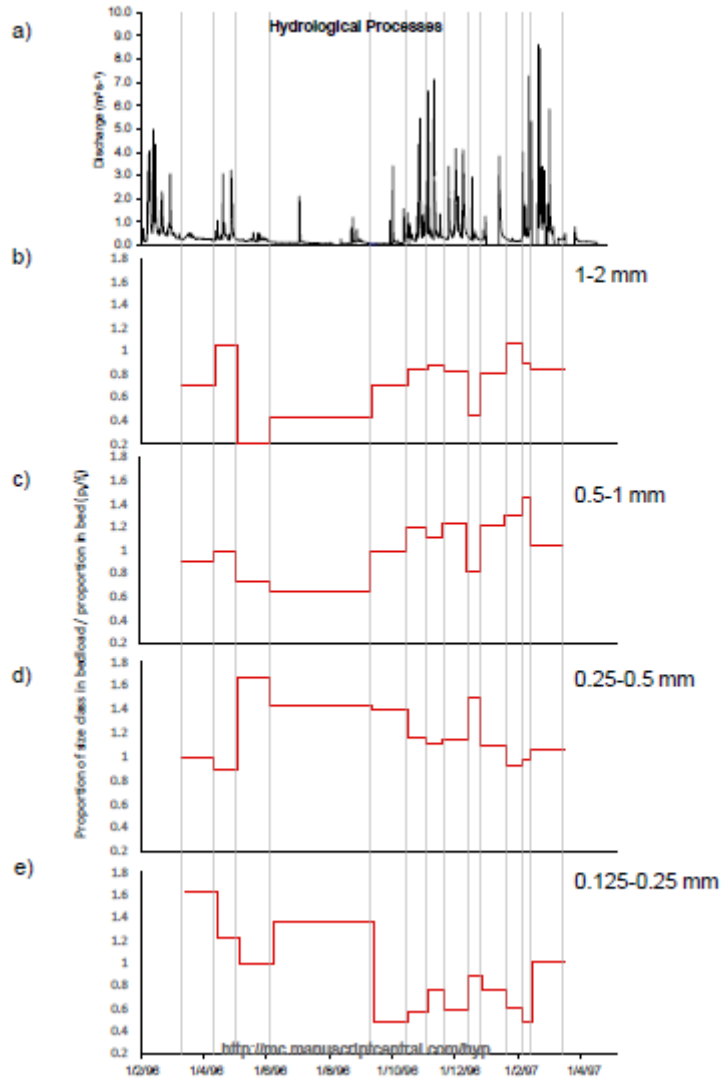
Figure 10   Temporal variations in proportions of different sand size fractions, relative to the proportions found in the substrate (p_i/f_i), for the weighted average load for all traps located on riffle A.
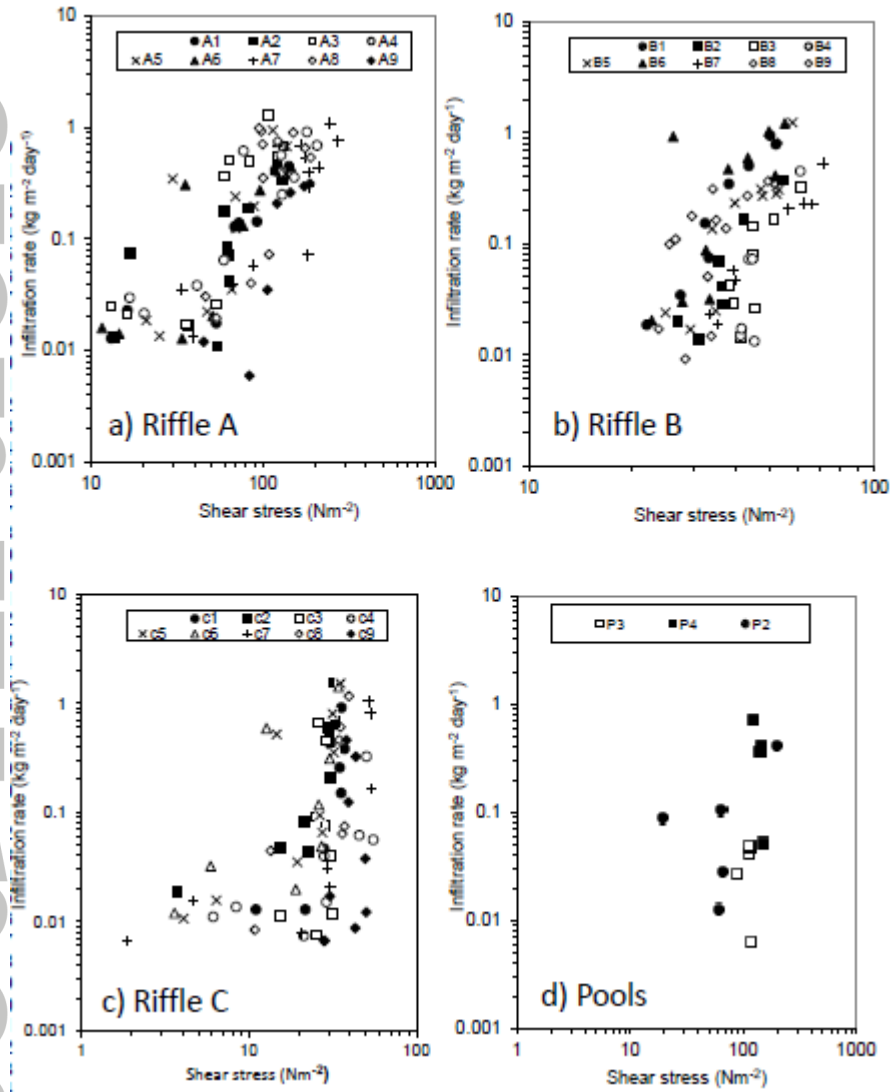
Figure 11 Relationship between boundary shear stress and infiltration rates for a) riffle A, b) riffle B, and c) riffle C. The position of cell numbers A1 to A9 are indicated in Figure 1c.
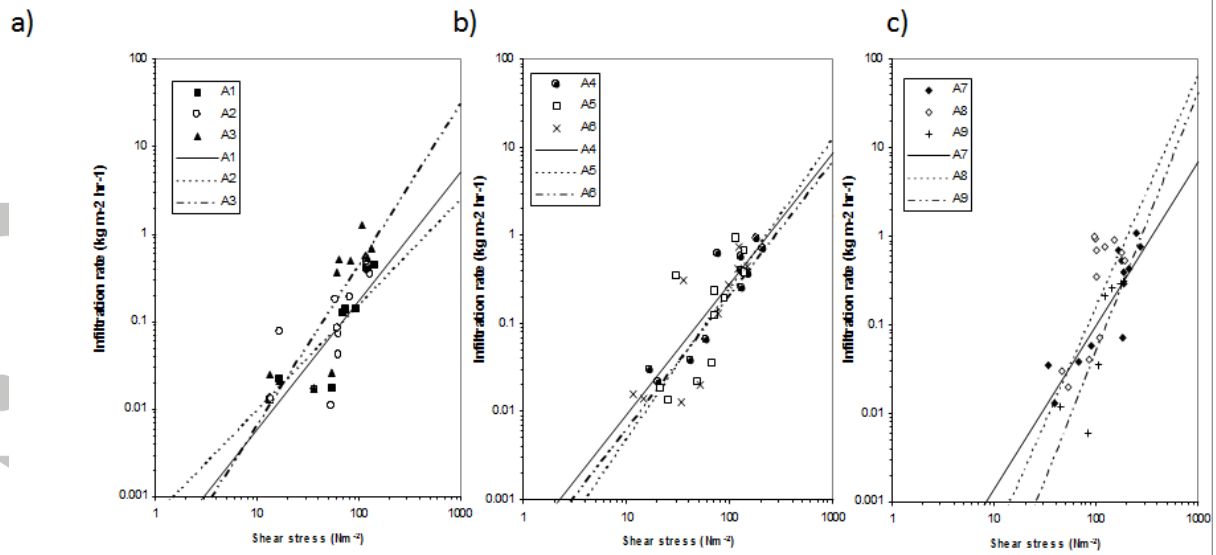
Figure 12 Relationship between shear stress and fine sediment (< 2 mm) infiltration for Riffle A traps, a) riffle head traps, b) riffle crest traps, c) riffle tail traps. The position of cell numbers A1 to A9 are indicated in Figure 1c.
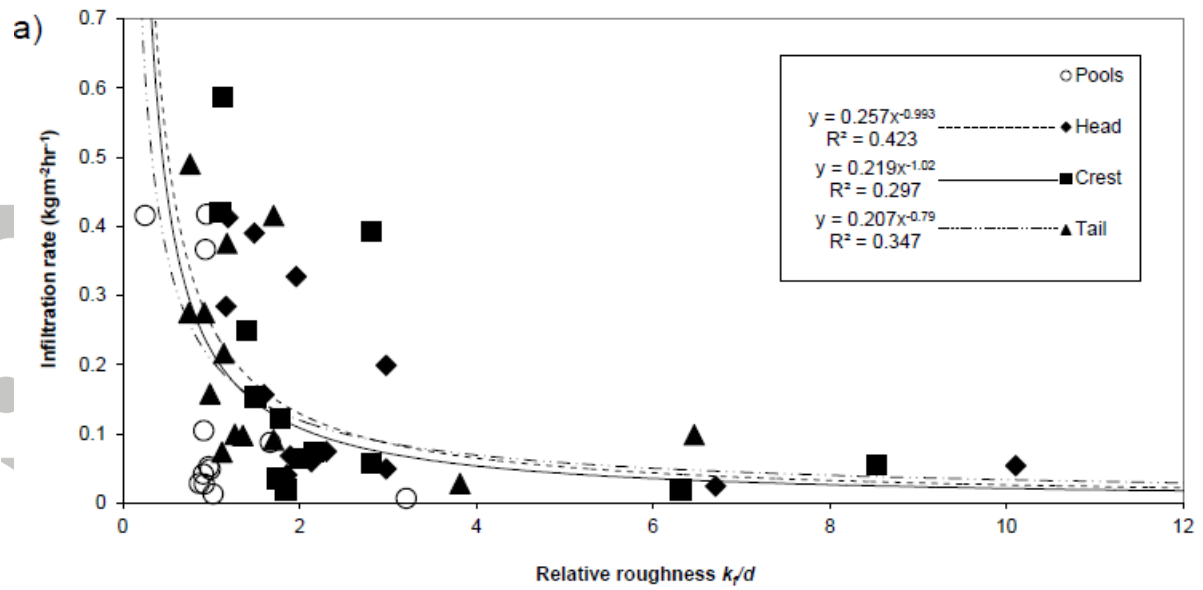
Figure 13 Relationship between fine sediment infiltration (< 2 mm) and relative roughness (k_f/d), a) down-riffle variation, b) cross-riffle variation. Pool data are also indicated.