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The clogging of coarse gravel river beds by fine sediment

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Key words: clogging, siltation, flushing flows, hydraulic conductivity, infiltration, river bed

Abstract

Laboratory investigations were carried out to examine the clogging process in coarse gravel river beds. Field samples taken from the Langeten river in Switzerland show that the intruded fine particles of the flow are deposited in the top layer of the river bed. For lower discharges the decrease of the hydraulic conductivity depends mainly on the dimensionless shear stress of the flow, the concentration of the suspended load, the hydraulic gradient between river and groundwater and the grain-size distribution of the river bed. However, when the armour layer breaks up during high discharges and the whole river bed is mobilized, the deposited fines are flushed downstream and a new layer with an initial maximum hydraulic conductivity is formed. The relationship between the dimensionless shear stress and the hydraulic conductivity is discussed. Changes in the nature of the catchment area or in the river itself which can accelerate the clogging process in the affected river are also discussed.

Introduction

The river bed forms the boundary between the river and the substrate. On the one hand it is the habitat for invertebrates and enables the reproduction and development of various fish species. On the other hand the river bed is the filter-layer influencing the exchange between river water and groundwater. Depending on the variable characteristics of the flow and the filter layer, the composition of the river bed and thus the hydraulics of seepage change with time.

For a given river bed, the following independent variables can have a dominant influence on the clogging process (compare Geldner, 1982; Beyer & Banscher, 1975):

Physical variables
- the flow conditions in the river, which can be represented by the dimensionless shear stress
- the suspended load
- the grain-size distribution and shape of the suspended particles
- the hydraulic gradient of the seepage flow and its direction

Biological variables
- the variety (of invertebrates, redds, algae) and their commonness
- the extent of eutrophy of the water

Chemical variables
- type and quantity of dissolved matter

In this paper only the influence of the physical variables are examined. The investigation reported considers rivers with high turbulent flow, coarse bed material and water with a comparatively low level of pollution.

The clogging processes in river beds have been described in several publications (Beyer & Banscher, 1975; Beschta & Jackson, 1979; Cunningham *et al.*, 1987; Diplas & Parker, 1991). The flow of each river contains a variable amount of suspended fine particles. In response to interaction between the turbulence of the channel flow, the settling properties of the suspended particles and the seepage rate, a certain amount of the fine particles intrude into the river bed. As a result of different processes these fines are deposited on the river bed or are incorporated into its top layer so that the pore space is reduced, i.e. the river bed is progressively clogged. The characteristics of such clogged river beds are: (a) a dense positioning and a compact texture (low porosity), (b) comparatively high resistance against increasing discharges, and (c) reduced hydraulic conductivity. Under natural conditions this clogged layer can break up during high flood events, so that the deposited fine particles are resuspended and flushed downstream.

The aims of the presented research reported here were: (a) to examine the texture of a river bed by testing different sampling techniques in the field; (b) to observe and measure the clogging and flushing processes in the laboratory; and (c) to describe the function between the hydraulic conductivity and the dominant physical variables using mathematical formulae.

Field investigation

Two different sampling techniques were applied to remove several layers of the river bed. The first used a 0.5 × 0.5 m steel frame which is knocked step by step into the bed at an unsubmerged site. The coarse material of the bed requires that the frame is exposed all the way around, so that big stones immediately underneath the frame can be taken away from the outside. The advantage of this method is the high quality of the samples. On the other hand, if samples have to be taken at a submerged site this can only be achieved with difficulty because the flow winnows the fines as samples are withdrawn. The second method was based on collection of frozen core samples by using liquid nitrogen (modified from Ryan (1970) and Bretschko & Klemens (1986)). One or several connected tubes are knocked about 0.4 m into the bed and filled several times with liquid nitrogen (Fig. 1). After a few minutes the frozen core can be pulled out. With this method, two different points need special attention: (a) the lower part of the tube should be grooved (no holes) so that there is a reliable connection with the surrounding material; (b) according to the roughness of the river bed several attempts may be required before a site is found where the tube can be inserted to the desired depth.

Figure 2 shows the result of size analysis of layers collected by the steel frame method. A total of 6 layers were analyzed to a depth of 0.45 m.

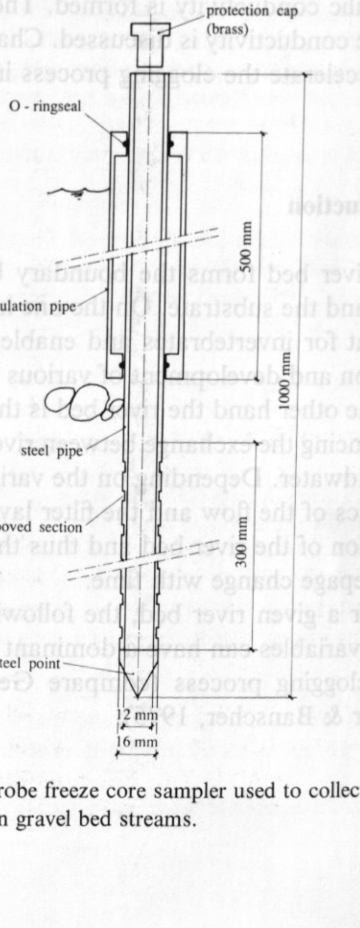

Fig. 1. Single probe freeze core sampler used to collect substrate samples in gravel bed streams.

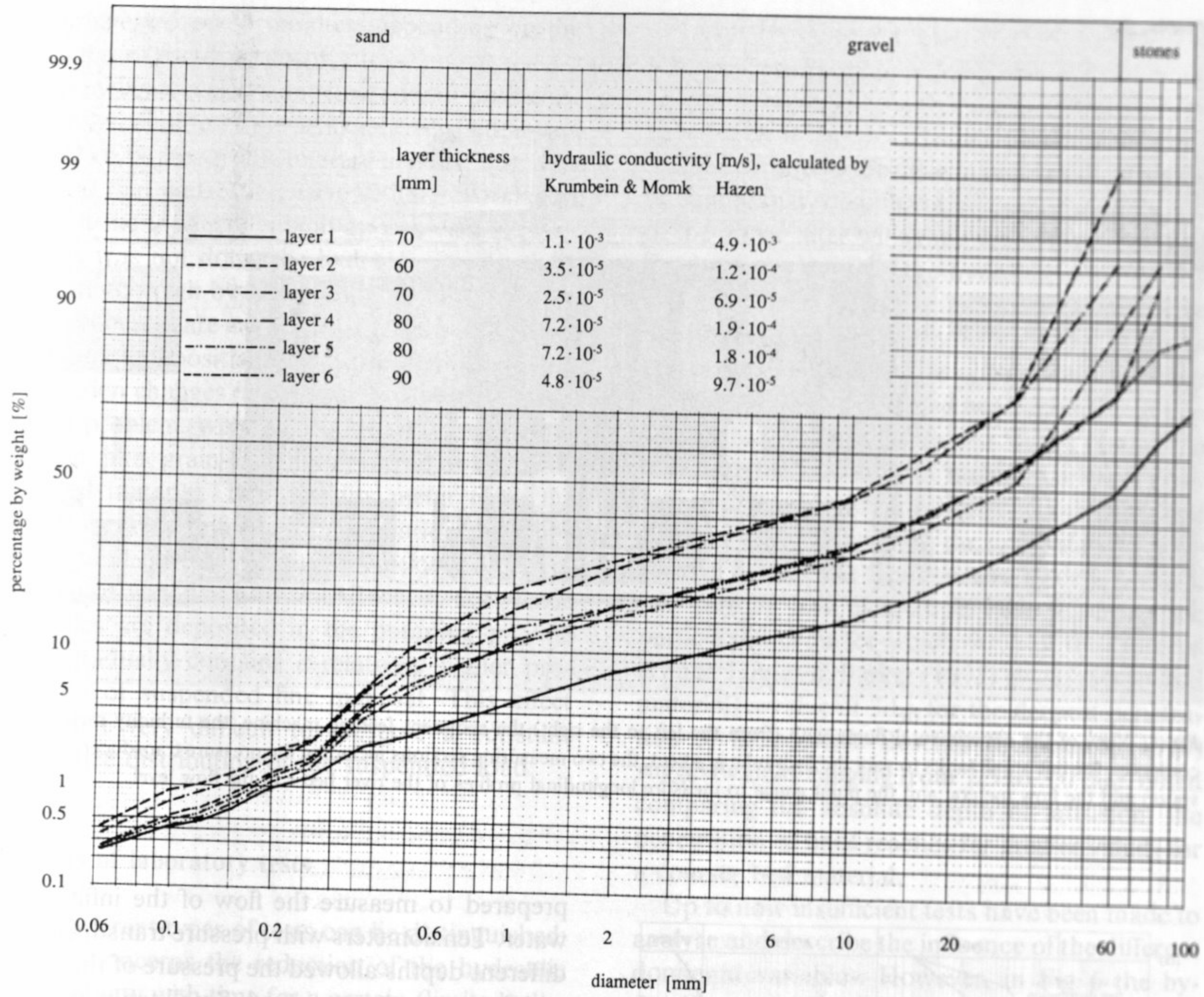

Fig. 2. Grain-size distributions of different layers from samples taken at the Langeten stream. Also given are the corresponding hydraulic conductivities calculated by the methods of two different authors.

The coarse armour overlies two layers with visibly finer material, whereas layers 4 to 6 show a rather constant average grain size distribution. Other samples taken from different sites show almost identical grain size distributions under the armour layer. From this it can be concluded: (a) that in a natural river there are sections where the top layer includes finer particles (i.e. the pore space and the hydraulic conductivity are reduced), and (b) that the intrusion of fine particles does not extend below a certain depth.

Laboratory investigation

Laboratory tests were carried out in a 8 m long and 0.5 m wide flume, to assess the influence of the dominant physical variables on the clogging process (Fig. 3). The river bed material and the suspended matter used in the model were taken directly from the river Rhine upstream of the Bodensee (see grain-size distributions Fig. 4). A reduction in the required flow-depth was achieved by increasing the slope by a factor of 10. Thus the velocity and the shear stresses near the bed are

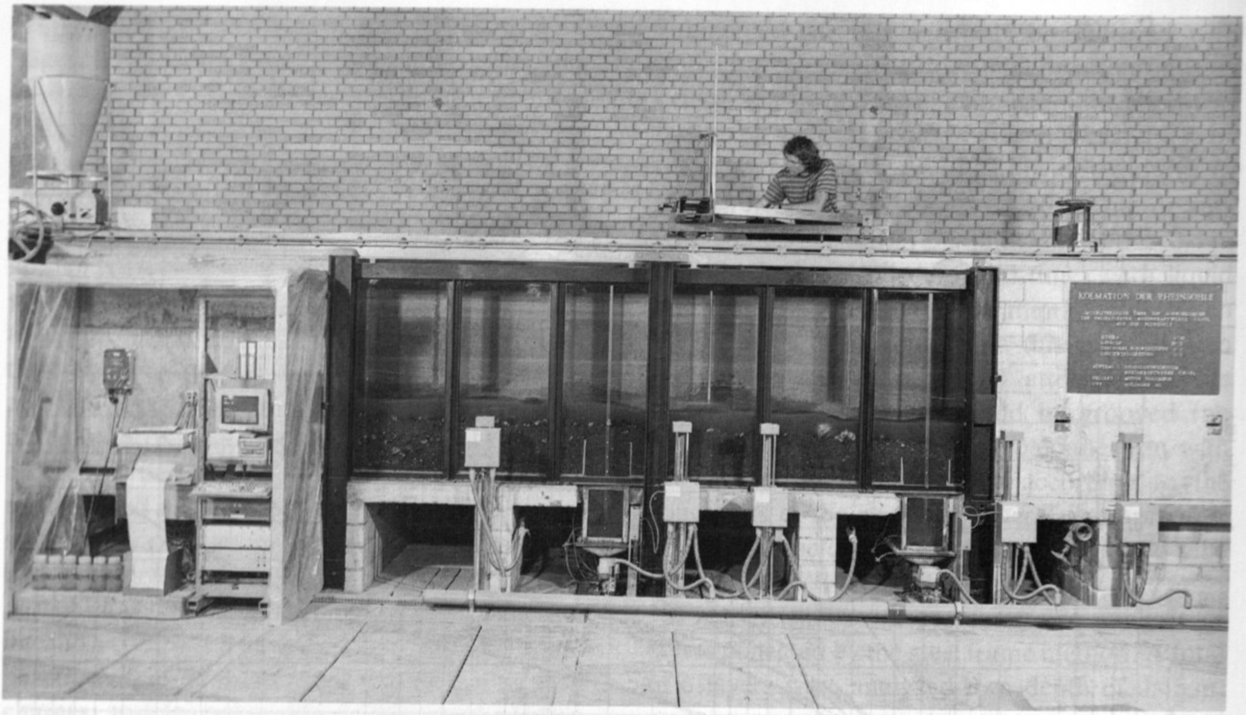

Fig. 3. View of the experimental flume with (from the left to the right) the sediment feeding machine, the turbidity meter, the computer, the fine small tanks to vary the hydraulic gradient, the two measuring sections including the pressure transducers (white spots) and the flow meters, and the point gauge to measure longitudinal profiles of the river bed r of the flow level.

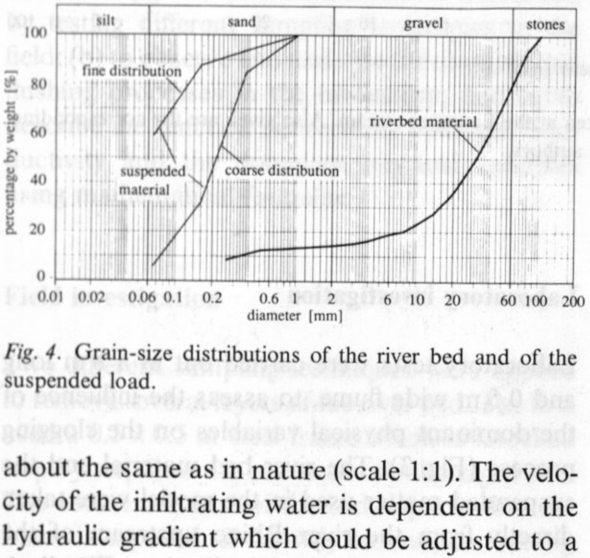

Fig. 4. Grain-size distributions of the river bed and of the suspended load.

about the same as in nature (scale 1:1). The velocity of the infiltrating water is dependent on the hydraulic gradient which could be adjusted to a desired value (see below). The transport of the fines over or into the river bed together with the clogging process are therefore reproduced.

Two sections in the flume (0.3 m × 0.5 m) were prepared to measure the flow of the infiltrating water. Tensiometers with pressure transducers at different depths allowed the pressure of the interstitial water to be measured. Small tanks with an overflow section represent the groundwater level and make it possible to vary the hydraulic gradient. At the upper end of the model a turbidity meter measured the concentration of the suspended load. If the given value was too low, a computer gave the sediment feeding machine a signal to add some more fines to the flow. Additionally from time to time samples of the suspended load were taken by hand (filling a bottle with the flowing water in the model, filtering and drying the ingredients) to determine the proportion of fines smaller than 0.063 mm, i.e. of the cohesive material. Since the deposition and intrusion of the suspended particles and the clogging of the top filter layer are processes which can taken several weeks or even months, all the data were logged on a computer. Measurements were taken every 5 or 30 minutes, depending on the duration of the experiment.

The tests revealed some operational problems. After installation of the artificial river bed, it was found to be important to start the first test with a flood that causes intensive sediment transport so that the top layer is built up in a natural way. If this was not done, the hydraulic conductivity may be too high by a factor of 100 and the clogging processes are not reproduced correctly, since the unnatural positioning of the particles can lead to sudden changes in the texture of the top layer. Other problems were associated with the concentration and grain-size distribution of the suspended material. The turbidity meter gives the same signal for a higher concentration of coarse suspended particles as that for a lower concentration of very fine particles. Because the coarse particles are deposited in the pumping pit, the flow gradually contains a relatively higher proportion of suspended fine material. This effect makes it very difficult to preserve a constant grain-size distribution of the suspended load.

Results of laboratory tests

Two different types of tests can be distinguished: Type 1 concerns the reduction of the hydraulic conductivity with time for a certain (limited) discharge, suspended load and hydraulic gradient, whereas Type 2 concerns the changes of hydraulic conductivity for an initially clogged river bed with increasing discharges (flood flows).

The hydraulic conductivity K was calculated using Darcy's law

$$K = v/i \qquad (1)$$

which is valid for laminar flow conditions and a saturated river bed. For Eqn. 1 the seepage rate v is calculated from the measured seepage flow divided by the area of the infiltration section. The hydraulic gradient i_j of a specific layer j is calculated from the (measured) pressures of the interstitial water at consecutive depths h_j and h_{j+1}, and the thickness of the layer z_j:

$$i_j = [h_j + z_j - h_{j+1}]/z_j$$

Type 1 tests

Figure 5 shows the development of the hydraulic conductivity of different consecutive layers and of the entire filter with time for a Type 1 test. It can be seen that only the hydraulic conductivity of the top layer (thickness 0.15 m) decreases while the hydraulic conductivity of the other layers is more or less constant. The hydraulic conductivity of the entire filter, obtained by combining all layers, decreases slowly. This test shows that all the fines that intruded into the river bed are held back and deposited in the top layer. The thickness of this top layer depends on the grain-size distributions of the river bed and the suspended material, but may be less than $2d_{90}$, with d_{90} being the particle diameter for which 90% of the material is finer. Diplas & Parker (1991) give (for finer bed material) a value of $3d_{90}$ for the deepest penetration of fines, while Beschta & Jackson (1979) suggest values ranging from 2.5 to 5.0 d_{90}. When comparing the absolute depth of intrusion, the penetration of fines reaches far greater values for a coarser bed material.

Up to now insufficient tests have been made to analyse and describe the influence of the different dominant variables. However, in Fig. 6 the hydraulic conductivity of the top layers of 5 differ-

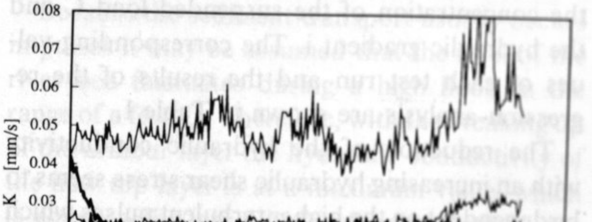

Fig. 5. Example of the changing hydraulic conductivity (K) of the top layer, of the 4 sub-layers and of the entire filter (river bed) with time (t).

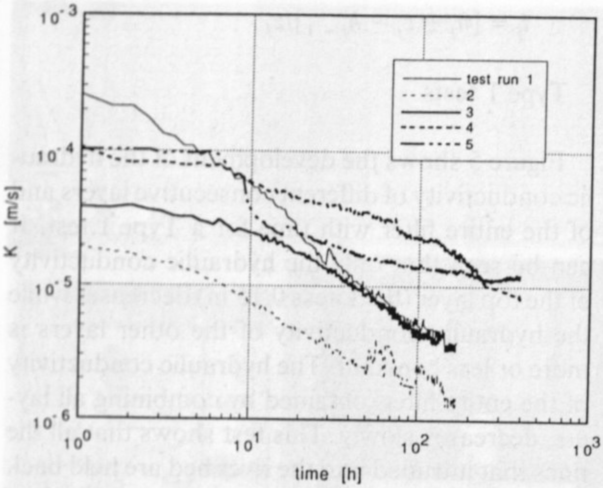

Fig. 6. Relationship between the hydraulic conductivity (K) and time (t) for five different type 1 tests.

Table 1. Gradient G, concentration of the suspended load C, dimensionless shear stress Θ and D_{10} representing the diameter where 10% by weight are smaller or equal than this value. The last three lines give the results of the regression analysis where -α represents the slope of the regression line, K_i the point of intersection with the K-axis and R^2 the correlation.

Variable		Test run				
		1	2	3	4	5
G	[-]	0.43	0.57	0.41	0.22	0.26
C	[mg/l]	354	354	840	120	120
Θ	[-]	0.075	0.017	0.033	0.014	0.010
D_{10}	[mm]	0.34	0.34			
α	[-]	0.935	0.605	0.797	0.566	0.328
K_i	[mm/s]	0.393	0.028	0.187	0.269	0.070
R^2	[-]	0.989	0.962	0.985	0.923	0.830

ent tests are shown in log K – log t diagram. Ten hours after starting the experiment the different tests can each be represented by a straight line. This means that the relationship between the time t and the hydraulic conductivity K follows the power-function of the form:

$$K = K_0\, t^{-\alpha}$$

where K_0 is the initial (maximum) hydraulic conductivity and α is the clogging exponent. This relationship corresponds with the observations of Banscher (1976). α depends on certain parameters of the test run, especially the dimensionless shear stress Θ (identical with the Shields factor), the concentration of the suspended load C and the hydraulic gradient i. The corresponding values of each test run and the results of the regression-analysis are shown in Table 1.

The reduction of the hydraulic conductivity with an increasing hydraulic shear stress seems to be dependent on the higher turbulent pulses which result in a compact structure of the river bed. It could not be determined whether the increasing shear stress led to an increased intrusion of fines. Beschta & Jackson (1979) found for higher sediment inputs an increasing intrusion of sand, whereas Carling (1984) found no significant relationship between the shear stress and the deposition of fines. However, the boundary conditions of the experiments were different and this makes a comparison of the results difficult.

Type 2 tests

The changes in the hydraulic conductivity during a flood event are shown in Fig. 7 (Type 2 test). The bold and thin line represent the hydraulic conductivity of the top layer and the entire filter respectively, whereas the dotted line shows the dimensionless shear stress Θ. Above the diagram the levels of the bed and the flow surface are shown. It can be seen that for Θ less than or equal to 0.060 the hydraulic conductivity of the top layer does not change significantly. When Θ increases to 0.076, due to slight erosion of the bed, the hydraulic conductivity of the top layer increases suddenly. This erosion-process continues until Θ reaches 0.086 and the hydraulic conductivity still increases by at least a factor of 100. This increase in hydraulic conductivity is based on the breaking up and the erosion of the clogged armour layer. The intruded and deposited fine particles are resuspended and flushed downstream.

The results of 10 tests with high floods are shown in a logK/Θ diagram in Fig. 8. Again it can be seen that for small dimensionless shear stresses less than 0.060, the K values decrease or remain constant (clogging phase).

Over a certain range of discharges it was ob-

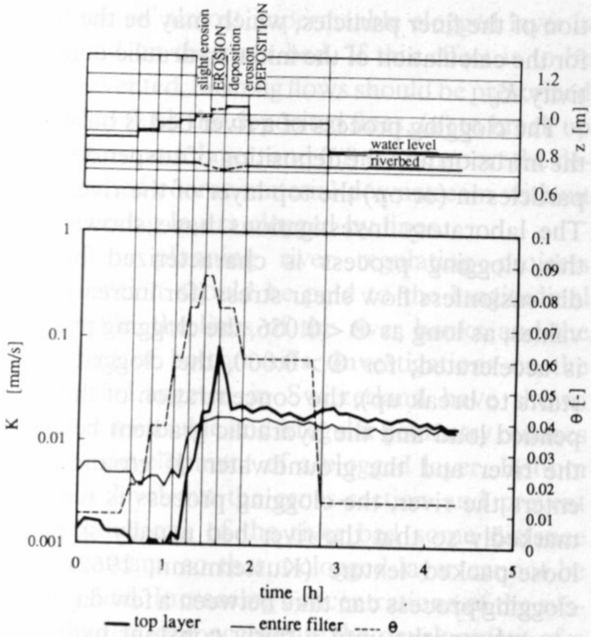

Fig. 7. Example of the changes of the hydraulic conductivity (K) of the top layer and the entire filter with increasing dimensionless shear stress (Θ).

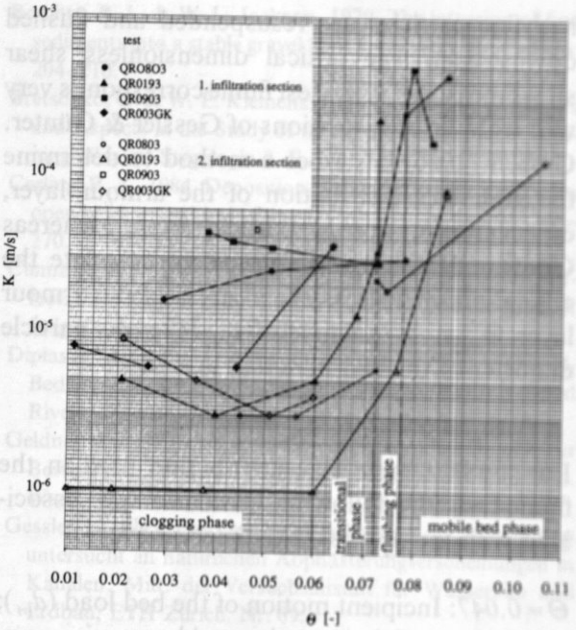

Fig. 8. Relationship between the hydraulic conductivity (K) and the increasing dimensionless shear stresses Θ for several type 2 tests.

served that depending on the local flow conditions (turbulence), three different processes are the main cause of an increase of the hydraulic conductivity of the top layer. These are:

(a) gravel transport can affect the clogged surface of turbulence-protected areas. Once this surface is broken the deposited fine particles at this spot are flushed away rapidly.
(b) because of the increasing shear stress the deposited fine particles in openings and gaps between the larger components of the armour layer are flushed away.
(c) the base of the stabilizing larger components of the bed is partly washed away while the armour layer is still stable. Due to this, the clogged layer erodes beside and underneath these stones.

These processes occur between the clogging phase and the flushing phase and thus can be called the transitional phase; they occur in a range $0.060 < \Theta < 0.072$. The observed increase in the hydraulic conductivity is dependent on the initial hydraulic conductivity at the beginning of the test run (Fig. 8). For lower initial K values these transitional processes have a greater influence than for higher initial K values.

When the discharge reaches the critical value of stability of the river bed, the armour layer breaks up and the intruded fines are flushed downstream (flushing phase). For even higher discharges the whole bed is mobilized (mobile bed phase).

Because the sediment transport usually occurs in pulses it may be assumed that the level of the river bed fluctuates during a high flood in the range of a few d_m. Therefore, with the breaking up of the armour layer the hydraulic conductivity of the new top layer is at a maximum value, which is equal to the initial hydraulic conductivity K_0. When the grain-size distribution of the bed material is known, K_0 can be calculated by different methods. However, the formulae of Krumbein & Momk (Krumbein & Sloss, 1951) and Hazen (1892) respectively give values that are too low. Further investigations should lead to better predictive equations.

As already described, the intruded and deposited fine particles are resuspended and flushed downstream. The critical dimensionless shear stress measured in the test flume corresponds very well with the investigations of Gessler & Günter. Gessler (1965) describes a method to determine the grain-size distribution of the armour layer, especially of its average particle size d_{A_m}, whereas Günter (1971) gives a formula to calculate the critical dimensionless shear stress of the armour layer Θ_A as a function of d_m (average particle diameter of the bed material) and d_{A_m}:

$$\Theta_A = 0.047(d_m/d_{A_m})^{2/3}$$

For the first grain-size distribution used in the flume-tests the following Q-values were associated with the processes outlined above:

$\Theta = 0.047$: Incipient motion of the bed load (d_m); the armour layer remains stable.

$\Theta < 0.056$: Clogging phase: Further reduction of the hydraulic conductivity.

$0.060 < \Theta < 0.072$: Transitional phase: The hydraulic conductivity of the top layer increases by a factor of 10.

$0.072 < \Theta_A < 0.078$: Flushing phase: Break-up of the armour layer. Increase of the hydraulic conductivity to maximum value K_0. The method of Gessler & Günter gives a value of $\Theta_A = 0.074$.

$\Theta > 0.0775$: Mobile bed phase: The whole river bed is mobilized. Dependant on fluctuations of the river bed, the hydraulic conductivity remains at the maximal value (further slow erosion) or starts to decrease (stable bed level or deposits).

Conclusions

The investigations so far have focussed on the natural phenomena concerning the clogging process of the river bed and the effect of large floods. By taking samples of the river bed, the clogging layer could be identified; it was observed that this layer with a higher proportion of fines is limited to a relatively thin zone. Samples of the river bed are important for an accurate determination of the grain-size distribution, especially of the portion of the finer particles, which may be the basis for the calculation of the initial hydraulic conductivity K_0.

The clogging process of a river bed is based on the intrusion and the deposition of suspended fine particles in (or on) the top layer of the river bed. The laboratory investigations have shown that this clogging process is characterized by the dimensionless flow shear stress (for increasing Θ values, as long as $\Theta < 0.056$, the clogging process is accelerated; for $\Theta > 0.060$, the clogged layer starts to break up), the concentration of the suspended load and the hydraulic gradient between the river and the groundwater. If groundwater enters the river, the clogging process is reduced markedly so that the river bed usually shows a loose-packed texture (Kustermann, 1962). The clogging process can take between a few days and several months until a fairly constant hydraulic conductivity is reached. Only during a sufficiently large flood, when the dimensionless shear stress exceeds the critical value for the stability of the armour layer, is the clogged filter layer destroyed and a new filter with an initial hydraulic conductivity K_0 formed.

In regions where there is great economic interest in the groundwater table, river water often plays a dominant role in groundwater recharge. Artificial changes in the nature of the catchment area or in the river itself may affect the characteristics of the flow or sediment transport and thus the texture and the hydraulic conductivity of the river bed. This happens in particular in river-storage basins or downstream of a water diversion structure:

(a) When water is diverted, the existence of flushing flows should still be guaranteed (Reiser *et al.*, 1985). The minimum peak discharge of these flushing flows can be determined by calculating the critical dimensionless shear stress by Gessler & Günter. Additionally, the clogging process should not be accelerated by increasing the concentration of the suspended load.

(b) In river storage basins the flow velocity is markedly reduced so that the suspended particles are deposited in a graded manner. With time an almost impermeable clogged layer is build on the river bed. If this effect is to be prevented, flushing flows should be prescribed (*i*) to flush the deposited fines, (*ii*) to break up the armour layer, and (*iii*) to transport the deposited coarse material downstream without covering layers clogged by fines.

(c) When planning river regulating projects attention should be paid to the longitudinal profile, the lines of the river banks and the effect of bottom sills. Investigations on the river Langeten in Switzerland have shown that a variable and irregular geometry reduces the development of a clogged layer. Bottom sills level out the cross-section and prevent fluctuations of the river bed some distance upstream, so that a clogged layer cannot be flushed. Increasing concentrations of the suspended load accelerate the development of a clogged layer.

Further tests in the laboratory with different grain-size distributions of bed material and suspended fines should help in understanding the functional relationship between the independent variables, the texture and the hydraulic conductivity of the river bed.

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Stabilizing self-organized structures in gravel-bed stream channels: Field and experimental observations

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Abstract. Stable reticulate structures, which we call "stone cells," have been observed in cobble-gravel channel beds with low bed material transport rates. Experiments show that such structures develop simultaneously with the armor layer during an extended period when flows do not exceed the Shields threshold by more than ~2 times, so that bed material transport is low. They are constructed by particles moving from less stable positions into more stable configurations against each other. Intermediate developments include clusters and stone lines. They reduce sediment transport by orders of magnitude and are evidently a major stability-promoting mechanism in gravel channels. The timescale for their development suggests that the boundaries of many gravel-bed channels are not in equilibrium with recent competent flows but reflect the history of recent "dominant" flows.

1. Introduction

Most alluvial stream channels change remarkably little over periods that can be as long as years or decades, even though they may be regularly subjected to sediment-transporting flows. Stream channels are stability-seeking entities. What we see is the product of a succession of changes; the morphology that persists is that which is most nearly stable in face of the usually imposed flows. Stability is gained when stream energy can be dissipated without the accomplishment of significant channel-deforming work, even though sediment transfer, including the exchange of sediment at the channel boundaries, may still occur. Energy-dissipating structures develop at all morphological scales within the channel, including the scales of channel pattern, pool and riffle, and sedimentary bed forms. However, the most basic level at which stability develops in gravel-bed channels is that of the granular boundary materials, the potentially mobile sediments themselves.

Grains are entrained in stream channels when the force of water acting on the alluvial bed material overcomes particle inertia. *Shields* [1936] expressed the force balance at entrainment as a "mobility number," a function of the ratio of fluid shear stress exerted on the bed to (submerged) particle weight. Subsequent investigators have considered the sheltering effect of large particles [*Einstein*, 1950], particle protrusion [*Fenton and Abbott*, 1977], the pivot moment to move a particle past its downstream neighbor [*Komar and Li*, 1988], and the effects of particle size grading [*Wilcock and Southard*, 1989] and particle shape [*Gomez*, 1993]. None of these factors eliminate the fundamental effect of particle weight. However, when particles become interlocked, the relative effect of particle weight becomes comparatively less dominant.

Shields [1936] estimated the threshold mobility number for particle motion as 0.06 on the basis of experiments using narrowly graded material, but subsequent experimental work and field studies have indicated a range of values varying from 0.01 for fully exposed grains [*Fenton and Abbott*, 1977] to more than 0.1 for some natural streambeds [*Church*, 1978; *Reid et al.*, 1985]. This wide variation has mainly been ascribed to the effects of variable exposure in mixtures of particles and to particle imbrication and interlocking [*Laronne and Carson*, 1976], but it has been observed that identifiable grain clusters may also influence conditions at entrainment [*Brayshaw et al.*, 1983].

In gravel-bed streams with low rates of bed material transport, we have observed much more complex grain structures, which we call stone cells [cf. *Gustavson*, 1974]. The purpose of this paper is to describe these features, to obtain some phenomenological understanding of the conditions under which they develop and persist, and to explore their influence on the promotion of streambed stability.

2. Field Observations

Figure 1 illustrates the pattern of bed material in Harris Creek, British Columbia, a cobble-gravel channel in the southern interior of British Columbia with a channel width of order 10 m and a snowmelt-dominated hydrological regime with mean annual flood 19 m^3 s^{-1}. The larger exposed grains form irregular reticulate networks within which finer material persists. Stones which form the evident cell-like structures are mainly larger than D_{84} (128 mm) (D represents bed material grain size), and the usually incomplete features have characteristic spacing of order 1 m, so the ratio of structure diameter to constituent clast diameter is of order 10:1. Visualizing the structures successively as linear features and as stone-bound circles, this ratio implies that the constituent stones occupy between 15 and 25% of the bed, which occupies the range of fractional areas ($0.12 < a < 0.25$, approximately) indicated from an analysis of experimental results by *Rouse* [1965; see

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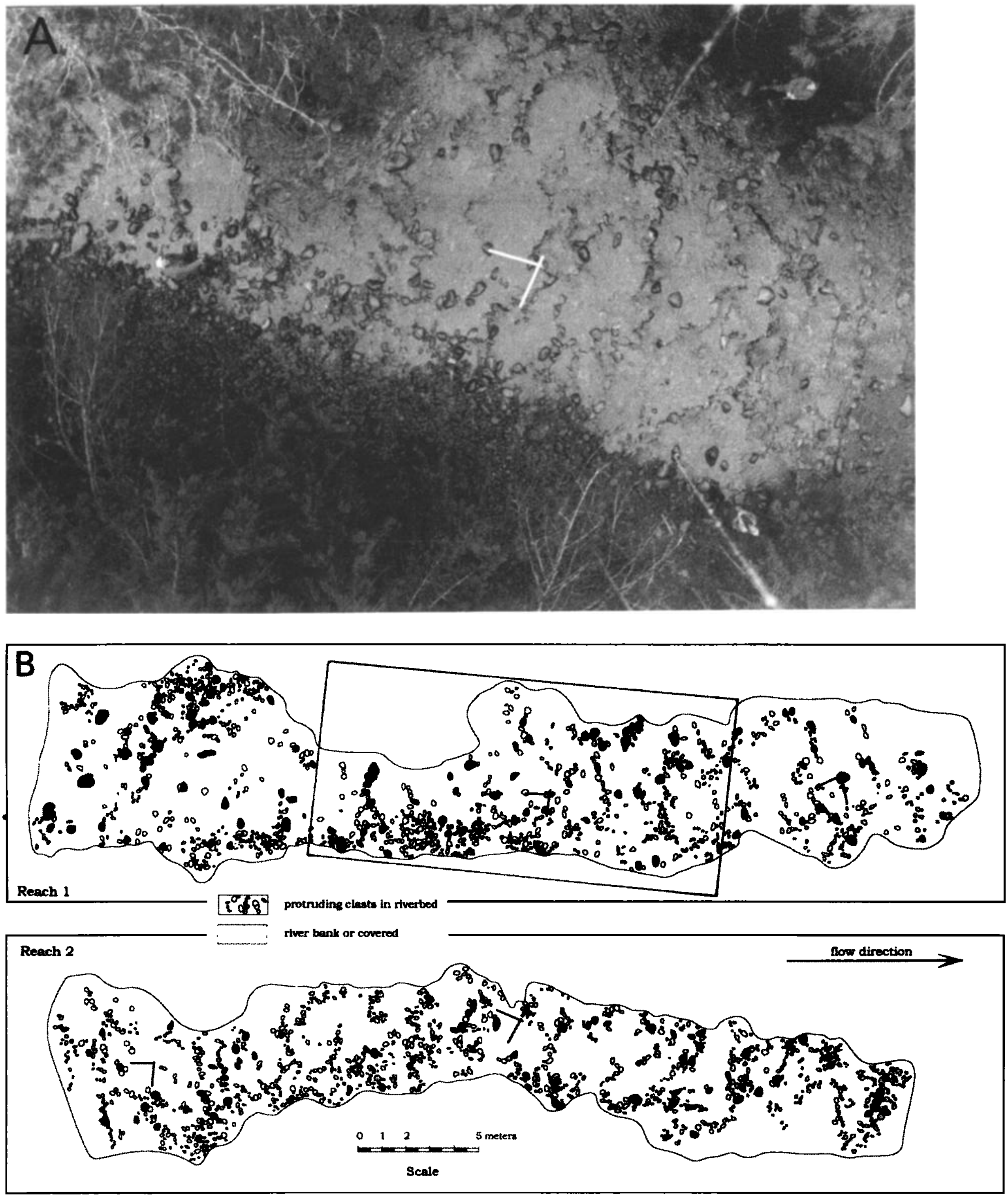

Figure 1. (a) Vertical air photograph of Harris Creek, a cobble-gravel channel near Vernon, British Columbia, with mean annual flood 19 m^3 s^{-1}. The photographs were made by suspending a radio-controlled camera in a gimbal mount below helium-filled balloons ~30 m above the surface. The rig was positioned along the channel by a "tripod" of kevlar lines (visible in the photograph). The scale bars are 1.2 m long. At low stage the cellular pattern of the dominant bed cobbles is clearly visible. (b) Map of stones which stand proud of the general surface level in the Harris Creek study reach. The map was constructed by tracing from stereo air photographs like that shown in Figure 1a, the position of which is outlined by the box. The solid black stones are those >260 mm in projected major axis diameter (this unusual definition was required by the automatic locating algorithm employed) and correspond approximately with the D_{99} of the riffle surface clasts in the stream. The generally reticulate but incomplete and irregular appearance of the stone cells is evident on this map (the map was constructed by S. Tribe).

also *Laronne and Carson*, 1976], to contribute most of the boundary frictional resistance to flow.

The features in Harris Creek tend to be transversely oriented, the principal structural element being arcuate ridges (see Figure 1b), either upstream or downstream facing. Characteristic axial ratios of the features are ~2:1. Elements of these structures have been described previously, including imbrication [*Johnston*, 1922], which is a pervasive feature of the streambed; compact clusters of stones [*Dal Cin*, 1968; *Brayshaw*, 1984]; and stone lines [*Laronne and Carson*, 1976] or transverse ribs [*Gustavson*, 1974; *Martini*, 1977; *Koster*, 1978]. Successive abstractions of progressively larger stones from the total pattern indicate that the pattern consists of arrangements of large stones formed around a random distribution of the very largest stones, consisting of stones of rank D_{99} and larger (Figure 1b). The latter, least mobile subset appears to form the stable "seed" population for the entire pattern. Cell-like structures have been observed casually in other streams and have been reported before [e.g., *McDonald and Banerjee*, 1971; *Gustavson*, 1974; *Bluck*, 1987; *Tait and Willetts*, 1992a] but have not been investigated systematically and may even be difficult for the untrained eye to recognize.

3. Experimental Arrangements

Since cellular structures are known to have great strength against shear forces, we conducted experiments to see how the structures develop and to determine the effect of the structures upon bed stability. Analyses of trapped bed load and of the surface texture of the bed provided complementary views of the evolution of the bed. Both indicate that the reluctance of the bed material to be entrained is a function of the architecture of the surface material as well as a function of grain size; the former supercedes the latter as structure develops.

Exploratory experiments in a 6 m × 0.5 m recirculating flume [*Wolcott*, 1990] were approximately scaled to field conditions in Harris Creek, and the main runs were carried out in a 10 m × 0.8 m flume with geometric scale ratios 1:16 or 1:10. The bed material was also scaled except that material scaled to finer than 180 μm was excluded. This preserved the entire gravel distribution, with maximum size 512 mm (scaled to 32 mm). The model was "generic" rather than specific in that no attempt was made to reproduce the geometrical details of the prototype channel. In fact, the Froude number within the main flow in Harris Creek varies between ~0.45 at a discharge of 7 m^3 s^{-1} when the gravel component of the bed first starts to move, and 0.60 at 25 m^3 s^{-1} when the bed becomes fully mobile. In our experiments, Froude numbers exceeded 1.0 at the highest flows (when full bed mobilization occurred in the flume). The difference relates to the lack of major channel form resistance in the model and means that the flume was not an exact model of the prototype. Nonetheless, the phenomena associated with bed mobility were recreated.

The bed was fixed in the first 0.5 m of the flume and consisted of a ~7-cm depth of potentially mobile material in the rest of the flume. Because the purpose was to study the evolution of bed stability, there was no sediment feed. Material evacuated from the flume was trapped. In a series of runs in the 6-m flume, flow depth was increased in steps to produce integer multiples of Shields number between 0.01 and 0.08. In the 10-m flume most runs had Shields number τ_* based on D_{50} of the bed surface material between 0.06 and 0.08, that is, moderately above the nominal threshold for motion of the widely graded sediment, given as 0.045 by *Wilcock and Southard* [1988] and *Komar and Li* [1988] (compare 0.047 of *Meyer-Peter and Muller* [1948]). In these runs the average value of the ratio τ_*/τ_{*c} was 1.75 ± 0.09. In an individual run, flow was maintained for up to 104 hours. Most of the 10-m flume runs were repeated (see Table 1 for details) to study the replicability of our experiments (see Figure 2a).

Before each experimental run, the bed was reconstituted by replacing the material that was transported out of the flume in the previous run and trapped and by thoroughly hand mixing the entire bed, followed by screeding it flat. In the 6-m flume runs, this bed was then sampled to determine the surface grain size distribution by pressing onto it a 0.1-m^2 plate coated with soft potter's clay, and the bed was then remixed. Within sampling error these samples were similar to the bulk mixture (but it is difficult to maintain fine material on the surface in the dry state), so this procedure was abandoned for the 10-m runs. Water was initially added slowly in order to expel all the air from the bed. In some runs, the flow was periodically stopped to allow the bed surface to be sampled using either the plate described above or, in the 10-m flume, a 15-cm-diameter piston coated with clay. In the latter case, six impressions were taken to aggregate a sampled area of 0.1 m^2 (as recommended by *Fripp and Diplas* [1993]). This procedure provides sufficient material to assure a representative surface sample, provided that segregation effects due to the development of structures are not unusual. Sometimes, replicate samples were taken in order to provide insurance against any such effects. Velocity profiles and photographs of the streambed were made at a fixed position about three-fifths of the way down the flume.

Griffiths and Sutherland [1977] have pointed out that in experiments lacking sediment feed the measured transport must vary downstream so long as material is contributed from the bed. The fixed measurement position in our experiments yields internally consistent results. However, it should be recognized that the time rate of evolution of the bed and of the sediment transport will vary down the flume according to the upstream area contributing to the transport.

We later conducted runs with sediment feed in order to obtain comparative results, but they are not reported here. Summary data of our experiments are given in Table 2. At the lowest flows in the University of British Columbia (UBC) 6-m flume, grain Reynolds number was below the usually accepted threshold for fully rough turbulent conditions, and the Weber numbers indicate that surface tension effects may have been significant, but sediment transport was not obviously anomalous.

4. Experimental Observations

During the passage of the wetting front during the entry of water into the flume, fine material (<1.4 mm) was observed to move downward into the bed. During the first hour of a run, fine material was removed from the surface, and a well-developed layer of fines could be observed (through the flume sidewall) just below the surface. After that the transport rate became very low (Figure 2a), with only a small number of grains visibly moving at any time. The texture of the surface material initially became finer than the bulk sediment texture as fines were evacuated from upstream, and then the texture of the surface material returned to near original values or coarsened (Figure 2b). After ~24 hours there was very little further change in the surface material texture. Similar observations

Table 1. Data of UBC Experiments

Run[c]	R_b, m	$S \times 10^3$	D_{50sfc}, mm	D_{50tr}, mm	τ_{*sfc}	τ_{*tr}	D_{50sfc}/D_{50tr} Observed	D_{50sfc}/D_{50tr} Expected
UBC 6-m Flume[a]								
3-1	0.0049	1.0	2.63[b]	0.45	0.0014[b]	0.0067	5.84[b]	
3-2	0.0097	1.0	2.63[b]	0.37	0.0028[b]	0.016	7.11[b]	
3-4	0.034	1.0	2.63[b]	4.11	0.0084[b]	0.0059	0.64[b]	
3-5	0.069	1.7	2.63[b]	1.25	0.033[b]	0.066	2.10[b]	
4-1	0.0050	10	2.63[b]	0.40	0.014[b]	0.076	6.58[b]	
4-2	0.0099	10	2.63[b]	0.54	0.0028[b]	0.112	4.87[b]	
4-3	0.020	10	2.63[b]	1.17	0.056[b]	0.104	2.25[b]	
4-4	0.029	10	2.63[b]	1.15	0.084[b]	0.158	2.29[b]	
UBC 10-m Flume								
I/3-1[c]	0.043	10	3.97	1.32	0.066	0.197	3.00	4.40
4-1[c]	0.050	10	3.92	1.02	0.077	0.297	3.84	6.62
5-1[c]	0.036	10	3.02	0.85	0.072	0.255	1.63	5.68
6-1[c]	0.061	10	4.70	1.31	0.078	0.281	3.59	6.25
7-1[c]	0.074	10	4.12	1.67	0.109	0.269	2.47	5.98
II/8-1[c]	0.040	11.5	4.17	0.97	0.068	0.290	4.30	6.46
9-1[c]	0.048	11.5	4.22	1.12	0.080	0.300	3.77	6.68
10-1[c]	0.053	10.4	5.12	1.52	0.065	0.220	3.37	4.90
11-1[c]	0.060	10.5	4.75	1.38	0.081	0.279	3.44	6.20
12-1	0.068	10	5.51	2.98	0.075	0.139	1.85	3.10
13-1	0.029	11.3	3.20	1.02	0.062	0.194	3.14	4.32
H/3-1	0.035	10.5	1.90	0.75	0.117	0.297	2.53	6.62
3-2	0.053	8.1	3.36	1.10	0.077	0.237	3.05	5.27
1	0.066	8.0	4.20	1.20	0.076	0.267	3.50	5.94

UBC, University of British Columbia.

[a] The reported slope is bed slope, and depth and velocity distribution tests were conducted to assure that the flow was uniform.

[b] Indicates the data of the 6-m experiments that are estimated. In these experiments a first series of runs was conducted to study the surface coarsening phenomenon. Bed surface samples were taken, but transported sediments were not trapped or measured. Series 3 and 4 were designed to replicate series 1 except that transported sediment was monitored, but no bed surface samples were taken in order to avoid disturbing the surface during the runs (all the runs in a series were sequentially accomplished by step increases of depth). Hence it was necessary to project the surface coarsening observed in series 1 onto the results of the later series. The shear stresses remained very low throughout these experiments, so surface modification was slight. Surface coarsening in series 1 never exceeded an 11% increase in D_{50}. A complication in comparing the runs is that a coarser sediment was used in the earlier runs (D_{50} = 3.44 mm), but the shear stresses were also higher. Recognizing these circumstances, it was estimated that surface textural coarsening over the bulk sediment in the later runs should be ~10% in the D_{50}. Accordingly, a surface D_{50} of 2.63 mm was assigned to all observations. The estimates are reported because they extend the results to very low transport rates.

[c] Indicates that the run was replicated (10-m flume). Experiment 10-1 was repeated twice (see Figure 2a).

have been reported by *Tait and Willetts* [1992b] and, in somewhat similar experimental circumstances, by *Hassan and Reid* [1990]. Declining sediment transport in previous experiments has been ascribed to continued degradation of the bed and coarsening of the surface [e.g., *Gessler*, 1970]. In our experiments, total degradation varied between 2 and 13 mm, i.e., between $0.6D_{50}$ and $4D_{50}$ of the bed material, and never appreciably exceeded $1.0D_{84}$. Between 1 and 10% of the bed material charge of the flume was removed in a run; one half to three quarters of it was removed during the first hour. Transported material was always much finer than the bed, on average (Figure 2b), but it tended to coarsen slowly throughout a run, and all sizes were moved.

Within a series of runs, the initial surface proceeded to coarsen at the lowest imposed flows as fine material was winnowed away or sifted into voids between the larger particles [cf. *Beschta and Jackson*, 1979], but very little additional coarsening occurred at higher flows. Larger particles typically rolled into contact with a static particle of similar size and stopped. This process resulted in cluster development. The clusters grew into particle lines, which linked up to form the reticulate structure illustrated in Figure 3. We were dependably able to replicate the development of this structure in different runs. Characteristic dimensions of the stone cells are $\sim 10D_{84}$ (longitudinal) × $6.5D_{84}$ (lateral), quite similar to the observations reported by *Tait and Willetts* [1992a] but somewhat more elongate than the geometry at Harris Creek. At their fullest development the stones forming the reticulate structures occupied of order 20% of the bed surface, and the smallest stones regularly found in the structures were ~9 mm in diameter, corresponding with the D_{75}–D_{84} size of the developed bed surface (see Figure 2b), as in Harris Creek.

Finally, when at the end of some runs the shear stress was increased beyond ~2 times that nominally necessary for entrainment, the surface layer was completely mobilized. The developing surface structure was thereby destroyed, surface grain size declined, sediment transport increased, and incipient bed forms appeared. In several cases this increased flow took the form of a "flood pulse" of ~15 min duration, after which flow was returned to its former level. Phenomena included the incision of a talweg and bar formation; surface fining as the structure was destroyed, followed by the reestablishment of the coarse surface when flow was reduced; and a dramatic increase in sediment transport during the flood. These phenomena were not pursued systematically.

In later experiments we fed sediment with the same size distribution as that in the bulk bed material. We observed that the structural development varied with the sediment feed rate, becoming less complete as sediment transport increased. This seems reasonable, since to sustain higher rates of transport requires more frequent exchanges between the mobile sediment and the bed. If all sizes take part in the transport, this will include the larger, structure-forming clasts. This picture is consistent with the appearance that in a flume (or river reach) with sediment feed, the transport process and the surface adjust to transport material in proportion to the feed rate [see *Dietrich et al.*, 1989; *Parker and Wilcock*, 1993], and it is consistent with the concept of partial transport [*Wilcock and McArdell*, 1997] at moderate transport rates. We have not detected any systematic variation in the structure dimensions in our experiments, but we expect that our procedures may not be sufficiently sensitive to provide a critical test of that possibility. Our analysis of the sediment feed experiments will be reported elsewhere.

5. Analysis

It has been established that a Shields number calculation using D_{50} of bed surface material reliably determines the force ratio at the bed producing sediment transport [*Parker and Klingeman*, 1982; *Wilcock and McArdell*, 1993]. *Dietrich et al.* [1989] took advantage of this fact to estimate the degree to which bed surface armoring should reduce sediment transport. They formed the ratio of transport rate for the armored surface compared with the transport rate estimated for a surface as fine as the load:

$$q_* = [(\tau_b - \tau_{cs})/(\tau_b - \tau_{ct})]^{1.5} \tag{1}$$

in which q_* is the dimensionless sediment transport (the transport ratio); τ_b is the shear stress imposed on the bed; τ_{cs} is the critical shear stress for the surface material, which is supposed to be proportional to the D_{50} size of the surface material; and τ_{ct} is the indicated critical shear stress that would be associated with the transported load. This formulation assumes that the transport function is of the form $f(\tau_b - \tau_c)^{1.5}$ (as does, for example, the well-known formula of *Meyer-Peter and Muller* [1948]), which seems reasonable for gravel. We estimated τ_c as $0.045g(\rho_s - \rho)D_{50}$, in which the value of D_{50} appropriate for the calculation is used. At the end of our experiments, the bed material transport rate q_b was typically of the order 0.1 kg h^{-1}. In comparison with $q_b|_{t=1}$, the value after 1 hour, which we take to be a reasonable estimate of the transport over an undeveloped surface, $q_* = q_b|_{t=100}/q_b|_{t=1}$ is of order 0.001 (Figure 2a). Using this value, (1) yields the approximate equality $D_{50s}/D_{50t} \approx (\tau_b/\tau_{ct})$, from which we may obtain an expected ratio of surface to transported grain sizes. Over the 14 experimental runs in the 10-m flume, we obtain an expected mean value of $D_{50s}/D_{50t} = 5.60 \pm 0.29$ (the second number is the standard error). The observed value of this ratio was 3.11 ± 0.20. The difference between these two results is the direct consequence of the surface structure. Conversely, (1) predicts values of q_* in the range $0.21 \leq q_* \leq 0.62$, more than 2 orders of magnitude larger than the observed results.

Further consideration of (1) yields quantitative insight into the effect of bed structure on the entrainment threshold. Inspection of (1) shows that q_* approaches zero within a reasonable range of τ_* only when τ_{*cs} increases, so that the numerator approaches zero. For $D_{50s} = 4.2$ mm, $D_{50t} = 1.35$ mm, and $\tau_b = 5.1$ Pa (all values being close to the means recorded in our 10-m flume runs), the upper limit of τ_{*cs} for nonzero sediment transport is 0.075. The mean-indicated value of τ_{*cs} in the same runs (using the observed values of D_{50s}) was 0.079 ± 0.005. At $\tau_{*cs} = 0.060$, $q_* = 0.12$. The function becomes very sensitive above that value. It appears, then, that

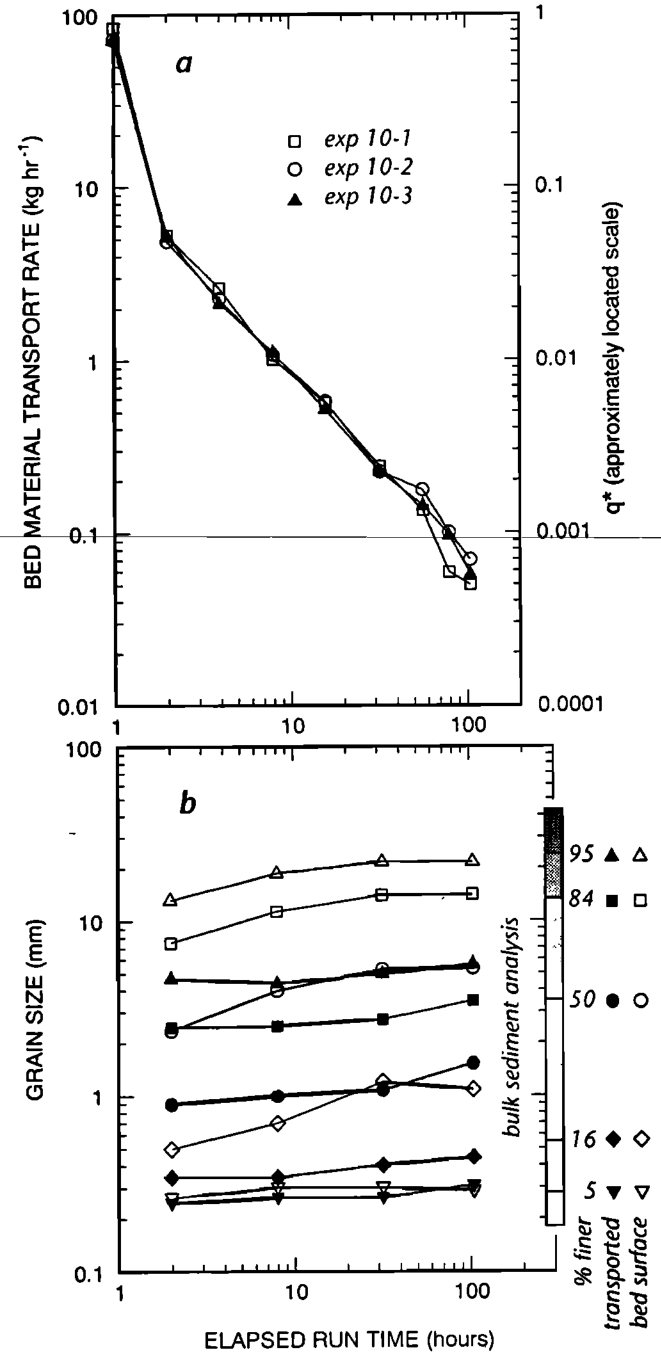

Figure 2. (a) Sediment transport at the end of the flume during three replicate runs. The similarity indicates that the results may be duplicated except that, late in the experiment, the vagaries of structure development influence the residual transport. The scale on the right-hand ordinate is approximately located. The definition of q_* is given by equation (1). (b) Evolution of bed surface and transported sediment texture over time, experiment 10-2. The bar graph on the right-hand ordinate indicates the size distribution of the initial bulk sediment placed in the flume, and the symbols code the corresponding proportions for the bed surface and the transported sediment trapped at the end of the flume.

Table 2. Range of Conditions Within Each Series of Experiments and Some Other Experiments Used in Our Analysis

	Key Grain Sizes of Bulk Sediment			Grain Reynolds Number		Froude Number		Weber Number[a]	
Series	D_{50}	D_{84}	Tr[b]	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
UBC Experiments									
6 m	2.39	3.90	11.8	153	13.9	0.98	0.25	190	0.33
10 m/I	2.20	8.10	16.2	530	311	1.2	0.65	1000	27
10 m/II	3.20	14.5	29.0	908	640	1.2	0.88	920	63
10 m/H	1.41	7.9	20.8	302	114	1.31	1.18	711	276
Lamberti and Paris [1992]									
I	2.69	5.27	3.63	316	311	0.74	0.47	210	110
II	3.68	7.73	7.73	456	433	1.1	0.42	1400	390
III	2.36	6.54	5.95	386	353	1.0	0.46	1200	160
Gomez [1993]									
Round	6.33	16.1	5.34	1733[c]	528[c]	0.77	0.63	2414[c]	957[c]
Flat	10.7	19.6	4.22	1417[c]	811[c]	0.89	0.73	2262[c]	1308[c]
Angular	7.61	14.7	4.43	1663[c]	793[c]	0.75	0.66	2373[c]	1225[c]

UBC, University of British Columbia.

[a] The Weber number is $\rho R v^2/\sigma$, in which ρ is the density of the fluid, v is the hydraulic radius, v is the mean velocity, and σ is the surface tension of water. It indicates the ratio of gravitational to surface forces and indicates the possibility for surface tension effects to be significant.

[b] $Tr = D_{84}/D_{16}$, which is different than the conventional definition.

[c] Data are estimated (water temperature is estimated as 15°C).

an increase of τ_{*cs} by ~67% above the nominal threshold for widely graded mixtures and by ~30% above the classical Shields datum covers a surface structural effect sufficient to reduce the transport of sediment derived from the bed in the same vicinity to near zero. A. C. Brayshaw [*Naden and Brayshaw*, 1987] has previously reported a 12% increase in shear stress necessary to entrain clasts from clusters in comparison with that necessary to entrain material from the open bed. This sensitivity has probably militated against the casual observation of complex structural effects in previous works.

Some investigators have noted that a decline in the bed sediment transport rate is associated with increasing resistance to flow associated with increasing bed roughness. *Hassan and Reid* [1990] demonstrated the effect by systematically increasing the density of stable cluster bed forms in experimental flume runs. They supposed that minimum transport would be associated with the onset of skimming flow, when substantially all of the fluid stress is borne by the stable structures [*Morris*, 1955] (further references given by *Hassan and Reid* [1990]). The question arises whether stone cells represent this "optimally stable" condition, as is suggested by spacing criteria in both the field and the flume.

We studied resistance to flow and roughness length by making measurements of the velocity profile at five positions in a cross pattern within our observing reach. The difficulty in making such measurements yields relatively poor estimations of these quantities [*Wilcock*, 1996]. Nonetheless, Figure 4 suggests that the roughness length k_s increases in our experiments by as much as an order of magnitude, although apparently by a lesser amount at the highest flow tested. Roughness length k_s is a conceptual length commonly supposed to be a small multiple of bed surface D_{50} or D_{84}. In the experiments illustrated, D_{84} was 8 mm, so k_s, so far as it is determined by grain roughness, ought to be in the range 0.016–0.032 m (i.e., for $2D_{84} < k_s < 4D_{84}$, which encompasses the range of commonly quoted results) and could not appreciably exceed 0.10, even if the surface coarsened to the point that it consisted only of the uppermost few percentiles of bed material (in the range 22–32 mm). In fact, the lowest observed value is ~0.1, and values increase to order 1.0. The range is far greater than that which could be accounted for by textural coarsening of the surface, and this range leads to roughness length estimates an order of magnitude greater than the grain sizes could support. Evidently, structural effects are significant. Total flow resistance, as indexed by Manning's n, behaves similarly, although these results are not conclusive because of the high variance associated with our measurements. Most of the change in n occurs in the first 24 hours while surface coarsening occurs, the main elements of the surface structure develop, and sediment transport declines most dramatically. *Whiting and Dietrich* [1990] concluded that the larger clasts on the surface constitute the most significant source of flow resistance in gravel-bed channels. However, *Gessler* [1990], following a careful analysis of experimental results on armored beds, claimed that the friction factor is indeed related to the arrangement of the coarser grains. The conditions at the end of our experiments present approximately the same situation as that analyzed by Gessler, and our roughness length estimates confirm his conclusion.

6. Discussion

The stability of the gravel bed is enhanced by two mechanisms. Textural coarsening of the surface, seen in the initial stage of our experiments when sediment transport was still substantial, has been widely remarked [e.g., *Parker and Klingeman*, 1982; *Dietrich et al.*, 1989; *Wilcock and Southard*, 1989; *Tait et al.*, 1992]. The bed derives stability from the relatively great inertia of the exposed surface material. Such vertical sorting has variously been described as "armor," "pavement," or simply as surface coarsening [*Harrison*, 1950; *Parker and Klingeman*, 1982; *Sutherland*, 1987]. *Gessler* [1970] expected that the bed would continue to coarsen until sediment transport fell to zero. The conventional Shields approach to bed stability encompasses only this aspect of bed character, which is indexed satisfactorily by texture.

Our results indicate that structural modification of the bed surface plays an important role. The implications of bed struc-

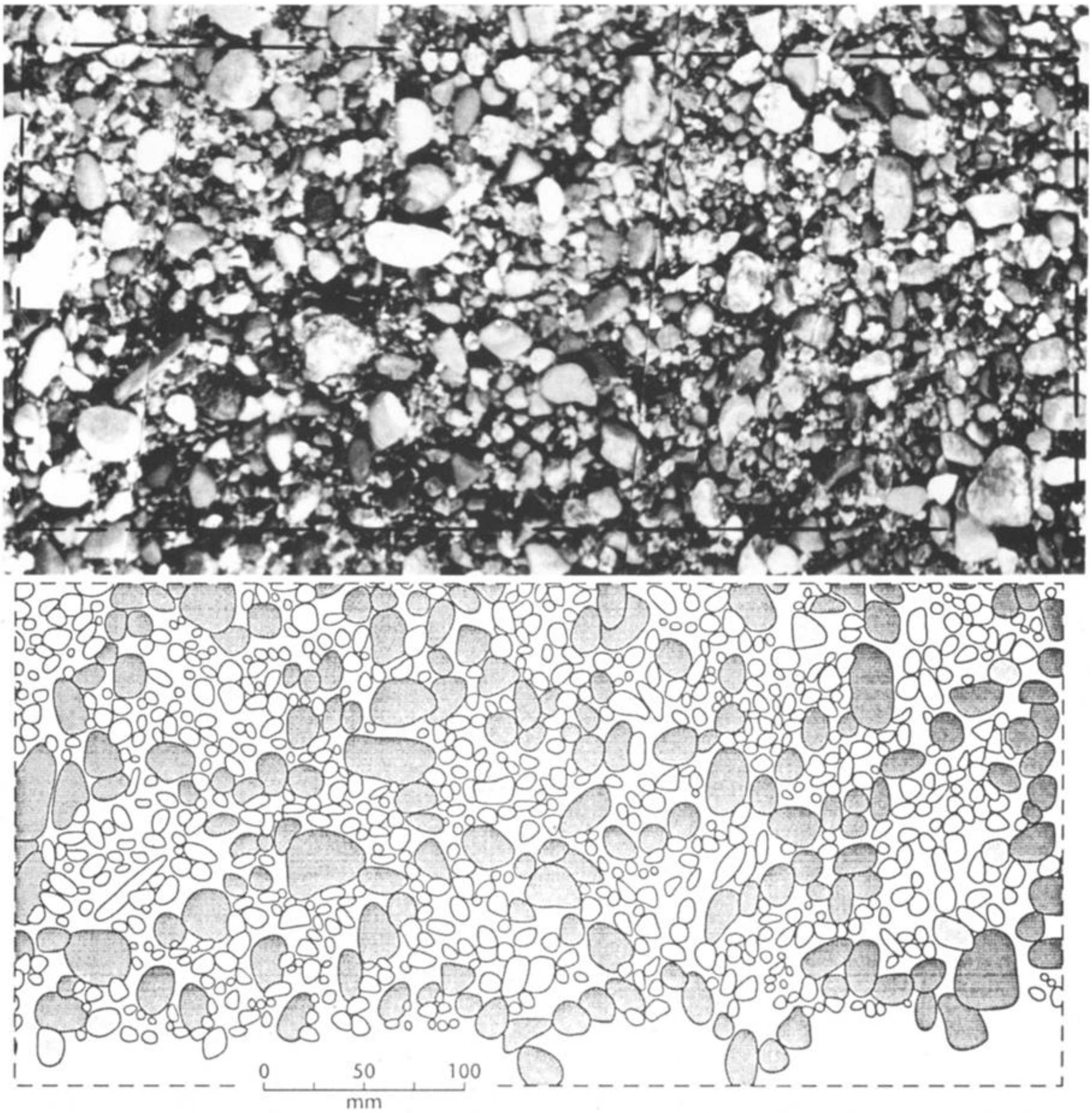

Figure 3. Pattern of large stones on the bed surface after the experimental flume run 10-3; the vertical photograph and drawing are to the same scale. The darkly shaded stones are those larger than D_{84} (12 mm) and the smaller stones in interlocked contact with them that form the reticulate structure of the bed surface. Different analysts operating independently identify the same structural pattern from the photographs.

ture for bed stability have been considered only qualitatively, except insofar as pivot angle analysis [*Wiberg and Smith*, 1987; *Komar and Li*, 1988], the analysis of friction angles [*Kirchner et al.*, 1990; *Buffington et al.*, 1992], and the stability of cluster bed forms [*Brayshaw et al.*, 1983; *Brayshaw*, 1985] approach the problem. The development of persistent structures on the bed surface, in fact, appears to limit the textural modification of the bed, since transport rates become much smaller than the change in surface grain size indicates it should. The key effect is substantial further reduction in the mobility of the larger stones, which then effectively hide smaller material. A self-organized reticulate web, as described in this study, appears to be the stable end point of structural development. Advanced stages of development are reached in channels with sufficiently wide grading of the bed material (see Figures 1 and 3) after an extended period of low to negligible sediment influx, such as is characteristic of the nival flow regime of Harris Creek and as is replicated in our flume.

A careful reading of *Shields'* [1936] report suggests that he controlled the effect of surface structure by creating a uniform particle arrangement prior to taking each set of measurements. He achieved this by using narrowly graded materials and by following the same starting procedure for each of his runs. If particle arrangement is held constant, bed strength is a reliable function of particle weight, as Shields discovered. If it is not, the development of an interlocked structure dominates the bed strength in mixed-size sediments.

The effect of the developing bed structure is quantified in Figure 5, which compares the critical Shields number based on the transported sediment with that expected for the surface bed material (data given in Table 1). Figure 5 includes results obtained by *Lamberti and Paris* [1992] and *Gomez* [1993] in

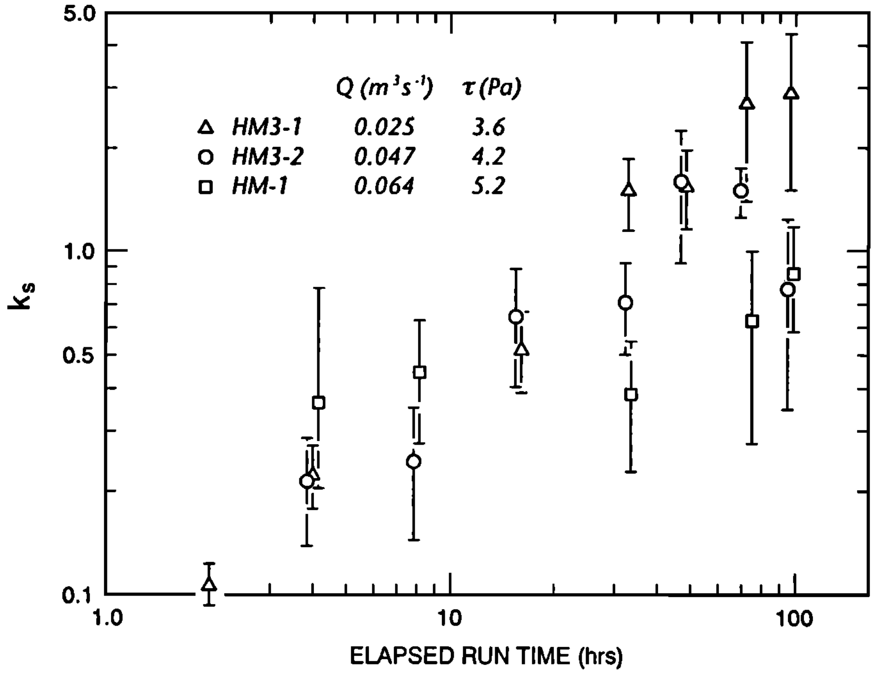

Figure 4. Evolution of k_s during relatively low, intermediate, and high flows, based on the average of four or five determinations from velocity profiles. The error bars represent two standard error ranges about the observations. It may be assumed that the observed changes depended on the evolution of the bed surface, since larger-scale form roughness was absent during these experiments. Estimates of flow and shear stress are the averages for the runs; minor variations occurred during the runs.

experiments conceptually similar to ours, conducted for the purpose of studying armor development (data given in Table 3). The effect is parameterized by a modest increase in Shields number. Eventually, however, the fluid shear may become so great that the surface configuration is destroyed and the difference between the two estimates of shear stress returns again to zero.

A range of material sizes is obviously necessary for recognizable structures to develop. Figure 5 suggests that when the modified sediment Trask coefficient D_{84}/D_{16} falls below 10 (compare our values with those of other investigators in Table 1), the difference between the two Shields numbers becomes more limited and so, correspondingly, does the structural modification of the bed. In their experiments, conducted mainly with only moderately graded material, neither *Lamberti and Paris* [1992] nor *Gomez* [1993] reported structural modifications other than armor development (but nor, probably, were they searching for any). There is also a hint that, based on Gomez's data, particle shape exercises a minor effect on the outcome.

Structural development occurs in the regime of partial transport of *Wilcock and McArdell* [1997] (Figure 6) because of the "keystone" role played by the mainly immobile largest stones. Early development occurs in the regime of "mobile armor" (all sizes in motion) because the largest stones are displaced, albeit relatively infrequently. However, late in the process, a stable armor in the sense of *Gomez* [1994] develops; bed load transport is reduced to a low rate and is systematically finer than the surface material. *Gomez* [1994, p. 2237] remarked that the development of stable armor entails "wholesale rearrangement of the surficial bed material," but he was no more specific. *Gessler* [1992] had previously considered pattern development in armor and reported statistical results of *Ahmed* [1989], which demonstrated that the grouping of the largest clasts becomes stronger with increasing stress, up to the point when the armor structure breaks down. These observations are consistent with ours.

Data of Figures 2 and 5 suggest the following qualitative model of gravel-bed surface response to increasing flows. If a widely graded surface initially has no structure, it will first coarsen by winnowing at flows with relatively low stresses and sediment supply. Fine material is transported away or sifted into voids just below the surface where it is sheltered from entrainment. The coarse grains move or settle into more stable individual positions and joint configurations on the surface (see *Tribe and Church*, this issue]. This process is self-limiting because the increasing bed stability limits further sediment transport. In our experiments this is exemplified by the asymptotic decline of sediment transport during an individual run, when the shear stress remains essentially constant.

Figure 1 suggests the time necessary to decrease the sediment transport by 1 or 2 orders of magnitude. Froude scaling of the flume provides a time ratio of 4 for a river 0.5 m deep; 100 hours in the flume is equivalent to 16 days in nature. Since flume conditions were steady within a run, whereas most rivers are not steady for 2 weeks at a time, it would appear that the beds of most small rivers are unlikely to be in dynamic equilibrium with flows over them during conditions of competent flow with low sediment influx. A similar conclusion has been reached with respect to primary bed form development on sand beds [*Allen*, 1973].

Since the degree of structural development depends on the history of recent flows, we may expect flow history to have a systematic but complex effect upon the history of bed material transport in natural rivers. This phenomenon has been observed by *Reid et al.* [1985]. They drew the conclusion, which our results emphasize [see also *Tait and Willetts*, 1992a], that simple functional relations between sediment transport and measures of stream power or tractive force, derived largely on the basis of equilibrium experimental studies (such as *Shields'* [1936] original experiments), are unlikely to cover the phenomena in nature. Natural streams exploit widely graded materials to create critically stable conditions at the bed, but the condition is not simply maintained because of the fluctuating flows. Most of the time, conditions are either subcritical, in the sense that the flow is insufficient to disturb the bed significantly, or the stresses applied by the flow create a transient situation in which the bed is adjusting toward a new critical state, so far as the accompanying sediment influx from upstream will allow it. One hopes that further study of the phenomena associated with the development of bed structures will reveal a satisfactorily expanded parameterization of the sediment transport problem.

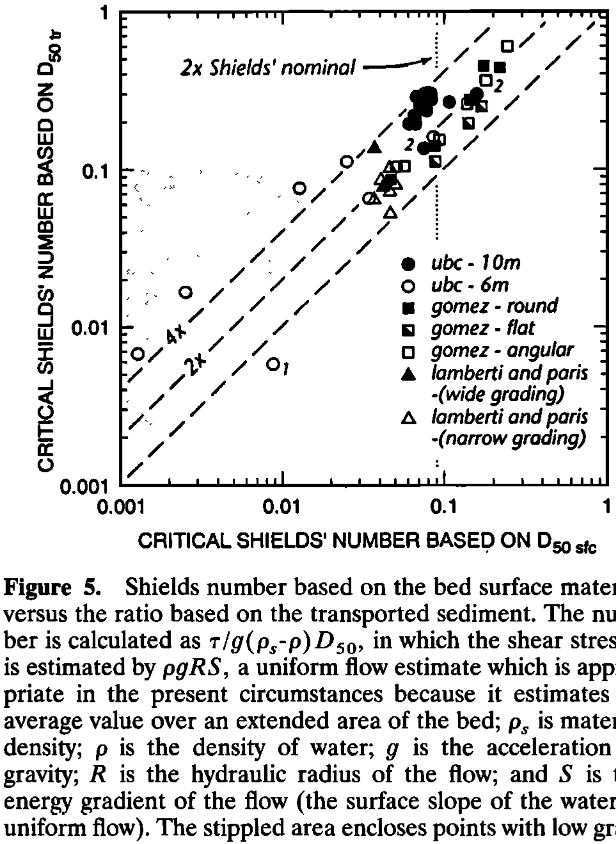

Figure 5. Shields number based on the bed surface material versus the ratio based on the transported sediment. The number is calculated as $\tau/g(\rho_s\text{-}\rho)D_{50}$, in which the shear stress τ is estimated by ρgRS, a uniform flow estimate which is appropriate in the present circumstances because it estimates an average value over an extended area of the bed; ρ_s is material density; ρ is the density of water; g is the acceleration of gravity; R is the hydraulic radius of the flow; and S is the energy gradient of the flow (the surface slope of the water in uniform flow). The stippled area encloses points with low grain Reynolds numbers. The point marked 1 had anomalously low transport of mainly larger material; points marked 2 were the high flows in which bed forms developed. The results of logistically similar experiments by *Lamberti and Paris* [1992] and *Gomez* [1993], with much narrower sediment grading, are shown for comparison (a summary of the experiments is given in Table 2, and data are given in Table 3). In the experiments of Lamberti and Paris, sediment transport was allowed to decline until it was a few percent of the initial value before flow conditions were changed; in Gomez's experiments, runs were ended when the transport was <1% of the initial value. However, results on τ_{*ct} may be slightly biased because the reported transport grain size is based on a composite sample of material transported during the entire experiment, not just on material trapped near the end of the run. Gomez replicated his runs 3 times; we have plotted the mean of each set.

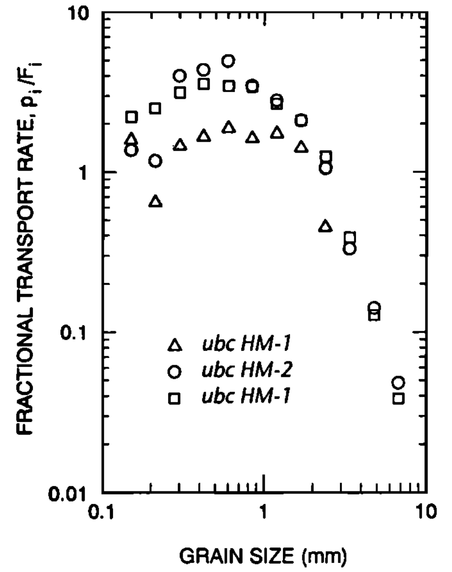

Figure 6. Fractional transport rate late in the experimental run as a function of grain size for the University of British Columbia (UBC) 10-m experiments with relatively low, intermediate, and high flow. The fraction of transported sediment in the ith size fraction is indicated by p_i; F_i indicates the fraction of bed surface material in the same fraction. The diagram shows that the largest material contributes very little to the transport, whereas most of the transported material is substantially smaller than D_{50} of the bed. These are the same runs as are illustrated in Figure 4.

7. Conclusions

In this paper we present observations of stable, reticulate stone cells developed on the bed surface in cobble-gravel streams with relatively widely graded sediments, and we give an experimental demonstration that these structures promote streambed (and therefore channel) stability by dramatically reducing the transport of bed material. The development of surface structure is a self-organized, critical phenomenon, the emergent product of stochastic encounters among individual grains.

The joint effect of armoring and structural development in our experiments increased the critical Shields number by ~2 times (above the accepted value of 0.045 for widely graded gravels), but a range of other observations indicates that larger changes may occur. Sediment transport is reduced by up to 10^3 times, in the partial transport regime of *Wilcock and McArdell* [1997]. Indeed, the development of persistent surface structures (including armor) appears to be the reason why most gravel-bed streams exhibit partial transport on most occasions when bed material moves at all. Some grains, although partially exposed on the surface, remain too well constrained by their neighbors to be entrained. As the proportion of streamflow energy expended in turbulent motion promoted by the streambed configuration approaches 100%, the friction factor also increases.

Since variable grain size is a prerequisite for recognizable structures to develop, the structural effect unsurprisingly appears to depend on particle grading. Characteristic particle

Table 3. Data of Other Experiments

Run	R_b, m	$S \times 10^3$	D_{50sfc}, mm	D_{50tr}, mm	τ_{*sfc}	τ_{*tr}	D_{50sfc}/D_{50tr} Observed
			Lamberti and Paris [1992]				
1-1	0.130	1.9	4.10	2.21	0.035	0.064	1.86
1-2	0.142	2.0	3.61	3.20	0.046	0.052	1.13
1-3	0.058	6.3	5.07	2.41	0.042	0.089	2.10
1-4	0.057[a]	5.0	3.78	2.26	0.044	0.074	1.67
2-7	0.057[a]	6.7	5.33	1.21	0.042	0.086	4.40
2-8	0.160	2.0	5.15	1.38	0.037	0.136	3.73
3-9	0.132	2.4	3.94	1.84	0.047	0.101	2.14
3-10	0.051	5.1	3.06	1.87	0.050	0.082	1.64
			Gomez [1993][b]				
1A	0.109	9.2	12.0	7.2	0.049	0.082	1.67
1B	0.106	10.3	12.9	5.9	0.050	0.109	2.19
1C	0.112	8.0	12.1	8.2	0.044	0.064	1.48
1D	0.124	15.8	13.3	9.7	0.087	0.119	1.37
1E	0.133	14.3	13.6	7.2	0.082	0.155	1.89
1F	0.140	15.2	13.6	8.9	0.092	0.141	1.53
1G	0.141	22.9	14.7	5.6	0.129	0.339	2.63
1H	0.151	24.3	13.7	9.0	0.158	0.240	1.52
1I	0.150	22.2	13.4	7.2	0.146	0.272	1.86
1J	0.153	30.7	14.8	6.3	0.187	0.439	2.35
1K	0.164	28.0	14.8	5.9	0.183	0.458	2.51
1L	0.161	24.8	14.5	5.2	0.162	0.452	2.79
1M	0.166	35.8	17.5	7.0	0.198	0.499	2.50
1N	0.170	31.1	15.2	7.7	0.205	0.404	1.97
1O	0.172	35.1	14.5	8.2	0.245	0.433	1.77
2D	0.125	13.9	10.0	9.3	0.102	0.110	1.08
2E	0.118	12.0	10.3	7.9	0.081	0.105	1.30
2F	0.124	12.1	11.1	8.2	0.080	0.108	1.35
2G	0.140	18.7	11.1	9.9	0.139	0.156	1.12
2H	0.138	21.0	12.1	7.4	0.141	0.230	1.64
2I	0.139	22.4	12.0	9.0	0.153	0.204	1.33
2J	0.147	26.2	12.2	8.4	0.186	0.270	1.45
2K	0.136	27.3	13.2	7.9	0.165	0.276	1.67
2L	0.140	24.6	13.2	8.3	0.153	0.244	1.59
3D	0.128	12.5	11.8	7.3	0.080	0.129	1.62
3E	0.134	15.0	11.6	7.2	0.100	0.164	1.61
3F	0.128	13.1	11.2	7.5	0.088	0.131	1.49
3G	0.148	22.8	12.5	6.8	0.159	0.292	1.84
3H	0.141	21.2	13.0	6.4	0.135	0.275	2.03
3I	0.139	23.3	13.8	6.9	0.138	0.276	2.00
3J	0.158	26.9	13.8	7.0	0.181	0.357	1.97
3K	0.162	29.3	14.3	6.4	0.195	0.436	2.23
3L	0.167	26.6	14.3	6.9	0.183	0.379	2.07
3M	0.169	39.3	16.8	7.5	0.233	0.521	2.24
3N	0.170	33.6	15.7	7.6	0.214	0.442	2.07
3O	0.178	37.1	14.5	7.2	0.268	0.540	2.01

[a] Data are estimated.

[b] The *Gomez* [1993] data are plotted in Figure 5 as averages of successive sets of three data.

shape also appears to have a minor influence. Critical Shields numbers based on the transported material increase above the critical number based on the bed surface by ~2 times for armored surfaces with cluster development and by as much as 4 times (see Figure 5) for highly structured surfaces. This is the basis for the high critical Shields numbers reported in some field studies and for a parameterization of the effect on sediment transport of the development of surface structures.

The timescale for the development of surface structures, which occurs at relatively low rates of sediment transport, is long in comparison with typical fluctuations in water discharge. A consequence is that most gravel-bed streams are probably not in equilibrium with imposed flows of typically limited competence.

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Evaluating the relationship between biotic and sediment metrics using mesocosms and field studies

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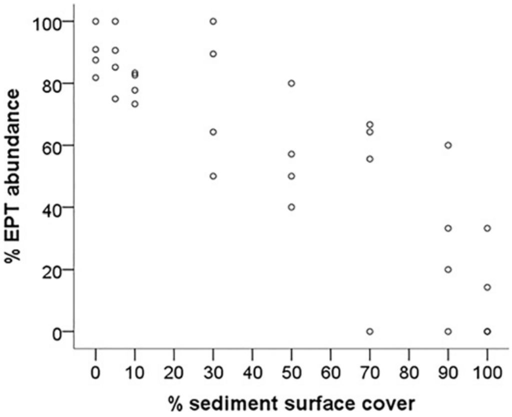
HIGHLIGHTS

- Sediment impact detection using appropriate bioassessment metrics is challenging.
- Mesocosm and field observations were used to assess the relationship between metrics.
- % EPT abundance and richness metrics were negatively correlated with surface cover.
- Inclusion of biotic and sediment metrics in fluvial monitoring would be beneficial

GRAPHICAL ABSTRACT



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ABSTRACT

An ongoing research challenge is the detection of biological responses to elevated sediment and the identification of sediment-specific bioassessment metrics to evaluate these biological responses. Laboratory mesocosms and field observations in rivers in Ireland were used to evaluate the relationship between a range of biological and sediment metrics and to assess which biological metrics were best at discerning the effects of excess sediment on macroinvertebrates. Results from the mesocosm study indicated a marked decrease in the abundance of sensitive taxa with increasing sediment surface cover. % EPT (Ephemeroptera, Plecoptera, Trichoptera) and % E abundances exhibited the strongest negative correlation with sediment surface cover in the mesocosm study. The field study revealed that % EPT abundance was most closely correlated with % sediment surface cover, explaining 13% of the variance in the biological metric. Both studies revealed weaker relationships with a number of other taxonomy-based metrics including total taxon abundance, total taxon richness and moderate relationships with the Proportion of Sediment-sensitive Invertebrates metric (PSI). All trait-based metrics were poorly correlated with sediment surface cover in the field study. In terms of sediment metrics, % surface cover was

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more closely related to biological metrics than either re-suspendable sediment or turbidity. These results indicate that % sediment surface cover and % EPT abundance may be useful metrics for assessing the effect of excessive sediment on macroinvertebrates. However, EPT metrics may not be specific to sediment impact and therefore when applied to rivers with multiple pressures should be combined with observations on sediment cover.

1. Introduction

Fine sediment is a vital element in freshwater systems and important to nutrient cycling, substrate composition and heterogeneity, all of which play a part in regulating the micro-environmental conditions in which macroinvertebrates reside (Rabeni and Minshall, 1977; Minshall, 1988; Richards et al., 1997; Wood and Armitage, 1997; Owens et al., 2005). Excessive fine sedimentation, however, may alter substrate composition, increase habitat homogeneity and is considered to be a major ecosystem stressor leading to ecological impairment (Rabení et al., 2005; Wood et al., 2005; Niyogi et al., 2007; Bryce et al., 2010). A suite of impacts including the clogging of substrate interstices, smothering of habitats and reduction in habitat stability (Wood and Armitage, 1997; Bilotta and Brazier, 2008; Jones et al., 2012) may cause significant environmental degradation and, in extreme cases, lead to a significant deviation from 'reference conditions' (Bilotta and Brazier, 2008).

A number of research strategies, such as field surveys, stream-side experiments and/or laboratory experiments (mesocosms) may help to detect ecological responses to, and differentiate between natural and anthropogenic stressors. (Robinson and Uehlinger, 2008; Townsend et al., 2008; Wagenhoff et al., 2012). Combining different research strategies, each with their own specific strengths and weaknesses, may also help to tease out the effects of confounding factors, e.g. multiple stressors and flow variations (Robinson and Uehlinger, 2008; Townsend et al., 2008; Wagenhoff et al., 2012). Using mesocosms allows for the isolation and direct manipulation of stressors while minimising confounding factors (Suren and Jowett, 2001; Connolly and Pearson, 2007; Wagenhoff et al., 2012; O'Callaghan et al., 2015; Piggott et al., 2015). However, the extrapolation of findings from mesocosm studies to whole river systems should be undertaken with caution due, in part, to differences in spatial and temporal scales (Townsend et al., 2008; Sandin and Solimini, 2009). While field surveys best represent natural conditions, they may be influenced by a range of co-varying drivers which may mask or exacerbate biological responses (Robinson and Minshall, 1986; Larsen et al., 2009; Matthaei et al., 2010; Robinson et al., 2011; Wagenhoff et al., 2011; Burdon et al., 2013; Glendell et al., 2014; Turley et al., 2014).

An array of biological metrics have been developed to detect the impact of specific environmental stressors such as nutrients, acidification, flow and habitat loss (Hilsenhoff, 1987; Hawkes, 1998; Extence et al., 1999; Davy-Bowker et al., 2005; Dunbar et al., 2010). In contrast, relatively few metrics have been specifically developed to detect the effects of sedimentation on macroinvertebrates (Relyea et al., 2000; Zweig and Rabení, 2001; Bryce et al., 2010), and the lack of a standardised bioassessment method to detect the impacts of fine sediment deposition makes inter-study comparisons problematic (Clews and Ormerod, 2009). Recently, Extence et al. (2013) developed a sediment-sensitive macroinvertebrate metric, Proportion of Sediment-sensitive Invertebrtes (PSI), based on expert review of existing literature and an assessment of biological traits to assign taxa to one of four sensitivity groups while Murphy et al. (2015) developed a combined fine sediment metric (CoFSIsp) based on two sub-indices which captures macroinvertebrate responses to organic sediment in erosional zones (oFSIsp) and to total fine sediment in depositional zones (ToFSIsp).

Conserving and protecting aquatic systems is of huge importance for environmental sustainability, but also politically and in terms of public perception (Strayer, 2006). Macroinvertebrates are key water quality indicators in many bioassessment programmes (e.g. Bonada et al., 2006) and their sensitivity to pollutants, including fine sediment, make them ideal organisms for assessing water quality (Rosenberg and Resh, 1993; Bonada et al., 2006). It is clear from previous studies that EPT taxa are sensitive to elevated sediment, but the mechanisms causing the responses are not well elucidated and thus a wide range of mechanisms have been proposed to explain observed changes in community structure (Zweig and Rabení, 2001; Niyogi et al., 2007; Bryce et al., 2010; Wagenhoff et al., 2011; Sutherland et al., 2012; Burdon et al., 2013). For example, ephemeropteran taxa can be impacted by sedimentation in a number of ways. Smothering of the periphyton by sediment can lead to impaired scraper feeding (Larsen and Ormerod, 2010). The grazer/clinger *Ecdyonurus* sp., requires clean interstices so as to maintain position in the substrate and the grazer *Baetis rhodani* have been shown to generally avoid fine substrates (Rabení et al., 2005; Wood et al., 2005; Larsen and Ormerod, 2010; Pollard and Yuan, 2010). Fine particles can also impair the gill respiring mechanisms of these two taxa (Lemly, 1982). In contrast, others have found positive relationships between sedimentation and baetid mayflies (Angradi, 1999; Sutherland et al., 2012). Taxa from some trichopteran families have also been shown to be negatively impacted by sediment (Larsen et al., 2009). The preferred habitat of hydropsychids is fast flowing, sediment-free habitats as sediment can interfere with the feeding nets of this taxon (Strand and Merritt, 1997). In contrast, a number of Limnephilidae (Trichoptera) and Caenidae (Ephemeroptera) taxa are known to be less sensitive to fine sediment (Turley et al., 2014). Clearly, a current research challenge is the detection of biological responses to elevated fine sediment and identification of sediment-specific bioassessment metrics. Furthermore, while many of the biological impacts of sedimentation are linked to sediment deposition, current guidelines, based on suspended sediment concentration as set out in the recently repealed Freshwater Fisheries Directive (78/659/EEC), may not be appropriate to protect ecological status (Cooper et al., 2008: Kefford et al., 2010; Bilotta et al., 2012; Jones et al., 2012).

The present study explores how a number of commonly used macroinvertebrate taxonomy- and trait-based metrics respond to measures of deposited sediment using both mesocosm laboratory channels and a field study, with the latter representing more realistic conditions. Three sediment metrics, % sediment surface cover, re-suspendable sediment and turbidity, which gave accurate estimates of deposited sediment levels (Conroy et al., 2016a, 2016b) were assessed together with a range of biological metrics to establish which were the most appropriate in detecting sediment effects. In addition, the mesocosms provided evidence of responses to sediment addition through analysis of macroinvertebrate drift and of the taxa remaining in the channels at the end of the experiment. In this regard it was hypothesised that the channels with high sediment loads would (i) show increased rates of macroinvertebrate drift during the first 24 h and throughout the experiment and (ii) have decreased abundance of taxa remaining in channel at the end of the experiment. The field study also assessed temporal variability in the strength of the associations between biological metrics and sediment metrics and whether taxonomic resolution, i.e. family versus species, influenced the strength of the associations. The hypothesis to be tested was that taxa richness and abundance metrics would be negatively correlated with % fine sediment surface cover.

2. Materials and methods

2.1. Mesocosm study

The experimental design consisted of eight levels of deposited fine sediment amounts with four replicates of each treatment giving a total of 32 experimental channels. A 3-cm bed of washed, sieved, gravel and pebble substrate (4–20 mm diameter), 9 L of river water (approximate water depth 120 mm) and four flat cobbles with attached algae sourced from a good status (WFD) river (Rathmore Stream, Co. Kildare, Ireland) were added to each channel (1500 mm × 150 mm). A 63-μm mesh 'drift net' was secured within each channel to capture drifting macroinvertebrates and flow was maintained using an aquarium pump (Fig. 1). Each channel was seeded with macroinvertebrates (from two Surber samples) collected from the aforementioned stream on the same day, reducing the potential for natural temporal variability in biological communities (Rosenberg and Resh, 1993). Macroinvertebrates were allowed to acclimatise for two days prior to sediment treatment. Sediment was sourced from an exposed river bank of a stream draining a catchment (Glencullen River, Co Wicklow, Ireland) with minimal human influence and no historic nutrient inputs thus reducing potential responses to multiple stressors (Ormerod et al., 2010). The sediment sampling site is within a woodland that is a designated nature reserve and the river that drains the site is at high status with low nutrient content. Thus, the sediments would not be expected to have anthropogenically enhanced nutrient levels so a detailed analysis of the sediment composition was not considered necessary.

The sediment was oven-dried, sieved and fine sediment (<1 mm) was retained. Sediment disposition was facilitated by turning off pumps prior to addition. A predetermined weight of fine sediment was evenly spread over the gravel substrate as undertaken by Wagenhoff et al. (2012) at 17.00 h on day one so as to achieve the required sediment surface cover of: 100%, 90%, 70%, 50%, 30%, 10%, 5% and 0% (control). These sediment levels were estimated by the same observer, thereby reducing possible observer bias (Wang et al., 1996). Macroinvertebrates were exposed to 1 of 8 fine sediment treatments in a randomised-block design with four replicates per treatment. Drifting macroinvertebrates were collected at midnight and 0600 h, and combined to give daily drift, on each of six consecutive days. While the experiment covered a short time period, previous studies have shown that macroinvertebrate responses to sediment generally occur within 24 to 48 h following sediment addition (Suren and Jowett, 2001; Larsen and Ormerod, 2010; Larsen et al., 2011; O'Callaghan et al., 2015). Macroinvertebrates remaining in the channels on day seven were retrieved by elutriating the substrate through a 250 μm-mesh sieve and preserved in 70% Industrial Methylated Spirits (IMS). In the laboratory, the macroinvertebrates were identified to the lowest practicable taxonomic level (species where possible) using Freshwater Biological Association (FBA) identification keys (Hynes, 1977; Macan and Cooper, 1977; Elliott and Mann, 1979; Elliott et al., 1988; Wallace et al., 1990; Edington and Hildrew, 1995; Nilsson, 1996, 1997). To ensure comparable conditions between treatments, daily measurements were taken of water pH, temperature, conductivity and dissolved oxygen (DO) using a WTW automatic field probe, velocity using a FLO-MATE flow meter and turbidity, using a HACH 2100NIS turbidity meter.

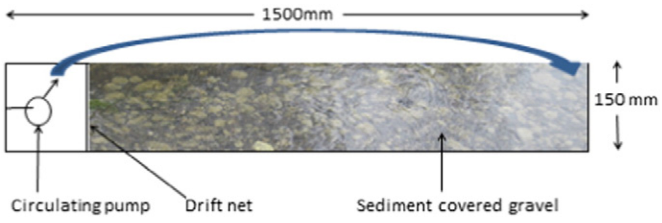

Fig. 1. Schematic illustrating experimental mesocosm (not to scale).

2.2. Field study

The field study was conducted during two seasons, spring (April/May) and autumn (Sept./Oct.) in 2013, across eight rivers located in the North East and midlands of Ireland (Fig. 2) where cattle access represented a potential point source of sediment. Dominant land use at all sampling locations was intensive agriculture (mainly dairy) while river typology was calcareous with low slope (Dodkins et al., 2005). In each study catchment, sampling was conducted at two locations, upstream and downstream of each cattle access drinking point. Six replicate Surber samples (1 mm-mesh) were taken within the mid-channel and margins at each sampling location, which included the first run/riffle area in each direction. Surber samples capture smaller-scale variations where the number of taxa collected can be related to a well-defined sampling area providing an absolute measure of taxon density per unit area (Carter and Resh, 2001). Surber samples also allowed for the collection of macroinvertebrates and sediment measurements at the same scale and location. Extence et al. (2013) suggested that any suitable sampling method can be used to collect macroinvertebrate sampling for PSI calculations. Macroinvertebrate samples were preserved in 70% IMS and processed as described for the mesocosm experiments.

Visual estimations of % deposited fine sediment (<2 mm), which gives an approximation of surface sediment levels, were made within each Surber sampler frame prior to macroinvertebrate sampling (Zweig and Rabení, 2001; Rabení et al., 2005; Matthaei et al., 2006; Larsen et al., 2009). Two additional sediment metrics were included in this study, re-suspendable sediment (RSS) and turbidity, both of which give an approximation of surface and subsurface sedimentation levels (Conroy et al., 2016a, 2016b). A stilling well (215 × 400 mm) was pressed into the stream bed within the frame of the Surber sampler. Water depth within the stilling well was recorded, the water and top 5 cm of the bed substratum was agitated manually for 30 s and a manual grab sample containing re-suspendable sediment was taken (Lambert and Walling, 1988; Wagenhoff et al., 2011; Conroy et al., 2016a, 2016b). Turbidity (NTU) of grab samples was also recorded using the HACH 2100nIS turbidity meter. Water samples were filtered, dried, weighed and calculated as re-suspendable sediments ($g\ m^{-2}$) (Lambert and Walling, 1988; Conroy et al., 2016a, 2016b).

3. Statistical analysis

The Asterics 3.3 programme (http://www.aqem.de/) was used to calculate a number of taxonomy-based metrics for the mesocosm and field studies including total taxon richness and abundance, Ephemeroptera (E) abundance, % Ephemeroptera, % Plecoptera and Trichoptera (% EPT) abundance, Biological Monitoring Working Party (BMWP) score and Average Score Per Taxon (ASPT), and habitat, feeding and locomotion trait metrics. PSI species scores (PSI_S) and PSI family (PSI_F) were also calculated (Extence et al., 2013). Habitat, feeding and locomotion trait metrics (e.g. grazers/scrapers, % gatherers/collectors and % sprawlers/walkers) and total taxon richness were only calculated for the field data because few taxa remained in the mesocosm channels at the end of the experiment. Summary statistics showing means and standard deviations for biological metrics and environmental variables are included in Appendix A while Appendix B shows summary statistics for biological and sediment metrics in the field study.

Friedman's ANOVA (non-parametric, repeated measures ANOVA, see Clews and Ormerod, 2010: Dytham, 2011; O'Callaghan et al., 2015) was used to compare numbers of drifting taxa (total taxon abundance and Heptageniidae abundance) between sediment treatments throughout the whole experiment. Post-hoc analysis using Wilcoxon signed-rank tests, with a significance level of $\alpha < 0.01$, were used to indicate where significant differences lay. One-way ANOVA followed by Tukey post-hoc tests were used to detect differences in macroinvertebrate drift within the first 24 h and total numbers of macroinvertebrates remaining in the channels at the end of the experiment between

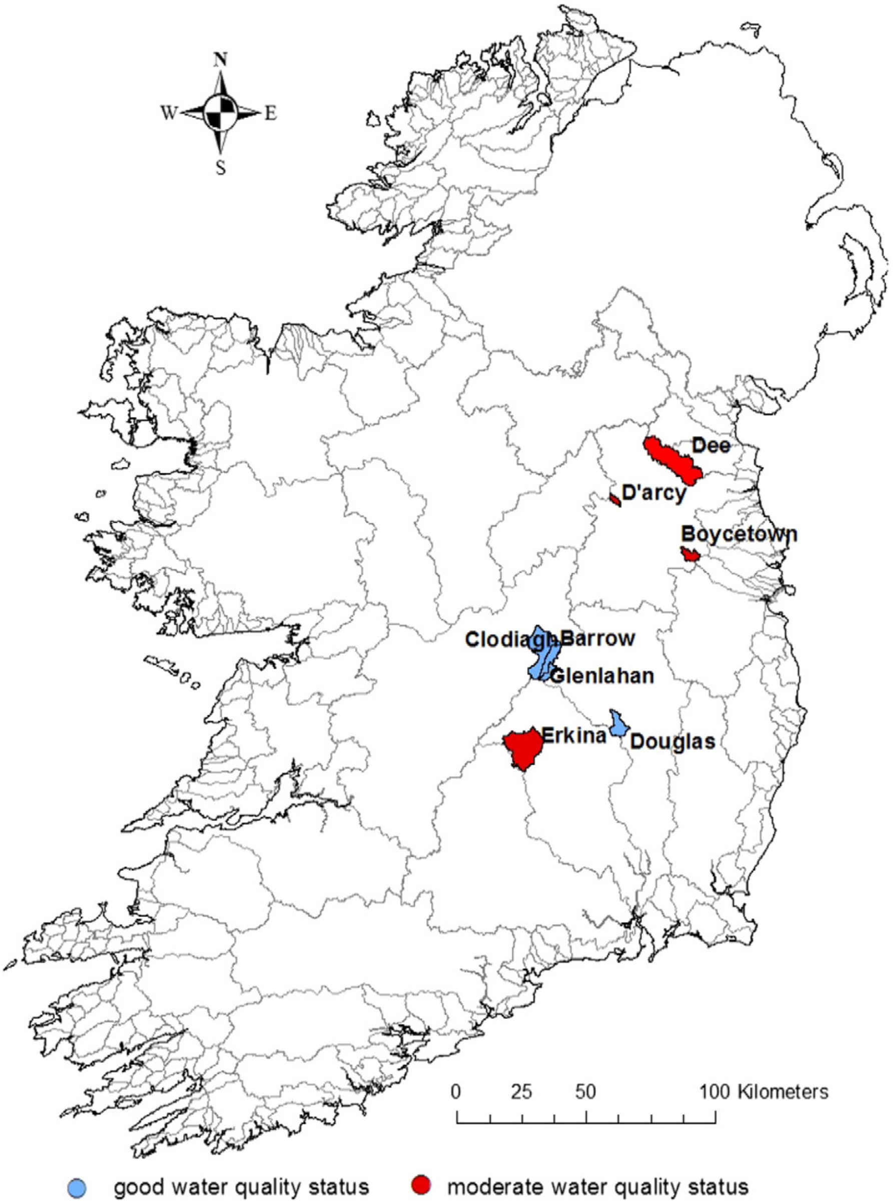

Fig. 2. Map showing the locations of the eight field study catchments in Ireland.

treatments. The association between biological metrics, derived from taxa remaining in mesocosm channels, and % sediment surface cover was measured using Kendall's tau rank correlation, τ.

In the field study, Spearman's rank correlations were used to analyse the association between biological metrics and three sediment metrics (% sediment surface cover, RSS and turbidity) for spring and autumn datasets separately using the software package PASW Statistics 18. Generalised linear mixed-effects models were used to establish how much of the variance in the biological metrics could be explained by the sediment metrics. The mixed model approach deals explicitly with the spatial and temporal non-independence and are appropriate for use on data which has a hierarchical structure (repeated sampling) (Gelman and Hill, 2006) and they take account of the differences in species composition and biological responses across rivers (Pinheiro and Bates, 2000; Pinheiro et al., 2007) and of multiple sites on the same river. The models were fitted by restricted maximum likelihood (REML) using the Imer function in the Ime4 library in R (Pinheiro et al., 2007). The function AIC was used to extract Akaike's information criterion and the R-function p norm was used to estimate the *P*-values. Site and location were treated as random effects while sediment variables (% sediment surface cover, resuspended sediment and turbidity) were fixed effects. Bonferroni corrections were not applied as a priori hypotheses were generated in relation to marcoinvertebrate metrics and sediment metrics (Moran, 2003). The R package r.squared GLMM was used to estimate the variance contribution from both the fixed factors and the combined fixed and random effect factors. The methods used are described by Nakagawa and Schielzeth (2013). The package and methods used are described at http://www.inside-r.org/packages/cran/MuMIn/docs/r.squaredGLMM

4. Results

4.1. Mesocosm study

Water temperature in the experimental channels varied between 5.6 and 7 °C (6.03 mean ± 0.03 SE). DO always remained >13 mgL-1 (12.36 mean ± 0.03 SE) while pH was between 7.8 and 8.3 (8.08 mean ± 0.01 SE). Velocity and turbidity ranged from 0.28 to 0.45 m/s (0.36 mean ± 0.01 SE) and 1.94 to 10.6 NTU (7.15 mean ± 0.02 SE), respectively. No significant differences were detected between treatments

($P > 0.05$). Visual observation and low turbidity readings indicated that sedimentation was maintained throughout the experiment.

The total mean abundance in the channels (calculated as total drifting plus total remaining in the channel at the end of the experiment) did not differ significantly between treatments ($F_{(7,24)} = 0.310$, $P = 0.942$). At the beginning of the experiment Diversity (Simpson-Index) and Eveness were not significantly different between treatments ($F_{(7,24)} = 0.310$, $P = 0.942$ and $F_{(7,24)} = 0.310$, $P = 0.942$, respectively) indicating that seeding of channels was relatively uniform. Total macroinvertebrate abundance remaining in channels at the end of the experiment was significantly different between the treatments ($F_{(7,24)} = 7.384$, $P < 0.05$). Abundances in the 5% treatment were significantly higher than all other sediment treatments ($P < 0.025$) bar the 10% sediment cover treatment.

Drift rates followed a diurnal pattern with peaks in drift observed during the hours of darkness. While there were no differences in total abundance drifting in the first 24 h between the treatments ($F_{(7,24)} = 1.37$, $P = 0.264$), there were significant differences in macroinvertebrates drifting over the duration of the experiment ($\chi^2(5) = 98.83$, $P < 0.05$). Abundance of Heptageniidae drifting was higher in the first 24 h than during the other time periods ($\chi^2(5) = 42.62$, $P < 0.05$). While post-hoc tests could not establish which sediment treatments were significantly different, the numbers of drifting Heptageniidae were generally higher in channels with higher sediment cover (>30% coverage) (Fig. 3).

All biological metrics (based on taxa remaining at the end of the experiment) were negatively correlated with % sediment surface cover (Fig. 4). Percentage EPT abundance (Fig. 4a) had the strongest relationship with % sediment surface cover ($\tau = -0.68$) followed by % E abundance (Fig. 4b) and E abundance (Fig. 4c) ($\tau = -0.67$ and $\tau = -0.64$, respectively at $P < 0.001$). The PSI_S metric (Fig 4e, $\tau = -0.52$, $P < 0.001$) and total abundances (Fig. 4d, $\tau = -0.48$, $P < 0.001$) had slightly weaker, moderate correlations, with % sediment surface cover). The weakest relationships were between BMWP (Fig. 4f) and ASPT and % sediment surface cover ($\tau = -0.25$ and $\tau = -0.29$, $P < 0.05$).

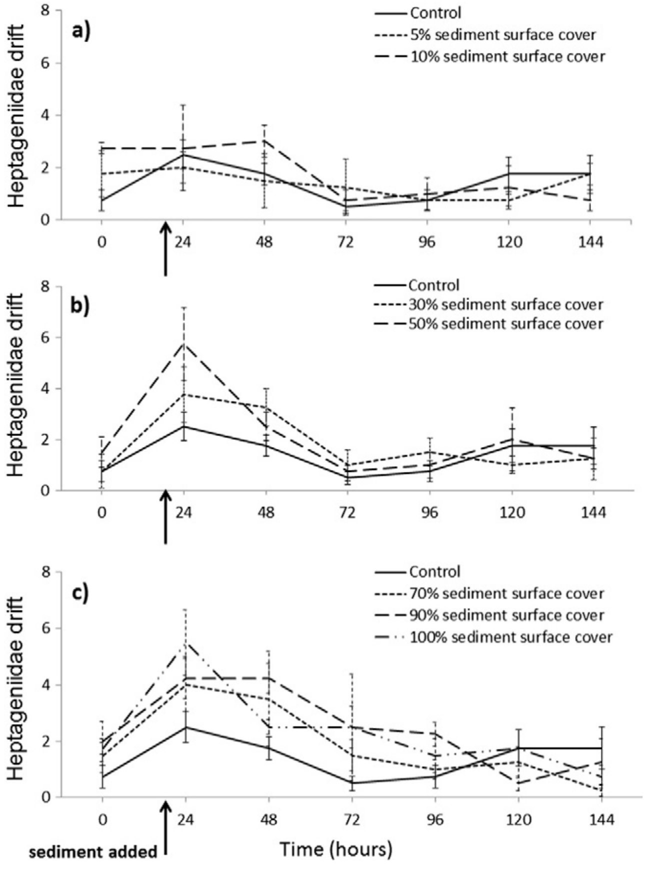

Fig. 3. Mean (± standard error) abundance of Heptageniidae drifting in a) control, 5% and 10% sediment surface cover, b) control, 30% and 50% sediment surface cover and c) control, 70%, 90% and 100% sediment surface cover in mesocosm study.

4.2. Field survey

A total of 384 Surber samples (patch scale) across two seasons were obtained in the field study. Sediment cover at patch scale ranged from 1 to 100% which is wider coverage than reported in other studies (Larsen et al., 2009; Sutherland et al., 2012). However, the sediment gradient was not evenly distributed in the current study, due to natural variability, as almost three quarters of the 384 observations had <50% sediment surface cover (mean 32% ± 1.4 SE). Re-suspendable sediment (RSS) varied between 1 and 3788 g m^{-2} (mean183 g m^{-2} ± 15.3 SE) while turbidity ranged from 2 to 2299 NTU's (mean183 g m^{-2} ± 15.3 SE).

A number of metrics (e.g. E abundance, % E abundance and PSI) showed evidence of seasonal variability in their relationship with sediment measures. The spring dataset showed stronger relationships with surface cover for all but ASPT (Table 1). These seasonal differences were particularly evident between E abundance and surface cover (spring $r_s = -0.43$, $P < 0.01$ and autumn $r_s = -0.16$, $P < 0.05$). The PSI metric also showed some seasonal variability at both species and family level. Spring PSI_S scores (Fig. 5a) were strongly correlated with surface cover ($r_s = 0.47$, $P < 0.01$) and correlations with autumn PSI_S scores were much weaker ($r_s = 0.26$, $P < 0.01$) (Fig. 5b). Similar results was detected for the PSI_F metric (spring data $r_s = -0.40$; autumn $r_s = 0.29$ $P < 0.01$) (Table 1).

Sediment cover (%) had a higher correlation with the biological metrics than either RRS or turbidity (Table 1) and explained a higher proportion of the variation in the models (Table 2).

The strongest associations were with % EPT abundance (spring) and sediment cover ($r_s = -0.57$, $P < 0.01$) and explained 13% of the variance in the models (Table 2). Both total taxon richness and abundance (spring and autumn) were weakly correlated with % surface cover (Table 1). The spring correlation coefficients for the other metrics ranged from −0.33 (BMWP) to −0.47 (PSI_S) while those for the autumn dataset ranged from −0.16 (E abundance) to −0.44 (% EPT richness). The species traits (e.g. % grazers/scrapers, % gatherers/collectors, % swimming/diving, % sprawlers/walkers and % coarse gravel taxa) explained less variance than taxonomy-based metrics and accounted for 1–8% of the variance, compared to 10–19% for the taxonomy-based metrics (Table 2). It should be borne in mind that there has been considerable debate in the scientific community about the usefulness of P-values in general and the position is further complicated in the case of mixed effects models. Thus the values reported here should only be used as initial rough guides.

5. Discussion

Elevated inputs of anthropogenic fine sediment is widely recognised as a significant threat to the ecological integrity of rivers (USEPA, 2002; Molinos and Donohue, 2009) resulting in changes in community structure and increased macroinvertebrate drift (Molinos and Donohue, 2009; Larsen and Ormerod, 2010; O'Callaghan et al., 2015). However, very few sediment-sensitive metrics have been developed to detect impacts due to this pervasive stressor. Furthermore, there is currently no generally accepted, standardised method for measuring deposited sediment and any method used in the field must be able to accurately estimate deposited sediment levels and be related to biological metrics.

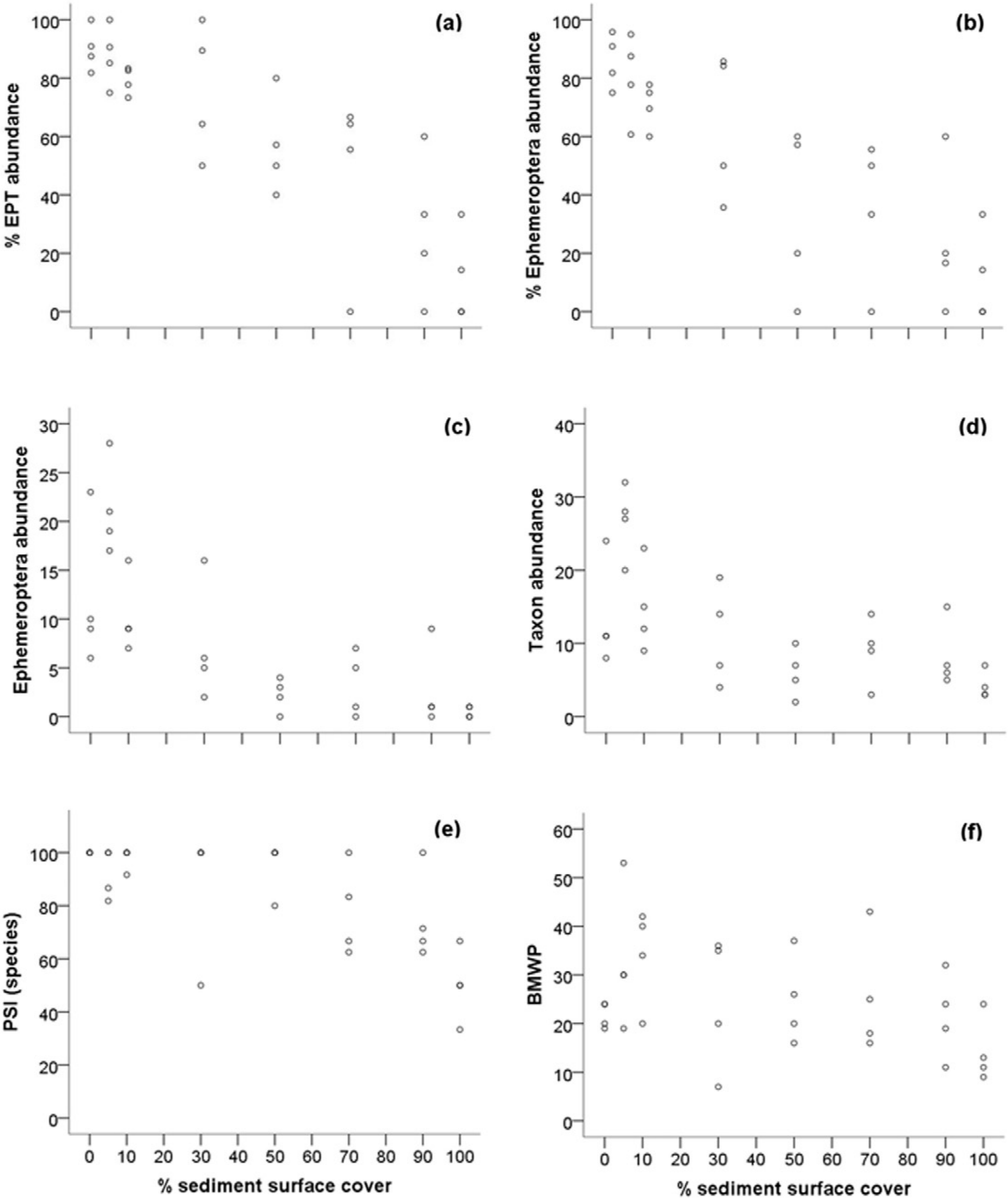

Fig. 4. Relationship between selected biotic metrics including a) % EPT abundance, b) % Ephemeroptera abundance, c) Ephemeroptera abundance, d) total taxon abundance, e) PSI species score and f) BMWP and % sediment surface cover in the mesocosm study. EPT: Ephemeroptera, Plecoptera, and Trichoptera; BMWP: Biological Monitoring Working Party; PSI: Proportion of Sediment-sensitive Invertebrates.

5.1. Responses to sediment in the mesocosm experiments and field study

As expected, macroinvertebrate drift was delayed until the hours of darkness after sediment addition: this is consistent with diurnal patterns as published in a number of other studies (e.g. Matthaei et al., 2006; Larsen and Ormerod, 2010). These responses were probably due to avoidance of impacted habitats rather than immediate behavioural displacement (Larsen and Ormerod, 2010). No significant differences were observed in drift rates between controls and high sediment treatments in the first 24 h. This is in contrast to the results obtained from a mesocosm study in Honduras (O'Callaghan et al., 2015) where taxa abundance doubled and taxa richness increased from 21% in control and low-sediment treatments to 37% in high-sediment treatments during the first 24 h following sediment addition. In the present study, there were significant differences in total abundance drifting and Heptageniidae abundance drifting over the time period of the experiment. Although the post-hoc tests could not link each of these to specific treatments, the data indicated that total drift abundance in the control channels were similar to those in low and moderate sediment treatments (5, 10 and 30% sediment surface cover). There was a 30 to 40% increase in drift rates in channels with higher sediment surface cover (50 to 100%) compared to the control. However, this was not statistically significant indicating that the different levels of sediment addition did not significantly affect the temporal pattern of macro-invertebrate drift they did affect the total abundance remaining in treatments at the end of the experiment. Suren and Jowett (2001) also reported substantial increases in drift rates for a number of species in response to sediment deposition in mesocosm channels in New Zealand while in Australia, Connolly and Pearson (2007) reported no overall differences in drift at channels ends although taxa did move a short distance downstream

Table 1
Correlations between biological metrics with sediment metrics for seasonal field data.

Metrics	% Sediment surface cover		Re-suspendable sediment (RSS)		Turbidity	
	Spring	Autumn	Spring	Autumn	Spring	Autumn
Total taxon richness	-0.25^{**}	-0.20^{**}	ns	ns	ns	-0.16^{*}
Total taxon abundance	-0.24^{**}	0.13^{*}	0.24^{**}	0.16^{*}	ns	ns
% EPT richness	-0.45^{**}	-0.44^{**}	-0.32^{**}	-0.21^{**}	ns	-0.27^{**}
% EPT abundance	-0.57^{**}	-0.41^{**}	-0.25^{**}	-0.20^{**}	ns	-0.29^{**}
% E abundance	-0.41^{**}	-0.23^{**}	-0.37^{**}	-0.20^{**}	-0.23^{**}	-0.17^{**}
E abundance	-0.43^{**}	-0.16^{*}	-0.12^{*}	-0.14^{*}	-0.17^{*}	-0.14^{*}
ASPT	-0.40^{*}	-0.42^{**}	-0.27^{**}	-0.31^{**}	ns	-0.27^{**}
BMWP	-0.33^{**}	-0.33^{**}	ns	-0.16^{*}	ns	-0.24^{**}
PSI_S	-0.47^{**}	-0.26^{**}	-0.41^{**}	-0.25^{**}	-0.14^{*}	-0.15^{*}
PSI_F	-0.40^{**}	-0.29^{**}	-0.32^{**}	-0.20^{**}	ns	-0.17^{*}

EPT: Ephemeroptera, Plecoptera, and Trichoptera; ASPT: Average Score Per Taxon; BMWP: Biological Monitoring Working Party; PSI: Proportion of Sediment-sensitive Invertebrtes; RSS: resuspendable sediment, * $P < 0.05$, ** $P < 0.01$ (one tailed), ns = not significant.

Table 2
Fraction of the variance explained by % sediment surface cover, re-suspendable sediment (g m^{-2}) and turbidity (NTU's) at patch-scale in the field study, indicated by generalised linear mixed-effects models.

Metrics	% sediment surface cover	Re-suspendable sediment (RSS)	Turbidity
Taxonomy-based metrics			
Total taxon richness	0.13^{***}	0.04^{***}	0.02^{**}
Total taxon abundance	0.01^{*}	ns	ns
% EPT richness	0.18^{***}	0.04^{***}	0.03^{***}
% EPT abundance	0.13^{***}	0.02^{***}	0.04^{***}
% E abundance	0.12^{***}	0.04^{***}	0.06^{***}
E abundance	0.19^{***}	0.05^{***}	0.08^{***}
ASPT	0.16^{***}	0.04^{***}	ns
BMWP	0.19^{***}	0.06^{***}	0.05^{***}
PSI_S	0.17^{***}	0.01^{*}	ns
Trait-based metrics			
% coarse gravel taxa	0.08^{***}	0.02^{**}	0.02^{**}
% grazers/scrapers	0.08^{***}	0.02^{**}	ns
% gatherers/collectors	0.04^{***}	0.02^{**}	0.03^{***}
% shredders	0.01^{*}	ns	0.01^{*}
% swimming/diving	0.08^{***}	0.03^{***}	0.06^{***}
% sprawlers/walkers	0.06^{***}	0.03^{***}	0.02^{**}

EPT: Ephemeroptera, Plecoptera, and Trichoptera; BMWP: Biological Monitoring Working Party; ASPT: Average Score Per Taxon; PSI: Proportion of Sediment-sensitive Invertebrtes $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$; Random factors season and site, fixed effects sediment measurement.

within the experimental channels. The second hypothesis was supported as total abundance remaining in treatments at the end of experiment reduced with increasing sediment addition. Interestingly, the numbers remaining in the control (with no added fine sediment) was lower than the 5% sediment treatment, perhaps supporting the assertion that some fine sediment is required in healthy fluvial systems (Yarnell et al., 2006; Kemp et al., 2011; Jones et al., 2012).

Results from the mesocosm study showed that all metrics tested were significantly correlated with sediment surface cover but the strongest correlations were with metrics derived from the abundance of sensitive taxa (% EPT abundance, % E abundance and E abundance) and sediment surface cover. Marked decreases in % EPT abundance, % E abundance and, to a lesser degree, E abundance occurred with increasing sediment cover. These findings concur with a number of other mesocosm studies (e.g. Wagenhoff et al., 2012; Piggott et al., 2015). In the field experiments, which are representative of more realistic conditions, both total taxon abundance and richness were poorly correlated with surface cover. These findings are in general agreement with Piggott et al. (2015), who found that total taxon richness decreased as sediment cover increased whereas total taxon abundance was largely unaffected owing to increases in sediment tolerant taxa (e.g. chironomids) offsetting decreases in sensitive EPT taxa. Overall, despite the potential for confounding factors, the field observations also returned the highest association between sediment surface cover and % EPT abundance. However, the percentage of the variance in any one metric explained by sediment cover was relatively low (maximum 19%). Larsen et al. (2009) found weaker sediment effects on macroinvertebrate community in lowland catchments compared to upland areas. It was suggested that, as lowland catchments have lower diversity compared to upland catchments, observed sediment effects may be site-specific and depend on the diversity and sensitivity of species present at each site (Larsen et al., 2009). These factors may also explain the relatively low percentage variances explained for the lowland rivers in the present study.

The PSI_S, a sediment-specific metric, showed a weaker relationship with sediment cover than % EPT abundance in both the mesocosm experiment and field study. In contrast, Turley et al. (2014) found a marginally stronger relationship between the PSI metric and sediment surface cover compared to the relationships for EPT abundance and richness metrics. There was also evidence of increased variability in PSI_S scores at higher sediment loadings which concurred with Turley et al. (2014) who suggested that this increased variability may have been due to natural variability within biological communities, responses to multiple stressors and/or the quality of biological data and sediment metrics. However, as the experimental design of our mesocosm study controlled for most, if not all, of these factors it is likely that the PSI_S metric is not sufficiently specific to register sediment impact. Furthermore, the very high sediment loadings (e.g. 100%) returned substantially higher than expected PSI scores (*c.* 63) than the expected PSI score of between 0 and 20 (Extence et al., 2013). It is worth noting that, in the

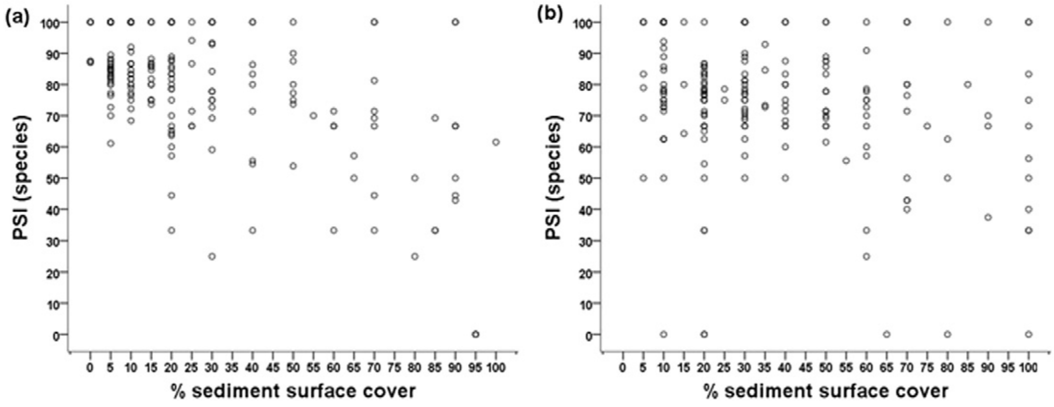

Fig. 5. Relationship between a) spring and b) autumn PSI (species) data with % sediment surface cover for field survey.

Turley et al. (2014) study, all sites were close to reference conditions and largely unimpacted by anthropogenic alterations, whereas sites in this study were lowland sites in agricultural catchments encompassing a wider diversity of environmental conditions. Despite this, surface cover explained 17% of the variance in the PSI model in the present study compared to 10.7% in another study which reviewed the relationship between the PSI metric and surface cover (Glendell et al., 2014). This higher variance in the current field study is probably explained by inclusion of all particles <2 mm as fine sediment. In contrast, while Glendell et al. (2014) assessed a number of sediment metrics and found that only % fine bed sediment cover, defined as particles <0.06 mm (and noted by the authors as difficult to accurately quantify), had a significant relationship with the PSI metric. Ongoing work in relation to the development of a new metric, E-PSI which incorporates species-specific sensitivity weightings, may help to further optimise the performance of the PSI metric (Turley et al., 2015). However, the E-PSI metric was not evaluated in the current study as it specifies a different sampling strategy to that used in the current study.

Other studies have linked changes in trait-based metrics to elevated sediment deposition (Rabení et al., 2005; Sutherland et al., 2012). Sutherland et al. (2012) found that only one functional feeding group (scrapers) was weakly related to deposited fine sediment while two habitat groups (sprawlers, swimmers) showed stronger responses. This contrasted with the results in this study, where most trait-based metrics were more weakly related to deposited sediment compared to taxonomy-based metrics. A better understanding of the mechanisms of biological response to deposited sediment would help in selecting appropriate trait-based metrics.

Visual estimates of surface cover have been described as subjective in nature and offering only a crude measure of levels of deposited fine sediment (Sutherland et al., 2012). Despite this, Sutherland et al. (2012) reported that visual sediment estimates were well correlated with, and were good predictors of seven macroinvertebrate metrics and were strongly related to riparian and catchment land cover. Furthermore, Conroy et al. (2016a, 2016b) found that surface cover estimates were strongly related to, and able to distinguish between known levels of added sediment. Zweig and Rabení (2001) found similarly strong relationships and suggested that this method was not alone more efficient in term of time and effort, but as good as, if not superior to embeddedness measurements. Results from the present study support this as most taxonomy based metrics showed moderate to strong correlations with % sediment surface cover while relationships with the two other sediment metrics (re-suspendable sediment and turbidity) were considerably weaker. These findings concur with Glendell et al. (2014) who found that PSI was not related to total suspendable bed sediment concentration. Differences in sampling resolution were cited by those authors as the most likely cause of this difference because macroinvertebrates were sampled at reach-scale while total suspendable bed sediment concentration was assessed at patch-scale at three points across the channel (Glendell et al., 2014). A number of other studies have also implied that the ability to detect impacts may be dependent on the choice of sampling scale (Townsend et al., 1997; Smiley and Dibble, 2008; Larsen et al., 2009). However, differences in sampling resolution was not a factor in the present field study as macroinvertebrates and sediment measures were taken sequentially within the frame of each Surber sampler. In effect the response to sedimentation by taxa such as EPT may be most pronounced to sediment draped on the surface of the river bed (captured in % surface cover estimates) and thus a more meaningful ecological measurement than RSS and turbidity which give a measure of sediment both draped on and deposited within the river bed.

5.2. Effects of season and taxonomic resolution on performance of biological metrics

The spring dataset showed stronger relationships with % surface cover than the autumn dataset for all but ASPT. The seasonal scatterplots indicate increased variability for autumn PSI and sediment relationships which may be due in part at least to biological responses to multiple stressors e.g. sediment and nutrients (Ormerod et al., 2010; Wagenhoff et al., 2011) in these lowland, agricultural catchments which are grazed from late spring to late autumn. Wood et al. (2011) also found seasonal variability for PSI scores in their study although no seasonal differences were detected in a separate study which examined two agricultural catchments in the UK (Glendell et al., 2014).

With regard to the effects of taxonomic resolution, the results in this study are in agreement with those of Turley et al. (2014) and Murphy et al. (2015) in that species-level identification is preferable to family/genus/order levels. The U.K. Environment Agency has also recognised the benefits of increased taxonomic resolution and its biologists are identifying taxa to species or genus level where feasible (Davy-Bowker et al., 2010). While increased taxonomic resolution may have additional time and cost implications and necessitates higher identification expertise, these considerations can be offset against the improved ability of the higher resolution metrics to highlight impacts, aiding regulatory authorities in the detection of sites which fail to meet environmental standards (Jones, 2008).

The present study explores how a number of commonly used macroinvertebrate taxonomy- and trait-based metrics respond to measures of deposited sediment using both mesocosm laboratory channels and a field study. Overall, this study has demonstrated that a range of biotic metrics respond clearly and negatively to increasing levels of deposited sediment. These results indicate that % sediment surface cover and % EPT abundance may be useful metrics for assessing the negative effect of excessive sediment on macroinvertebrates. However, variability in taxa-specific response to sedimentation indicates that refinement of biotic metrics needs to include those taxa with specific responses to sediment. This will require additional research on the mechanisms linking elevated deposited sediment levels and sediment composition to useful metrics of ecological response.

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Assessment of a rapid method for quantitative reach-scale estimates of deposited fine sediment in rivers

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ABSTRACT

Despite increasing concerns about the negative effects that increased loads of fine-grained sediment are having on freshwaters, the need is clear for a rapid and cost-effective methodology that gives precise estimates of deposited sediment across all river types and that are relevant to morphological and ecological impact. To date few attempts have been made to assess the precision of techniques used to assemble data on fine sediment storage in river channels. Accordingly, we present an investigation into the sources of uncertainty associated with estimates of deposited fine-grained sediment in rivers using a sediment resuspension technique, an approach that provides an instantaneous measure of deposited fine sediment (surface and subsurface) in terms of quantity and quality. We investigated how variation associated with river type, spatial patchiness within rivers, sampling, and individual operators influenced estimates of deposited fine sediment using this approach and compared the precision with that of visual estimates of river bed composition — a commonly applied technique in rapid river surveys. We have used this information to develop an effective methodology for producing reach-scale estimates with known confidence intervals.

By using a spatially-focussed sampling strategy that captured areas of visually high and low deposition of fine-grained sediment, the dominant aspects of small-scale spatial variability were controlled and a more precise instantaneous estimate of deposited fine sediment derived. The majority of the remaining within-site variance was attributable to spatial and sampling variability at the smallest (patch) scale. The method performed as well as visual estimates of percentage of the river bed comprising fines in its ability to discriminate between rivers but, unlike visual estimates, was not affected by operator bias.

Confidence intervals for reach-scale measures of deposited fine-grained sediment were derived for the technique, and these can be applied elsewhere.

1. Introduction

The transport of sediment by rivers to the oceans represents an important pathway in the global geochemical cycle and a key component of the land denudation system (Walling and Fang, 2003). Fine sediment storage, mobilization, transfer, and delivery play a critical role in the dispersal and fate of nutrients (Heathwaite, 1994; House, 2003; Jarvie et al., 2006; Collins et al., 2007; Ballantine et al., 2009) and contaminants (Rees et al., 1999; Kronvang et al., 2003; Collins et al., 2005).

The delivery of fine sediment to rivers is a natural phenomenon, and background levels of sediment in fluvial systems are essential to channel processes, habitat heterogeneity, and ecological functioning (Collins et al., 2011; Foster et al., 2011). Long-term records of sediment loads show that river sediment fluxes are sensitive to many drivers, including changes in climate and land use, which can dramatically increase sediment delivery to watercourses (Houben et al., 2006; Foster et al., 2011). In particular, sediment delivery to river channels in many areas of the world is increasing as catchments are progressively modified through human activities such as agriculture (e.g., Collins and Walling, 2007a), forestry operations (e.g., Davies and Nelson, 1993), construction (e.g., Angermeier et al., 2004), mining (e.g., Turnpenny and Williams, 1980; Yule et al., 2010) and the urbanization of drainage basins (e.g., Hogg and Norris, 1991). The expansion of agricultural land and intensification of farming practices, in particular, have the potential to increase sediment pressures on watercourses (Dearing et al., 1987; Farnsworth and Milliman, 2003; Kasai et al., 2005; Wagenhoff et al., 2011).

Unlike many other pollutants, a certain amount of fine sediment (i.e., particles <2 mm in size encompassing inorganic sand (>62.5 to 2000 μm), silt (>4 to 62.5 μm), clay (≤4 μm), and organic matter) is

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necessary for rivers to function normally; the negative impacts of fine sediment are expressed only where excess loading occurs (Lisle, 1989). Increased loads of fine sediment result in increased concentrations of suspended sediment (Sear et al., 2008; Walling and Collins, 2008). However, fine sediment has its most profound effects when deposited, with increased rates of deposition resulting in modification to the structure and chemical composition of the river bed (Schalchli, 1992; Rehg et al., 2005). This affects bed roughness, bed mobility, and the exchange between surface and groundwater.

Concern about the impact that increased fine sediment loads are having on freshwater has led to suggestions that the entrainment and deposition of fine sediment is one of the most widespread and detrimental forms of aquatic pollution, resulting in morphological and ecological change to freshwater and coastal systems (Ritchie, 1972; Lemly, 1982). Furthermore, increased sedimentation is often associated with wider habitat modifications and other instream stressors, resulting in complex synergistic or antagonistic morphological and ecological responses (Townsend et al., 2008; Wagenhoff et al., 2011).

The quantity, quality, and timing of the sediment loads received by rivers are dependent on key sources and delivery pathways (Collins et al., 2011, 2013). An important aspect of the management of fine sediment loads in rivers is determination of an acceptable level of input from these sources (Collins and Anthony, 2008a,b; Cooper et al., 2008; Collins et al., 2009, 2011). However, instream transport, bed character, and deposition processes eventually determine the extent to which fine sediment loads are stored as deposited fine sediment within the river channel. Hence, a reliable and pragmatic methodology for the quantification of deposited fine sediment is imperative for improving the evidence base to support catchment management with respect to fine sediment pressures.

A number of approaches have been used to characterise deposited fine sediment in stream monitoring programmes, management strategies, and research methodologies (Lambert and Walling, 1988; Bunte and Abt, 2001; Sutherland et al., 2010; Clapcott et al., 2011). Visual estimates of percent cover, embeddedness, or particle size are frequently used for assessments of bed composition. However, such estimates are constrained to the surface drape of fines, rather than including ingressed material as well, and cannot provide information on key quantitative characteristics such as the organic content of deposited sediment. Measurement of deposited fine sediment using accumulation techniques, such as traps based on sedimentation plates (Kozerski, 2002), permeable infiltration baskets (Acornley and Sear, 1999; Soulsby et al., 2001; Collins et al., 2013), or boxes (Frostick et al., 1984; Wood and Armitage, 1999), can provide quantitative estimates of the rate of deposition and/or ingress. However, they do not provide an assessment of the amount of sediment stored or the current status of the river bed. Other techniques to assess quantitatively the deposited material at an instant in time (rather than the rate of ingress) include the removal of cores using either push-tube (Doyle et al., 1995) or freezing devices with liquid nitrogen (Stocker and Williams, 1972) or carbon dioxide (Petts et al., 1989); but these require substantial effort, particularly if a number of representative cores are required per reach. Resuspension techniques using stilling wells provide a flexible and pragmatic compromise to bed sediment cores, where fine sediments are resuspended by agitation to mobilise them from the bed matrix in the field, reducing the effort required to obtain a sample (Lambert and Walling, 1988). It is a widely used technique for estimating the mass of fine sediments sequestered on, and in, the river bed (Lambert and Walling, 1988; Quinn et al., 1997; Wharton et al., 2006; Collins and Walling, 2007b,c; Quinn et al., 2009; Clapcott et al., 2011; Wagenhoff et al., 2011).

However, to date few attempts have been made to assess the precision of such measurements. The need is a clear, from a geomorphic and from an ecological perspective, for a methodology that gives precise quantitative estimates of deposited fine-grained sediment and performs equally well in all river types. This paper therefore presents an investigation into the uncertainty associated with estimates of deposited fine bed sediment in rivers. The aim was to establish how variation associated with river type, spatial patchiness within rivers, sampling, and individual operators influenced measurements of deposited fine sediment using the resuspension technique. The intention was to use this information to develop an effective methodology for producing reach-scale estimates with known confidence intervals. To assess the performance of the method, the precision was compared with that of visual estimates of river bed composition.

2. Materials and methods

2.1. Site selection

The assessment of variation in measures of deposited fine sediment using the resuspension procedure was structured to test:

- performance in different amounts of deposited sediment across a range of river types as defined by substrate composition;
- consistency within river reaches; and
- reproducibility between and within operators (persons taking the samples).

This was achieved with a nested configuration of samples taken by three workers across a geographically and geologically diverse area of England and Wales (Fig. 1). Sites were selected to provide a wide range of river type and gradient of fine sediment retention. As substrate composition was expected to influence the distribution of fine sediment within river reaches and the effectiveness of sample collection, sampling sites were categorized on the basis of prior visual assessments of substrate composition (Murray-Bligh et al., 1997) viz.:

- coarse substrate: reaches of ≥60% cobbles and boulders (>64 mm);
- moderate substrate: reaches of ≥60% pebbles and gravels (>2–64 mm);
- fine substrate: reaches of ≥60% silt and sand (≤2 mm).

Using prior instantaneous resuspension assessments of deposited fine sediment, four sites within each category were selected to provide examples of low, medium, high, and very high deposited fine sediment for that individual substrate type (Table 1). Within each sampling site, samples were collected during clear water conditions from three similar short, contiguous, homologous segments.

2.2. Sampling strategy

Fine sediments are not deposited evenly on the river bed, neither within nor between reaches. This patchiness results from the interaction of reach- and patch-scale hydraulic and sedimentological factors, which are typically characterised by significant spatial heterogeneity. Whilst visual observations of bed composition can be made at the river channel/reach scale, direct quantitative measures of deposited fine sediment are typically made at smaller scales. However, scaling-up measurements from the patch to the whole river channel is associated with considerable difficulties (Larsen et al., 2009). The issue of scaling is further complicated as the extent to which spatial heterogeneity influences quantification of fine sediment at larger (reach) scales is not known. A rapid and cost-effective approach to quantifying deposited fine sediment that captures patch-scale variation in quantity and quality to provide a reach-scale estimate is required in order to assess accurately the impacts of fine sediment at a scale relevant to targeted management decisions.

Hence, a stratified random sampling strategy was used in order to capture spatial variability in deposited fine sediment in a structured way. Samples of both the surface and the total (i.e., combined surface drape and subsurface) deposited fine sediment were collected from six erosional and six depositional patches distributed across three

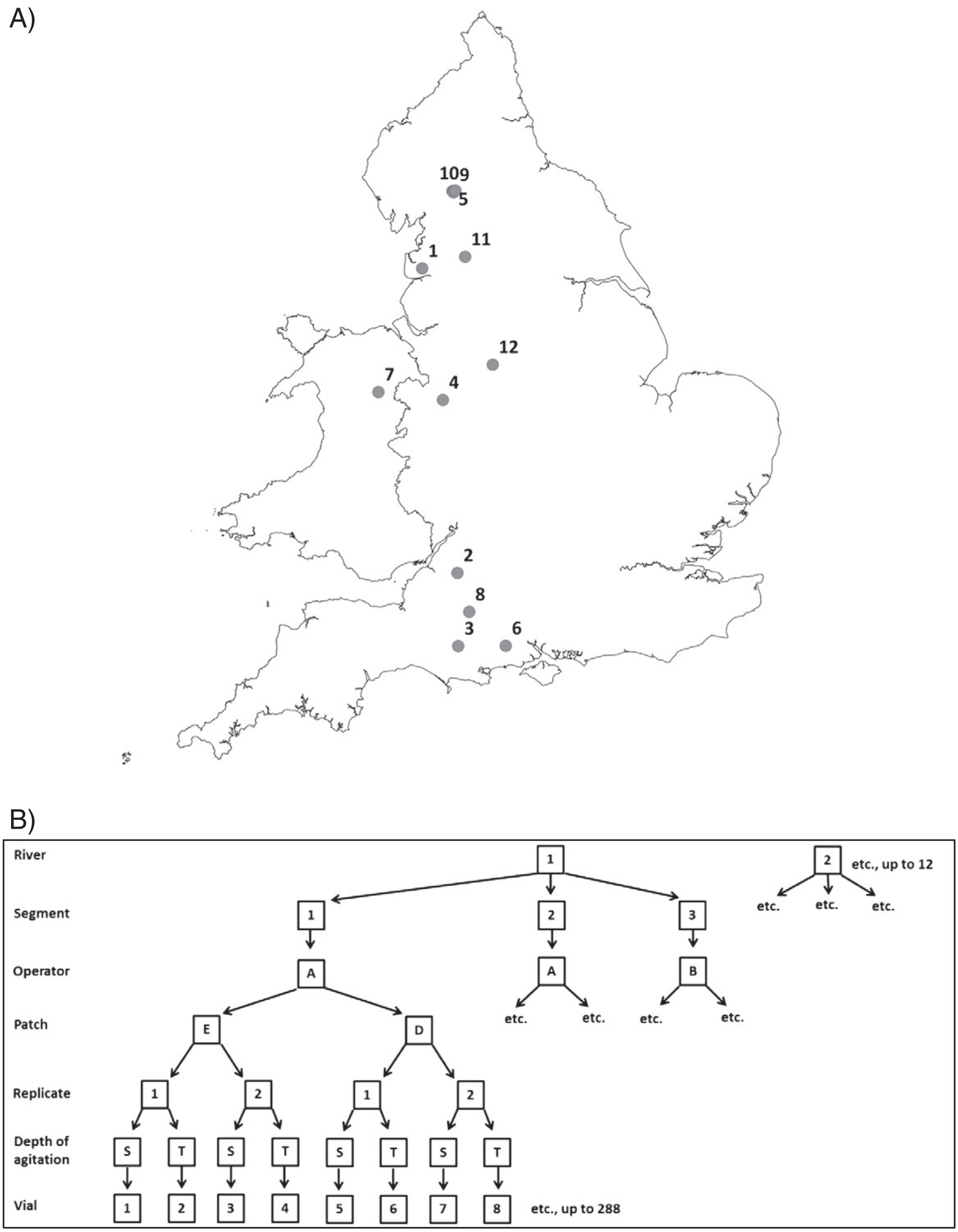


Fig. 1. A) Map showing the locations of the test sites. B) Schematic diagram of sampling strategy. Samples were collected from three homologous segments in 12 rivers, by either the major (indicated by A) or minor (indicated by B) operator, who sampled the surface- and total- (surface and subsurface) deposited sediment from two replicate erosional or depositional patches. See methods for details.

segments at each river site (i.e., from six erosional/depositional pairs of patches within each river reach). The selected patches within a river were sampled working from downstream to upstream. To quantify the variance between operators and to separate this from sampling variance, samples were collected from two segments by one operator (the major) and from the other segment by another operator (the minor). A team of three operators was used to conduct the survey across the 12 rivers to determine if there was any bias among operators (Table 1). Lots were drawn to assign the operator combinations randomly.

Prior to sediment sampling, the river channel was assessed visually from the bank; percentage bed composition was estimated according to the RIVPACS protocol (Murray-Bligh et al., 1997). This records the percentage cover, ignoring areas of bedrock, of silt/clay (≤0.0625 mm), sand (>0.0625–2 mm), pebbles/gravel (>2–64 mm), and boulders/cobbles

Table 1
Test sites, substrate composition, fine sediment category, and operator.

	River	Site	NGR	Substrate[a]	Fine sediment	Major operator	Minor operator
1	Unnamed	Hale Hall	SD458353	Fine	Low	A	B
2	St Catherine's brook	Great Moody's Wood	ST762726	Fine	Medium	B	A
3	Platt Brook	Potford Farm	SJ636220	Fine	High	C	B
4	Unnamed (Droop)	Lower Fifehead Farm	ST769093	Fine	Very high	A	C
5	Thackthwaite Gill	Banks	NY719021	Moderate	Low	C	B
6	Rhaeadr	Tyn-y-Wern	SJ080288	Moderate	Medium	A	C
7	Dockens water	Linwood Bog	SU179096	Moderate	High	B	C
8	Wylye	Brixton Deverill	ST864389	Moderate	Very high	C	A
9	Lockholme Beck	Ellergill	NY727010	Coarse	Low	B	C
10	Heck Gill	Brunt Hill	NY745024	Coarse	Medium	C	A
11	Hamps	u/s Pethill Farm	SK066525	Coarse	High	A	B
12	Swanside Beck	d/s Middop Hall	SD829454	Coarse	Very high	B	A

[a] Coarse substrate: reaches of ≥60% cobbles and boulders (>64 mm); moderate substrate: reaches of ≥ 60% pebbles and gravels (>2-64 mm); and fine substrate: reaches of ≥60% silt and sand (≤2 mm).

(>64 mm) over the whole sampling area, i.e. full width of the river along the whole length sampled (all three segments).

Subsequently, two patch types were identified within the main channel of each segment sampled, those with either a propensity to erode or to deposit fine sediment. In broad terms, patches with a propensity to erode fine sediment (hereafter *erosional*) were defined as those higher velocity areas in or close to the thalweg, whereas patches with a propensity to deposit fine sediment (hereafter *depositional*) were in eddies or areas of lower flow velocity such as pools or backwaters. The ultimate purpose of this evaluation was to identify two positions representing the extremes of the range of fine-grained sediment retention within the river channel (cf. Collins and Walling, 2007b, c). As deposited fine sediment is unlikely to be evenly distributed across the river bed, rather following a highly skewed distribution, a reach-scale average derived using the geometric mean of these extremes will provide a better measure of central tendency than the mean of random samples (Sokal and Rohlf, 1998). Thus, following Walling et al. (2006), samples were collected from each of these two patch types and the reach-scale estimate derived as the geometric mean of these extremes.

2.3. Field sampling method

Deposited fine sediment was collected using the sediment resuspension technique that was first described by Lambert and Walling (1988) and refined by Collins and Walling (2007b,c) and is equivalent in approach to the Quorer method described by Quinn et al. (1997). For the collection of each individual estimate of deposited fine sediment, an undisturbed patch was approached from downstream and an open-ended, stainless steel cylinder (height 75 cm and diameter 48.5 cm, with handles to allow ease of transportation and better purchase for insertion) was manually pushed at least 10 cm into the bed until an adequate seal with the substrate was achieved. This was done in a way to prevent winnowing, whilst introducing minimal disturbance to the deposited fine sediment within the cylinder. Once in position, the depth of water within the cylinder was measured. The water within the cylinder was then vigorously agitated for 60 s with an auger without touching the river bed but sufficient to bring fine sediment from the surface of the bed into suspension. The water and suspended sediment was then immediately sampled by plunging an inverted 50-ml vial to the bottom of the cylinder, which then filled as it was turned upright and brought to the surface. Subsequently, a further 60 s of agitation was undertaken, this time including 30 s digging/stirring the top 10 cm of the bed substrate with the auger to raise any subsurface fine sediment into suspension. Again, immediately following agitation a sample of the suspended material was collected by drawing a second 50-ml vial up through the water column. In this way separate samples of both the surface and the total (i.e. combined surface drape and subsurface) deposited fine sediment were collected from the patch. All sites were sampled during clear water conditions; use of the approach at sites with high background suspended solids would necessitate the collection and processing of an additional sample prior to disturbance to correct for any background suspended solids. The samples were refrigerated and kept in the dark until analysed, and each sample was treated independently.

2.4. Laboratory processing

Fine-grained sediment mass, and nonvolatile solids, were measured within 1 week of return to the laboratory. The samples were passed through a 2-mm sieve prior to filtration using pre-ashed, washed, and dried 90-mm Whatman Glass Microfibre GF/C filters. The filtered samples were dried in a preheated oven at 105 °C overnight and cooled in a desiccator for 1 h before weighing. The samples were then ashed in a preheated muffle furnace at 500 °C for 30 min and cooled in a desiccator for 1 h before weighing. Volatile fine sediment mass was calculated by subtraction of nonvolatile fine sediment mass from fine sediment mass. The depth of water within the stilling well was used to convert the laboratory weights to a mass of fine-grained sediment per square metre of river bed sampled. Laboratory procedures involved no further subsampling but were conducted on the whole sample.

2.5. Statistical analysis

Statistical hierarchical analysis of variance (ANOVA) was used to estimate the variance in estimates of deposited fine-grained sediment collected using the resuspension technique. Data were $\log_{10}$ transformed before analysis to avoid heteroscedasticity. The components of variance assessed were caused by:

- differences between sites;
- differences between operators (person taking the field sample) at the same site;
- larger scale spatial differences between segments within sites;
- spatial differences between patches of differing characteristics (i.e. between erosional and depositional patches);
- spatial differences between patches of similar characteristics (i.e. among erosional or depositional patches);
- spatial differences caused by the depth from which the sample was collected (i.e. surface or surface and subsurface); and
- small-scale spatial and sampling differences within patches of similar characteristics taken by the same operator at the same site.

At the smallest spatial scale, spatial variability (patchiness), sampling variability, and any variation introduced by laboratory processing are combined.

Specifically, if $Y_{klmnopq}$ is the value of fine sediment for depth p, from replicate position o, from patch type n, in replicate segment m, taken by operator l, at site k, then $Y_{klmnopq}$ can be expressed in terms of the sum of the components contributing toward the overall variation in its values, namely:

$$Y_{klmnopq} = \mu + a_k + b_{kl} + c_{klm} + d_{klmn} + e_{klmno} + f_{klmnop} + g_{klmnopq} \tag{1}$$

where

μ	overall mean value of Y;
a_k	deviation of mean value for site k from the overall mean value μ;
b_{kl}	deviation of mean value for operator l at site k from the mean for site k;
c_{klm}	deviation of mean value for replicate segment m by operator l at site k from the mean for sampling operator l at site k;
d_{klmn}	deviation of mean value for patch type n for replicate segment m by operator l at site k from the mean for replicate segment m by sampling operator l at site k;
e_{klmno}	deviation of mean value for replicate position o of patch type n for replicate segment m by operator l at site k from the mean for patch type n for replicate segment m by sampling operator l at site k;
f_{klmnop}	deviation of mean value for depth p of replicate position o from patch type n for replicate segment m by operator l at site k from the mean for replicate position o patch type n for replicate segment m by sampling operator l at site k;
$g_{klmnopq}$	deviation of water sample q from depth p of replicate position o from patch type n for replicate segment m by operator l at reach k from the mean for depth p from replicate position o patch type n for replicate segment m by sampling operator l at site k;

and where

σ_K^2	variance of a_k, i.e. variance caused by differences in mean value between sites;
σ_L^2	variance of b_{kl}, i.e. variance caused by differences between operators within a site;
σ_M^2	variance of c_{klm}, i.e. variance caused by differences between replicate segments sampled by the same operator at the same site;
σ_N^2	variance of d_{klmn}, i.e. variance caused by differences between patch types within replicate segments sampled by the same operator at the same site;
σ_O^2	variance of e_{klmno}, i.e. variance caused by differences between replicate positions within patch types of replicate segments sampled by the same operator at the same site;
σ_P^2	variance of f_{klmnop}, i.e. variance caused by differences between depths within replicate positions from patch types of replicate segments sampled by the same operator at the same site; and
σ_Q^2	variance of $g_{klmnopq}$, i.e. variance caused by differences between water samples collected from the same depth within replicate positions from patch types of replicate segments sampled by the same operator at the same site.

This approach correctly distinguishes and estimates that part of the overall variance in instantaneous measures of deposited fine-grained sediment at a site that is caused by systematic differences between people in the way they take the sample (namely σ_L^2) from that part caused by pure replicate sampling variability arising from small-scale spatial heterogeneity in sediment deposition and sampling variability at the site (namely σ_M^2 and constituents σ_N^2, σ_O^2, σ_P^2, σ_Q^2). Given that, on arrival at the laboratory, whole samples (rather than subsamples) are processed using standard techniques, the error associated with laboratory processing is assumed to be very small compared to the field sampling. Furthermore, as the laboratory analysis of samples is destructive, i.e., the same analysis cannot be repeated on the same sample, the approach cannot assess the variance caused by laboratory processing. However, this is implicitly included in the lowest level of assessment (namely σ_Q^2), which represents the residual variance inherently associated with the technique. As a consequence of the limited sampling (only two replicates by one operator and one by a second operator, within one season at each site), these estimates of variance components will themselves be subjected to estimation error.

The total variance (σ_T^2) in deposited fine sediment mass across all rivers is estimated by

$$\sigma_T^2 = \sigma_K^2 + \sigma_L^2 + \sigma_M^2 + \sigma_N^2 + \sigma_O^2 + \sigma_P^2 + \sigma_Q^2. \tag{2}$$

The within-site variance (σ_W^2) in deposited fine sediment mass is estimated by

$$\sigma_W^2 = \sigma_L^2 + \sigma_M^2 + \sigma_N^2 + \sigma_O^2 + \sigma_P^2 + \sigma_Q^2. \tag{3}$$

Some of this within-site variance is caused by small-scale spatial variability that has been controlled for (erosional or depositional patches, surface and subsurface deposits), whereas some of the variance is caused by spatial and sampling variability that has not been controlled for (replicate segments, replicate positions (patches within reaches), and sampling variability). These two components of small-scale spatial and sampling variability, controlled for (σ_{Wc}^2) and uncontrolled for (σ_{Wuc}^2), can be separated:

$$\sigma_W^2 = \sigma_L^2 + \sigma_{Wc}^2 + \sigma_{Wuc}^2 \tag{4}$$

where

$$\sigma_{Wc}^2 = \sigma_N^2 + \sigma_P^2 \tag{5}$$

$$\sigma_{Wuc}^2 = \sigma_M^2 + \sigma_O^2 + \sigma_Q^2. \tag{6}$$

When characterising a site, the principal concern is the within-site variance. By deconstructing the variance associated with the different components of the sampling procedure, we could determine if the uncontrolled for within-site variance had a substantial influence on the uncertainty of estimates of deposited sediment. An effective sampling strategy needs a design that adequately controls the known components of small-scale spatial and sampling variability. Whilst some of the variance will be specific to the method used to collect the sediment sample, the relative importance of within-river spatial variability in deposited fine sediment is relevant to all methods.

When considering the comparison of measured deposited sediment among rivers, the percentage of the overall total variance (σ_T^2) in deposited fine sediment across all rivers, that can be attributed specifically to controlled and uncontrolled small-scale sampling variation within a site is estimated by:

$$P_{W/T} = 100\sigma_W^2/\sigma_T^2. \tag{7}$$

If $P_{W/T}$ is large, then the sampling process will give results that are imprecise and cannot reliably be used to detect differences between sites. Conversely, a small percentage of within-site sampling variance indicates high statistical precision and repeatability of results.

3. Results

3.1. Assessment of variance

When the variance associated with sediment sampling using the resuspension technique was assessed, the majority of the variation in measures of the quantity of deposited fine-grained sediment was between sites (Table 2). Differences between sites in the measured fine sediment mass, nonvolatile fine sediment mass, and volatile fine sediment mass were highly significant. Less of the variation in the quality of deposited fine-grained sediment (i.e. percentage volatile matter) was attributable to differences between sites (48% cf > 67%), although differences between sites were still highly significant (Table 2).

The spatial patchiness of deposited fine-grained sediment was expected to have a substantial influence on the data assembled using the resuspension technique. Within-sites, patch type (erosional or depositional) and the depth from which the deposited fine-grained sediment was obtained (surface or total) had statistically significant effects on all three measures of deposited sediment mass (Table 2). As expected, the mass of deposited fine sediment tended to be higher in depositional patches than erosional patches, and the mass of total deposited fine sediment (i.e. surface and subsurface deposits) was higher than the mass of surface-deposited fine sediment alone (Fig. 2). Over half of the within-site variance of all of the measures of fine sediment mass was attributable to these two elements of small-scale spatial variability (i.e. patch type and depth). The majority of the remaining within-site variance was attributable to individual replicate water samples, i.e., to spatial and sampling variability at the smallest scale. Despite concerns that the patchiness in deposited fine-grained sediment mass would introduce considerable variation into measured mass using the stilling well, < 0.4% of the total variation in any of the three measures of fine sediment mass was attributable to replicate river segments and replicate positions within segments, and < 14% to smaller scale spatial variability and sampling. Hence, a spatially focussed sampling strategy, which captures in equal proportions areas of high and low deposition of fine-grained sediment (cf. Collins and Walling, 2007b,c), is recommended to assess deposited fine-grained sediment mass, as it will control for the dominant aspects of small-scale spatial variability and provide a more precise instantaneous estimate of deposited fine sediment.

Table 2
Estimates of component sources of variance in deposited fine sediment mass (g m^{-2}), nonvolatile deposited sediment mass (g m^{-2}), and volatile deposited sediment mass (g m^{-2}); where the variance component was statistically significant in ANOVA tests is indicated by *** = 0.001 and ** = 0.01 test probability level.

Variance		Sediment mass	Nonvolatile mass	Volatile mass	% Volatile
Between-site	σ^2_K	249.40***	262.56***	157.70***	10.13***
Operator	σ^2_L	0.14	0.14	0.15	0.00
Segment	σ^2_M	0.81	1.13	0.16	0.45**
Patch type	σ^2_N	24.09***	23.35***	25.31***	0.11
Position	σ^2_O	0.4	0.37	0.29	0.02
Depth	σ^2_P	37.88***	41.43***	18.73***	2.73***
Water sample	σ^2_Q	45.53	48.77	32.28	7.67
Total	σ^2_T	358.35	377.75	234.61	21.11
%Between-site		69.62	69.51	67.22	47.98
%Operator		0.04	0.04	0.06	0.00
%Segment		0.23	0.30	0.07	2.12
%Patch type		6.72	6.18	10.79	0.50
%Position		0.11	0.10	0.12	0.08
%Depth		10.57	10.97	7.98	12.95
%Water sample		12.71	12.91	13.76	36.37
%Within-site		30.38	30.49	32.78	52.02
Of within-site					
%Operator		0.13	0.12	0.19	0.00
%Controlled for		56.93	56.24	57.25	25.85
%Uncontrolled		42.94	43.64	42.56	74.15

The quality of deposited fine sediment, measured here as percentage volatile matter, appeared more variable within sites than measures of fine-grained sediment mass, largely as a consequence of this being expressed as a percentage. Depth of ingress had a statistically significant influence on the percentage volatile-deposited sediment, with surface-deposited sediment having a higher percentage volatile matter than total-deposited sediment. Of the total variation in percentage volatile-deposited sediment, 12.6% was attributable to depth. Patch type had no statistically significant influence on percentage volatile-deposited sediment, and only contributed 0.5% of the total variance in this measure of fine sediment quality. Although differences between replicate segments were statistically significant, this accounted for only 2.1% of the total variance. A large proportion of the total variance, 36.4%, was attributable to variation among individual replicate water samples, i.e., attributable to spatial and sampling variability at the smallest scale and to any variability involved in the laboratory processing of the replicate samples.

Despite concerns that individuals may differ in their ability to collect samples using the resuspension technique, particularly in their ability to raise fine-grained sediment from the river bed by digging and water column stirring to provide agitation, < 0.1% of the total variation in sediment mass, nonvolatile sediment mass, and volatile sediment mass was attributable to operator. Of the within-site variation, < 0.2% of the variation in any of the three measures of sediment mass was attributable to operator, further supporting the assertion that the difference between individuals using the resuspension technique was not substantial. None of the variation in percentage volatile-deposited sediment was attributable to operator.

As the spatially focussed approach to collecting samples of deposited fine sediment was effective at controlling for a large proportion of the within-river spatial variation, we decided to retain this structured approach when deriving a reach-scale method. To investigate the relationship between the number of spatial samples collected and the accuracy of the estimate of the mean, the standard deviation (SD) and mean were calculated using all pairs of samples from each river, where a pair comprises one sample from a depositional patch and one from an erosional patch (i.e. six pairs per river). Residual plots were examined for each model produced and found to be acceptable in their approximation to normality and constant variance. The average SD across all rivers was then calculated, and the coefficient of variation for varying numbers of samples on the least variable, most variable, and *average* river derived for the surface- and the total-deposited fine sediment mass (Fig. 3). The coefficient of variation, in the *average*, and the most variable rivers, was larger for surface- than total-deposited fine sediment mass reflecting a greater patchiness in the mass of surface drape deposits. However, increasing the number of pairs of samples did not reduce the coefficient of variation substantially. Consequently, as our intention was to develop a rapid, cost-effective method for the assessment of deposited fine-grained bed sediment, we decided to use two pairs of samples (i.e., collected from two erosional and two depositional patches) to provide estimates of surface- and total-deposited fine sediment at the river site/reach scale.

To investigate sources of variance at the reach scale, the hierarchical analysis of variance (ANOVA) was repeated using reach-scale estimates of deposited fine sediment mass, each derived from four constituent stilling well samples. Here, > 95% of the variance in the three measures of total-deposited fine sediment mass was attributable to differences between sites (Table 3), whereas < 0.3% of the total variance was attributable to operator (Fig. 4). A similar distribution of variances was seen for the three measures of surface-deposited fine sediment mass, although slightly more of the total variance (6.3% cf. 4.3%) was within-site. Again < 0.3% of the total variance was attributable to operator.

To determine if the resuspension technique performed equally across different river types, the homogeneity of variance was investigated: we hypothesised that local effects on performance (e.g., flow, patch substrate composition, operator) would cause the variance in estimates

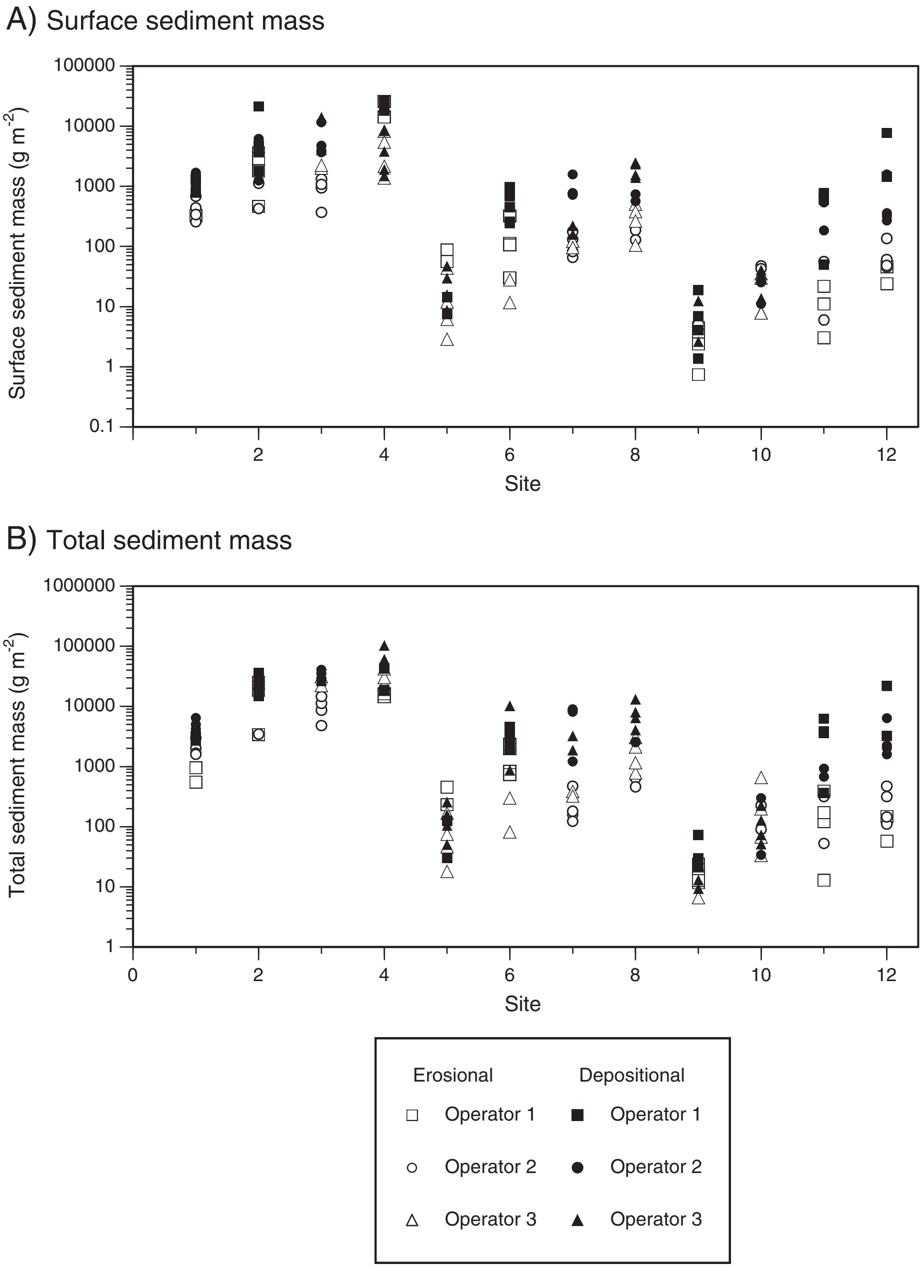


Fig. 2. Sampling variation in mass of A) surface- and B) total-deposited fine sediment collected from each constituent stilling well sample from the three segments within each site. The influence of different operators and different patch types (erosional or depositional) is indicated. Sites ranked by substrate bed composition and site mean total sediment mass. For site details see Table 1.

to be the greatest in river types where the technique was the least effective. Despite sites of varying substrate composition being chosen for the study, Bartlett's test for homogeneity of variance only returned a significant result for percentage volatile matter of total-deposited fine sediment (Table 4). Furthermore, as Levene's test was not significant for any measure of deposited fine sediment (Table 4), the results of the Bartlett's test using percentage volatile matter of total-deposited fine sediment probably indicates deviation from normality rather than heteroscedasticity. These results indicate that the resuspension technique performed equally well in all rivers tested for all measures of surface- and total-sediment mass or quality.

When the replicate reach-scale estimates of sediment mass and percentage volatile matter were compared to the mean for the site, the within-site variance apparently was evenly distributed among all river sites (Fig. 5). Confidence intervals were calculated for predictions of each reach-scale measure of deposited fine sediment, for the surface and the total (surface and subsurface) separately (Table 5). These values can be used as confidence intervals of reach-scale estimates of fine-grained sediment deposits from any site using this sampling technique.

3.2. Comparison with visual estimates

In order to put the findings on instantaneous sampling of deposited fine sediment into perspective, the results were compared to variation in visual estimates of percentage cover of fine sediments. As an individual cannot make independent repeat visual estimates (even within a river site), we could not adopt the same methodology to estimate variance in visual methods as that used here to assess sampling of deposited

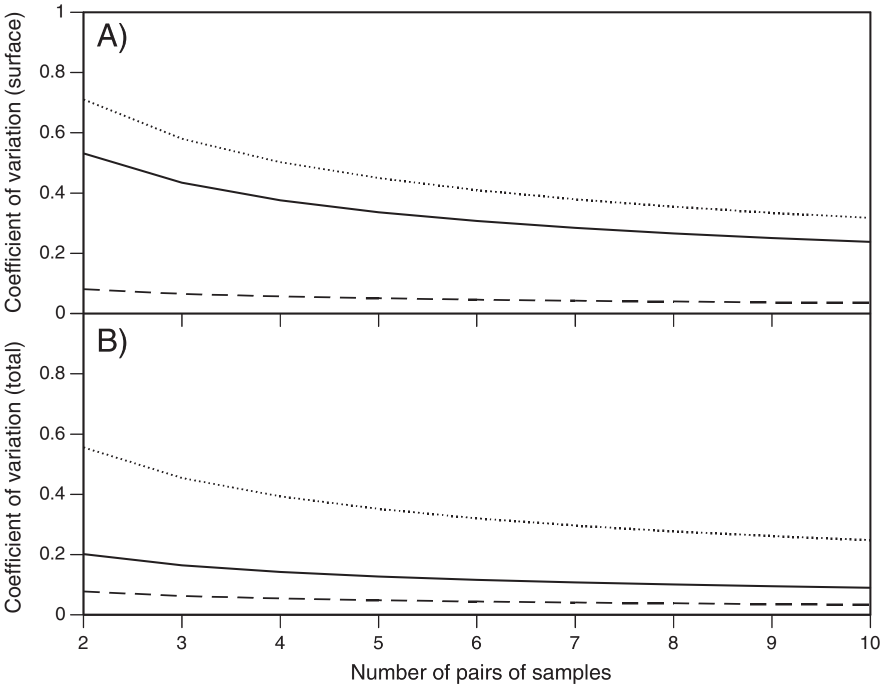


Fig. 3. Relationship between the number of sample pairs (one from an erosional and one from a depositional patch) and the coefficient of variation in A) surface-deposited fine sediment mass and B) total-deposited fine sediment mass for the most variable (short dash), least variable (long dash), and *average* river (solid line).

material. Hence, we used data collected for the Biological Assessment Methods (BAMS) study (Clarke et al., 2002), which was conducted to assess variation in assessments of ecological quality using the RIVPACS model (Wright et al., 1997). Here, field operators were required to assess bed composition by visually estimating the percentage cover of four size classes of substrate, namely boulders/cobbles (>64 mm), pebbles/gravel (>2–64 mm), sand (>0.0625–2 mm), and silt/clay (≤0.0625 mm). Estimates of bed composition were made by four different operators at each of 16 stream sites on three occasions (spring, summer, autumn). Two workers provided estimates at all sites, whilst the other two workers at each site were drawn randomly from a pool. For the current study, the percent cover of the size classes sand and silt/clay were combined to provide an estimate of deposited fine sediment for the site. Variation in these visual estimates of fine sediment cover was assessed using hierarchical analysis of variance (ANOVA) techniques, as above. The components of variance assessed were caused by:

- differences between sites on different rivers;
- differences between operators (person making the visual estimate) at the same site; and
- temporal differences between seasons at the same site.

We note that within-river spatial variation was not assessed; as visual estimates are nondestructive, they were made covering exactly the same short reach of river bed. Hence, comparisons between operators include only that variation which is attributable to differences between operators, whereas the equivalent estimates made for deposited fine sediment with the resuspension technique include smaller scale spatial variation.

Specifically, if Y_{klrs} is the value of the percentage cover estimate made by operator l at site k on occasion r in season s, then Y_{klrs} can be expressed in terms of the sum of the components contributing toward the overall variation in its values, namely:

$$Y_{klrs} = \mu + a_k + b_{kl} + h_{klr} + i_{klrs} \tag{8}$$

where

μ overall mean value of Y;
a_k deviation of mean value for site k from the overall mean value μ;
b_{kl} deviation of mean value for operator l at site k from the mean for site k;

Table 3
Estimates of sources of variance in reach-scale estimates of surface- and total-deposited fine sediment mass (g m^{-2}), nonvolatile sediment mass (g m^{-2}), volatile sediment mass (g m^{-2}), and percentage volatile matter; *** indicates where the variance component was statistically significant in ANOVA tests at the 0.001 test probability level.

Variance		Surface sediment mass	Surface nonvolatile mass	Surface volatile mass	Surface % volatile	Total sediment mass	Total nonvolatile mass	Total volatile mass	Total % volatile
Between-site	σ_K^2	29.52***	33.63***	31.30***	32.41***	31.3***	32.41***	19.42***	1.91***
Operator	σ_L^2	0.04	0.05	0.07	0.07	0.07	0.07	0.01	0.01
Replicate reach	σ_M^2	1.95	2.20	1.28	1.37	1.28	1.37	1.29	2.10
Total	σ_T^2	31.51	35.87	32.62	33.85	32.62	33.85	20.72	
%Between-site		93.68	93.74	95.86	95.73	95.86	95.73	93.75	90.78
%Operator		0.11	0.13	0.21	0.22	0.21	0.22	0.05	0.46
%Replicate reach		6.20	6.13	3.93	4.05	3.93	4.05	6.21	8.76
%Within-site		6.32	6.26	4.14	4.27	4.14	4.27	6.25	9.22
Of within-site									
%Operator		1.81	2.03	5.17	5.05	5.17	5.05	0.79	4.98

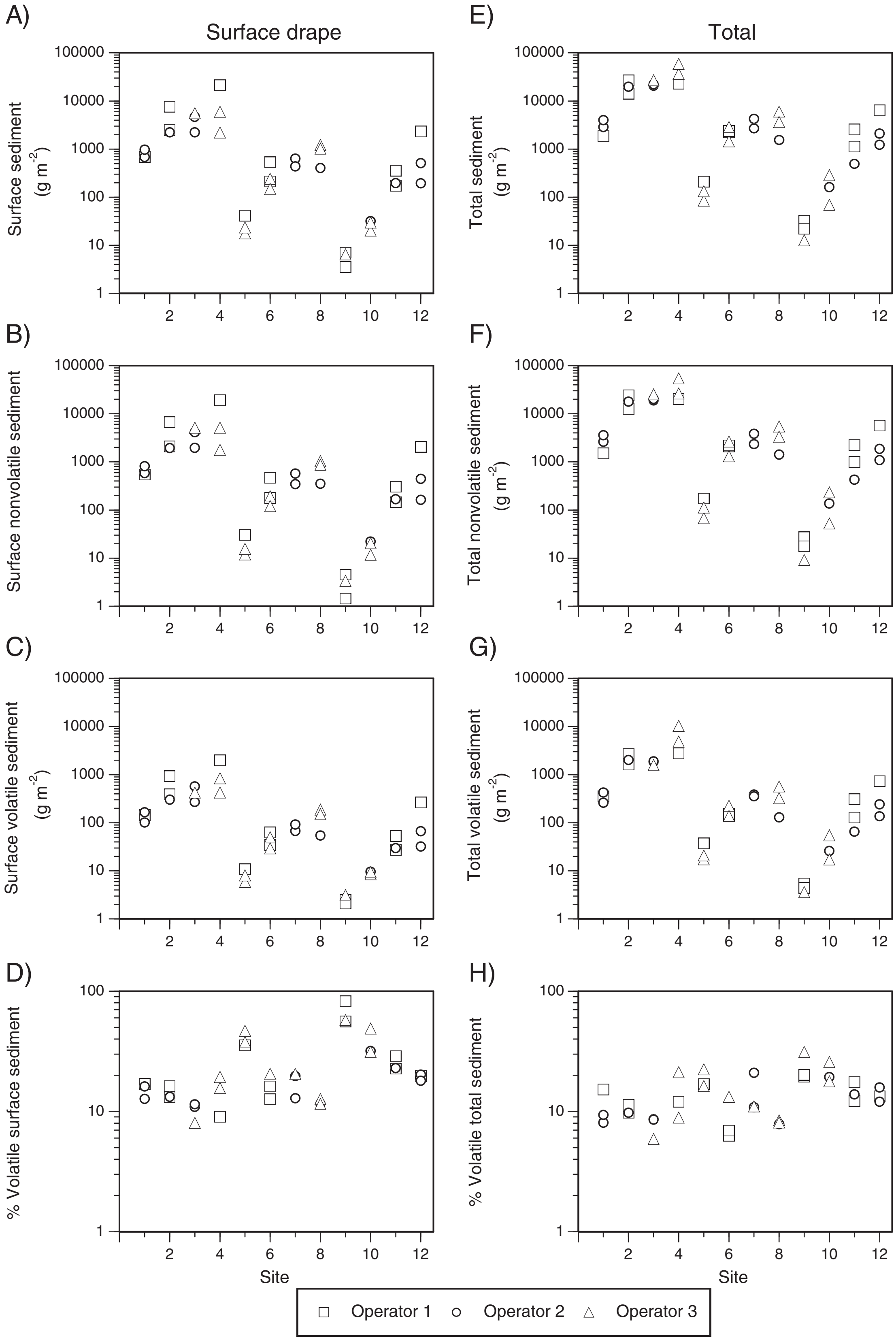


Fig. 4. Sampling variation in surface- (A, B, C, D) and total- (E, F, G, H) deposited fine sediment estimated by a composite sample of four stilling well samples (two from erosional and two from depositional patches): A & E) mass of deposited fine sediment, B & F) mass of deposited nonvolatile fine sediment, C & G) mass of deposited volatile fine sediment, D & H) percentage of the deposited fine sediment comprising volatile matter at each site. The individual operators who collected the samples are indicated by different symbols. Sites ranked by substrate bed composition and site mean total sediment mass. For site details see Table 1.

Table 4
Statistical probability of homogeneity of variance of deposited fine sediment samples collected from rivers of different bed composition (or site names and details see Table 1); P values shown, >0.05 = homogeneity of variances among rivers of different bed composition.

		Bartlett's test[a]	Levene's test[b]
Surface	Log_{10} sediment mass (g m^{-2})	0.549	0.754
	Log_{10} nonvolatile sediment mass (g m^{-2})	0.588	0.816
	Log_{10} volatile sediment mass (g m^{-2})	0.336	0.721
	Log_{10} percentage volatile matter	0.113	0.939
Total	Log_{10} sediment mass (g m^{-2})	0.478	0.760
	Log_{10} nonvolatile sediment mass (g m^{-2})	0.638	0.826
	Log_{10} volatile sediment mass (g m^{-2})	0.210	0.675
	Log_{10} percentage volatile matter	0.009	0.821

[a] Bartlett's test detects where normally distributed data are not homogeneously distributed, but is sensitive to departures from normality.

[b] Levene's test determines if the variances of the populations from which different samples are drawn are equal for any continuous distribution of data.

h_{klr} deviation of the estimate for occasion r for operator l at site k from the mean for operator l at site k;
i_{klrs} deviation of mean value for season s for site k from the mean for site k;

and where

σ_K^2 variance of a_k, i.e., variance caused by differences in mean value between sites;
σ_L^2 variance of b_{kl}, i.e., variance caused by differences between operators within a site;
σ_R^2 variance of h_{klr}, i.e., variance caused by differences between estimates made by the same operator at the same site; and
σ_S^2 variance of i_{klrs}, i.e., variance caused by differences between seasons within estimates made at the same site.

This approach correctly distinguishes and estimates that part of the overall variance of percentage cover of fines at a site that is caused by systematic differences between people in the way they make the estimate (namely σ_L^2). As two individuals made visual estimates of fine sediment cover at all sites, any consistent difference between these two could be assessed and compared to the variation apparent by the other (random) individuals making estimates at each site (i.e. the overall population of estimates) to determine if either of these two individuals were exceptional in their estimates.

The total variance (σ_T^2) in percentage cover of deposited fine sediment across all rivers is estimated by

$$\sigma_T^2 = \sigma_K^2 + \sigma_L^2 + \sigma_R^2 + \sigma_S^2. \tag{9}$$

The within-site variance (σ_W^2) in percent cover of deposited fine sediment is estimated by

$$\sigma_W^2 = \sigma_L^2 + \sigma_R^2 + \sigma_S^2. \tag{10}$$

Whilst a direct comparison between the variance in visual estimates of fine sediment cover and that of the measurements of instantaneous deposited fine sediment made with the stilling well cannot be made (the two studies were conducted in different ways in different rivers), the relative contributions of some components of the variance can be compared. In particular, the relative importance of within-site variance and the influence of individual operators on estimates of deposited fine sediment made using the two methods can be evaluated.

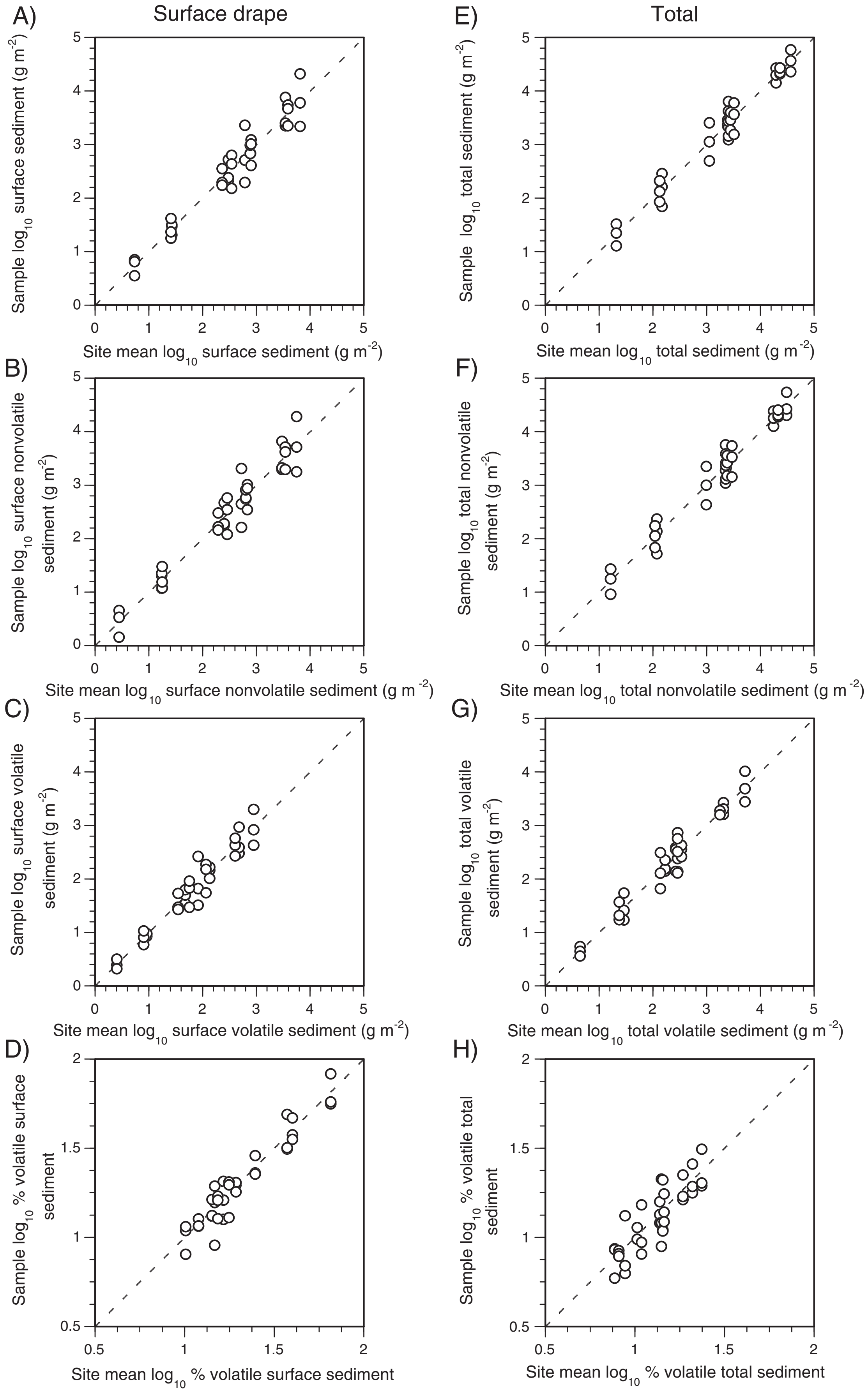
In this analysis the pertinent source of variance for comparison with the resuspension approach is that of the operator. In order for the resuspension approach to be worthy of uptake, it would need to perform at least as well as the next best single visit estimation technique available. When the components of the variance associated with the percentage cover visual estimate were apportioned, the between-site and the between-operator variances were found to be highly significant; i.e., although visual estimates were good at discriminating between sites, the person making the visual estimate affected the results (Table 6). These two components represented 94.02% and 2.31% of the total variance, respectively, with 39.38% of the within-site variance attributable to the operator. The ability of visual estimates of deposited fine sediment to discriminate between rivers was comparable to the resuspension approach, where 95.86% of the variance of total-deposited sediment mass was found to be between sites. However, interoperator variability affected estimates of deposited fine-grained sediment made with the resuspension technique far less than visual estimates, with only 5.17% of the within-site variance attributable to operator.

This comparison between the two methodologies has limitations, so this evaluation should be considered as illustrative without being absolute. More sites were included in the BAMS study with repeated visits to the same sites, which introduced temporal variation not apparent in the study reported here. Both of these differences will lead to greater total variance in the BAMS study. However, as visual estimates are nondestructive, they were made covering exactly the same short reach of river bed, which would exclude the influence of small scale spatial variability on visual estimates. Despite these differences, and although both approaches appear to be of similar sensitivity to the amount of deposited fine-grained sediment in rivers, visual estimates of percent cover appear subject to operator bias, which does not affect reach-scale estimates made using the resuspension technique.

4. Discussion

Recent increasing concern about the impact of human activities on fine-grained sediment loads and their effect on bed sediment deposition has highlighted the need to quantify the extent of this problem. Clearly, an approach that provides reliable estimates that are representative of the current state of the river bed is required. Whilst a variety of methods have been proposed, the influence of scale and other factors on the variation in measurements has rarely been quantified. Yet, as deposited fine-grained sediment is often distributed within river reaches in a patchy, highly skewed manner, the scale at which measurements are made is likely to have a substantial influence both on individual measures (typically made at the patch scale) and estimates for the river reach. The scale at which measurements are made is critical: if estimates are made at a scale such that within-site variation (caused by patchiness) is relatively large, the ability to discriminate between sites will be poor. By controlling for the main components of within-site variation (i.e., patch type and depth of ingress), we have developed a sampling method using a resuspension technique that can provide precise estimates of deposited fine-grained sediment mass at the channel-reach scale. The vast majority of the remaining unexplained within-site variation was caused by spatial patchiness at the smallest scale: together, river segment, position within segment, and operator accounted for <1.5% of the within-river variation in measures of deposited sediment mass. Furthermore, by using the geometric mean of the extremes based on a stratified random design, the method provides an efficient approach to establishing a measure of central tendency at the reach scale: only two pairs (i.e. from two erosional and two depositional patches) of samples were required in even the most variable of the rivers sampled. As it is less likely that the extremes of a highly skewed

Fig. 5. Relationships between site mean and individual reach-scale samples of surface- (A, B, C, D) and total- (E, F, G, H) deposited fine sediment: A & E) mass of deposited fine sediment, B & F) mass of deposited nonvolatile fine sediment, C & G) mass of deposited volatile fine sediment, and D & H) percentage of the deposited fine sediment comprising volatile matter at each site.


A)
Surface drape
Sample log$_{10}$ surface sediment (g m^{-2})
Site mean log$_{10}$ surface sediment (g m^{-2})
B)
Sample log$_{10}$ surface nonvolatile sediment (g m^{-2})
Site mean log$_{10}$ surface nonvolatile sediment (g m^{-2})
C)
Sample log$_{10}$ surface volatile sediment (g m^{-2})
Site mean log$_{10}$ surface volatile sediment (g m^{-2})
D)
Sample log$_{10}$ % volatile surface sediment
Site mean log$_{10}$ % volatile surface sediment
E)
Total
Sample log$_{10}$ total sediment (g m^{-2})
Site mean log$_{10}$ total sediment (g m^{-2})
F)
Sample log$_{10}$ total nonvolatile sediment (g m^{-2})
Site mean log$_{10}$ total nonvolatile sediment (g m^{-2})
G)
Sample log$_{10}$ total volatile sediment (g m^{-2})
Site mean log$_{10}$ total volatile sediment (g m^{-2})
H)
Sample log$_{10}$ % volatile total sediment
Site mean log$_{10}$ % volatile total sediment
0
1
2
3
4
5
0.5
1
1.5
2

distribution (often typical of deposited sediment) will be included, an entirely random design will require more samples to establish a stable estimate of central tendency (Sokal and Rohlf, 1998). Nevertheless, our findings regarding spatial patchiness of deposited fine sediment could be applied to other sampling methods in order to establish reach-scale estimates.

To be effective, any method for assessing deposited fine-grained sediment must work in rivers that vary in substrate composition, geomorphology, and heterogeneity. Here, we have shown that this resuspension method works across a wide range of river types, which varied in substrate composition (from ≥60% cobbles/boulders to ≥60% silt/sand) and within-river spatial heterogeneity, with equal precision for all measures of surface and total sediment mass and quality. We would expect that the method would return more variable results where site conditions rendered it ineffective. The fact that the method was not affected by variation in river type suggests that it is an adequate approach for large-scale (e.g. national) monitoring and evaluation programmes designed to assess the extent of deposited fine-grained sediment across a wide variety of rivers. As the method provides estimates of deposited fine-grained sediment at a scale relevant to targeted management decisions, it is highly appropriate for such programmes. In terms of cost, the approach is efficient compared with volumetric methods in that it does not require substantial sample volumes to be collected. Furthermore, the method does not suffer from operator bias, which we have shown here does have a significant influence on visual estimates of percentage cover, the most commonly used reach-scale method for assessing deposited fine-grained sediment in river channels. As national scale monitoring programmes typically involve a number of staff, any technique that is influenced by operator bias will be less able to confidently attribute differences in measurements to real differences in the amount of deposited fine-grained bed sediment rather than variation introduced by the staff collecting the samples. Notably, the resuspension technique tested here does involve substantial disturbance of the river bed at the point of sampling, which will influence repeat assessments of the same patch; however, this is unlikely to cause a substantial issue when deriving reach-scale estimates except in the smallest of streams as the area sampled (four patches, each 0.75 m^2) is small relative to the entire river reach.

As well as providing a reliable approach for monitoring the amount of deposited fine-grained bed sediment in rivers, the method can be used to address questions of geomorphological significance. A number of studies have used the resuspension technique tested here to estimate reach and channel system scale fine-grained sediment storage (e.g. Lambert and Walling, 1988; Walling et al., 1998; Walling and Amos, 1999; Collins et al., 2005; Collins and Walling, 2007b,c; Marttila and Kløve, 2013) and to place such estimates in the context of catchment suspended sediment budgets (e.g. Walling and Amos, 1999; Walling et al., 2002, 2003, 2006; Walling and Collins, 2008; Marttila and Kløve, 2013). Sediment budgets provide an important tool for understanding fluvial geomorphological processes (Reid and Dunne, 2005). The findings reported here demonstrate that the estimates reported in earlier work provide reliable data on this component of the fine-grained sediment cascade through catchment systems.

Issues of scale are critical when establishing the impact of increased loads of deposited fine-grained sediment on ecology (Jones et al., 2012a, b). The method tested here can provide reach-scale estimates of the extent of deposited fine sediment that can be related to ecological measures without the complications of scaling up from the patch to the whole river channel that render patch-scale measurements difficult to interpret (Larsen et al., 2009). Furthermore, the method enables quantification of subsurface deposited fine-grained sediment and thereby links the estimates to the interstices used by aquatic species as essential habitat.

5. Conclusions

This paper has presented an assessment of the uncertainty associated with measurements of deposited fine sediment at the scale of river reaches using a resuspension technique. In particular, it has, for the first time, quantified the precision and sources of uncertainty associated with the measurements. Here we present a rapid sampling method for assessing the amount (as mass/m^2) and quality (as percentage volatile matter) of surface- and total- (surface and subsurface) deposited fine sediment at reach scale. The method performs equally well across a wide range of substrate conditions. It compares favourably with visual estimates of the percentage of the river bed surface comprising fines in its ability to discriminate between rivers but, unlike visual estimates, is not affected by operator bias. It also enables quantification of subsurface-deposited fine-grained sediment and sediment quality. We have provided confidence intervals for reach-scale estimates of deposited fine sediment using the resuspension technique tested here, which can be applied elsewhere and as part of studies focussing solely on bed sediment deposition and/or composition or on catchment fine-grained sediment budgets.

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Table 5
95% confidence intervals of instantaneous measurements of surface- and total- (surface and subsurface) deposited fine sediment mass and quality.

		95% confidence intervals
Surface	Log_{10} sediment mass (g m^{-2})	±0.324
	Log_{10} non-volatile sediment mass (g m^{-2})	±0.346
	Log_{10} volatile sediment mass (g m^{-2})	±0.263
	Log_{10} percentage volatile matter	±0.102
Total	Log_{10} sediment mass (g m^{-2})	±0.269
	Log_{10} non-volatile sediment mass (g m^{-2})	±0.278
	Log_{10} volatile sediment mass (g m^{-2})	±0.261
	Log_{10} percentage volatile matter	±0.131

Table 6
Estimates of sources of variance in visual estimates of % fine sediment (sand, silt, clay) of bed composition from the BAMS study; *** indicates where the variance component was statistically significant in ANOVA tests at the 0.001 test probability level.

Variance		% Fine sediment
Between-site	σ_K^2	253,090***
Operator	σ_L^2	6229***
Replicate sample	σ_R^2	9588
Season	σ_S^2	272
Total	σ_T^2	269,178
% Between-site		94.02
% Operator		2.31
% Replicate sample		3.56
% Season		0.10
% Within-site		5.86
Of within-site		
% Operator		39.38

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Multiple stress response of lowland stream benthic macroinvertebrates depends on habitat type

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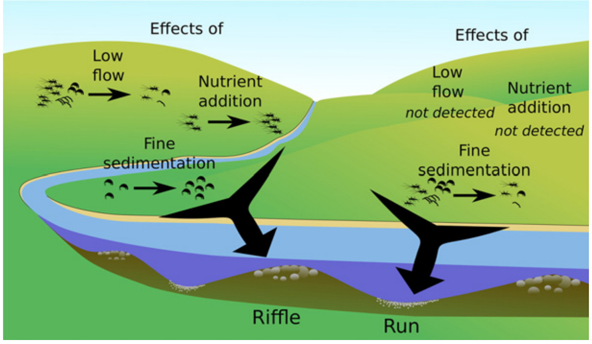
HIGHLIGHTS

- Macroinvertebrates in runs are affected by fine sediment, not by low flow.
- Strong response to low flow in riffles, mitigated by fine sediment and nutrients
- Fast reaction of macroinvertebrates to low flow and fine sediment, if responses detected
- Habitat dependency of effects advises habitat restoration measures.

GRAPHICAL ABSTRACT



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ABSTRACT

Worldwide, lowland stream ecosystems are exposed to multiple anthropogenic stress due to the combination of water scarcity, eutrophication, and fine sedimentation. The understanding of the effects of such multiple stress on stream benthic macroinvertebrates has been growing in recent years. However, the interdependence of multiple stress and stream habitat characteristics has received little attention, although single stressor studies indicate that habitat characteristics may be decisive in shaping the macroinvertebrate response. We conducted an experiment in large outdoor flumes to assess the effects of low flow, fine sedimentation, and nutrient enrichment on the structure of the benthic macroinvertebrate community in riffle and run habitats of lowland streams. For most taxa, we found a negative effect of low flow on macroinvertebrate abundance in the riffle habitat, an effect which was mitigated by fine sedimentation for overall community composition and the dominant shredder species (*Gammarus pulex*) and by nutrient enrichment for the dominant grazer species (*Baetis rhodani*). In contrast, fine sediment in combination with low flow rapidly affected macroinvertebrate composition in the run habitat, with decreasing abundances of many species. We conclude that the effects of typical multiple stressor scenarios on lowland stream benthic macroinvertebrates are highly dependent on habitat conditions and that high habitat diversity needs to be given priority by stream managers to maximize the resilience of stream macroinvertebrate communities to multiple stress.

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1. Introduction

Worldwide, stream benthic macroinvertebrates are facing a plethora of anthropogenic environmental stressors. Altered precipitation patterns (Arnell, 1999) and water abstraction (Vanneuville and Uhel, 2012) create periods with critical low flow that result in loss of macroinvertebrate species typical for stream ecosystems (Graeber et al., 2013; Hille et al., 2014; Lorenz et al., 2016). At the same time, increased loads of fine sediments and elevated nutrient concentrations (Kronvang et al., 2005; Pacheco et al., 2014; Townsend et al., 2008) adversely impact the structure of stream macroinvertebrate communities (Piggott et al., 2015; Townsend et al., 2008; Wagenhoff et al., 2013). Although the interactive effect of these stressors is difficult to predict, stream mesocosm experiments consistently document that the effects of flow reduction on macroinvertebrate community structure are stronger when combined with fine sedimentation than with nutrient enrichment (Piggott et al., 2012; Townsend et al., 2008). Furthermore, these experiments have shown that subsidy effects of nutrient enrichment commonly appear in macroinvertebrates feeding on benthic biofilms (i.e. scrapers; Gruner et al., 2008) and that the effects of nutrient enrichment may be counteracted by fine sedimentation (Wagenhoff et al., 2012).

Field-based studies further document that the susceptibility of stream macroinvertebrate communities to different environmental stressors depends on physical habitat characteristics (Dewson et al., 2007; Rasmussen et al., 2012). For example, the effects of low flow on macroinvertebrate communities depend on the availability of suitable habitats acting as refugia, and this refugial capacity is intrinsically linked to other habitat-specific characteristics such as fine sediment cover and availability of food resources (Lancaster and Hildrew, 1993). Conversely, the effects of fine sediment cover on macroinvertebrate community composition depend on habitat type (Roy et al., 2003). Therefore, evaluating the effects of different stressor combinations in different habitat types is a fundamental prerequisite for robust quantification of the summed impacts of typical anthropogenic stress scenarios on stream macroinvertebrate communities.

In the present study, we explored how habitat-specific characteristics shape the response of macroinvertebrates to flow reduction, nutrient enrichment, and increased coverage of fine sediment by applying multiple combinations of these three stressors in a controlled experimental setup. We used twelve 12-m long outdoor flumes to assess the effects of the stressor combinations on the benthic macroinvertebrate community in contrasting habitat types typical for lowland streams (riffle and run habitats, Pedersen, 2003). In more detail, we assessed the effects of nutrient enrichment during a normal-flow phase followed by a low-flow phase with a reduction in discharge representative of summer time low-flow periods in lowland streams (Graeber et al., 2015). Within the low-flow phase, fine sediment collected from a nearby stream was added to half of the outdoor flumes. During both the normal- and low-flow phases, macroinvertebrate samples were collected with weekly intervals in both habitat types to assess the temporal development of the benthic macroinvertebrate community induced by the selected multiple stressors. Based on these samples, we tested the following hypotheses with specific focus on the temporality of responses:

1. The combined effects of low flow and fine sediment addition on macroinvertebrate composition depend on habitat characteristics, with the strongest influence in run habitats compared with riffle habitats as fine sediment accumulation in run habitats is more pronounced than in riffle habitats.
2. Nutrient enrichment changes the structure of the benthic macroinvertebrate community in both run and riffle habitats towards increasing abundance of grazers due to a stimulating effect of nutrients on the biomass of epibenthic algae. This effect is reduced by addition of fine sediment, which diminishes the algae biomass available to grazers.

2. Materials and methods

2.1. Experimental setup

We conducted the experiment in twelve outdoor flumes during summer 2015 in Denmark (56°4′ N, 9°31′ E). The flumes consisted of rectangular 12 m long, 60 cm wide, and 30 cm deep channels. In each flume, four run-riffle sequences were created, resembling natural habitat conditions in lowland streams (Pedersen, 2003). Each of the four riffle and run habitats covered 1.5 m of the stream flume length with an average sediment depth of 5.5 cm (0.5–2, 2–4, 4–8, and 8–16 mm grain-sized sediment at a volume ratio of 3:1:1:1) in the runs and 15 cm (4–8, 8–16, 16–32, 32–64, and 64–120 mm grain-sized sediment in equal volumes) in the riffles. The stream flumes were continuosly supplied with water from a nearby source stream (Lemming stream) using a central stream feeder pump. To obtain the desired discharge volume, part of the water volume was recycled from twelve water reservoirs. With this setup, invertebrate drift into the flumes was allowed in order to simulate the natural drift within the source stream (refer to Neif et al. (2016) for further details on the stream flume setup).

2.2. Experimental phases

2.2.1. Pre-treatment phase

The pre-treatment phase was initiated on 15 June 2015 and lasted eight weeks. During this phase, the average discharge of the flumes was 5.4 L s^{-1} (±0.4 1SD, n = 12), which is comparable with discharges typical for hydrologically undisturbed small lowland streams (Pedersen, 2003).

After two weeks, benthic macroinvertebrates were collected from the source stream using kick sampling along a reach of approximately 500 m to be introduced to the flumes. In total, 120 kick samples were transferred to each flume, corresponding to a sampled source stream bed area of approximately 7.5 m^2, which is of a size similar to one flume (7.2 m^2). The colonization was successful as the source stream and the stream flume contained similar macroinvertebrate communities (see Appendix A for detailed comparisons of the macroinvertebrate communities in stream flumes and source stream and Appendix B for species lists).

2.2.2. Normal-flow phase

The normal-flow phase lasted four weeks and was initiated immediately after the pre-treatment phase. Six randomly chosen flumes were subjected to nutrient enrichment by adding fertilizer (SweDane NPK 21-3-10 and GrowHow NS 24-6, DLG, Copenhagen, Denmark) (NP treatment). The nutrients were mixed in a 600 L tank and continuously transferred to the respective flumes using a peristaltic pump (BVP-Process with a 12-channel CA pump head, Ismatec, Wertheim, Germany). In brief, target concentrations of nitrate-N, ammonium-N, and phosphate-P were elevated by a factor of 2, 20, and 4 in the NP treatment (Table 1, see Appendix A for methods used to quantify nutrient concentrations). These increases in dissolved inorganic nitrogen and phosphate represented concentrations in lowland streams draining catchments with intensive agriculture (Larsen et al., 1999).

The cover of fine sediment was low during the normal-flow phase (see Appendix A for estimation methods of fine sediment cover), and the flow was therefore sufficient to avoid precipitation of suspended matter from the water column (Table 1).

Twelve leaf litter bags with coarse mesh size (10 mm), allowing macroinvertebrates to access the leaf material, were deployed in each flume between the riffle and run habitats at the beginning of the normal-flow phase. Each bag contained 1 (±0.01) g DW leaves of beech (*Fagus sylvatica* L.), which is the dominant broad-leaf tree species in the area.

Table 1
Mean ± 1SD of discharge, current velocity, water depth, temperature, nutrient concentrations, and fine sediment cover during the normal-flow and low-flow phase. FS = fine-sediment treatments, NP = nutrient-enrichment treatments.

	Normal-flow phase (NF)	Low-flow phase (LF)
Discharge (L s^{-1}, n = 48)	4.65 ± 0.28	1.05 ± 0.12
Current velocity (cm s^{-1}, n = 12)		
Run, below surface	0.15 ± 0.05	0.02 ± 0.01
Run, half depth	0.11 ± 0.04	0.02 ± 0.01
Run, above sediment	0.07 ± 0.04	0.02 ± 0.01
Riffle	0.46 ± 0.04	0.04 ± 0.02
Water depth (cm, n = 12), run[a]	10.4 ± 0.9	12.4 ± 1.0
Temperature (°C, NF n = 31,667, LF n = 33,408)	12.9 ± 1.3	12.1 ± 1.1
NO_3^- (mg N L^{-1}, NF n = 42, LF n = 54)		
non-NP treatments	1.22 ± 0.14	1.19 ± 0.23
NP treatments	2.96 ± 0.79	2.77 ± 0.75
NH_4^+ (mg N L^{-1}, NF n = 42, LF n = 54)		
non-NP treatments	0.09 ± 0.15	0.13 ± 0.18
NP treatments	1.81 ± 0.75	1.84 ± 0.81
PO_4^{2-} (mg P L^{-1}, NF n = 42, LF n = 54)		
non-NP treatments	0.012 ± 0.005	0.014 ± 0.004
NP treatments	0.049 ± 0.019	0.042 ± 0.016
Fine sediment cover, run (%, NF n = 48, LF n = 24)[b]		
non-FS treatments	9.3 ± 10.7	22.2 ± 22.0
FS treatments	–	79.6 ± 19.3

[a] Water depth was measured in detail in the run habitat to check for too low water depths during the low-flow phase; it was always >3 cm in the riffle.

[b] No fine sediment cover was detectable in the riffle habitat; during normal flow the fine sediment treatment was not applied.

2.2.3. Low-flow phase

Immediately after the normal-flow phase, the low-flow phase was initiated by reducing discharge but keeping the water depth and water temperature stable (Table 1). Current velocity was reduced by 90% compared with the normal-flow phase (Table 1; see Appendix A for methods used to measure current velocity).

The NP treatment was continued in the low-flow phase to maintain stable eutrophic conditions.

After initiating the low-flow phase, fine sediment was added to six randomly chosen flumes, hereby creating four treatments (n = 3): no treatment, NP, fine sediment addition (FS), and combined nutrient enrichment and fine sediment addition (NP + FS). The organic-rich fine sediment was collected from the source stream (Lemming stream) and introduced manually into the flumes until >90% fine sediment cover was reached (consult Neif et al. (2016) for details). On average, the fine sediment treatments (FS) were characterized by an increase in the fine sediment cover by a factor of 4 compared with the flumes with no sediment addition (Table 1).

Similar to the normal-flow phase, leaf litter bags with coarse mesh size (10 mm) and each containing 1 (±0.01) g DW of beech leaves were deployed at the beginning of the low-flow phase. In total, 12 leaf bags were deployed in each flume and positioned between the riffle and run habitats.

2.3. Macroinvertebrate sampling and identification

One week before the start of the normal-flow phase and weekly during the normal-and low-flow phases (9 sampling occasions), macroinvertebrates were sampled using a surber sampler (area = 195 cm^2, mesh size = 200 μm). For each flume and on each sampling occasion, one Surber sample was collected in an upstream run or riffle habitat and one in a downstream run or riffle habitat. The samples were pooled habitat-wise (riffle or run, resulting in 216 samples in total). The purpose of restricting the number of samples per sampling occasion was to avoid removing an excess number of individuals from the stream flumes in the repeated samplings.

All macroinvertebrate samples were preserved in 95% ethanol in the field. All macroinvertebrate taxa were identified to species level except for Chironomidae (sub-family), Oligochaeta (class), as well as Empididae, Tipulidae, and Simuliidae (family). In cases where individuals were too small to be identified to species level, they were identified to genus level, and at this level all individuals of the same genus were used for further statistical computations. Please refer to Appendix B for the species data used in our study.

2.4. Statistics

2.4.1. Community response to multiple stress

We used principal response curves (PRC) to analyse the temporal development in macroinvertebrate community composition in the stream flumes (Van den Brink and Ter Braak, 1999). The PRC model is based on the first axis of a principal coordinate analysis using Bray-Curtis similarity to generate site and species scores using the “capscale” function of the “vegan” R package (Oksanen et al., 2015) in R (version 3.3.2, R Core Team, 2016). The PRC consists of treatment scores and species weights. The treatment scores can be interpreted as the principal response of the community to a treatment (Van den Brink and Ter Braak, 1999). The species weights allow determination of taxon-specific reactions since higher species weights indicate stronger responses of the species to the treatment patterns in the PRC (Van den Brink and Ter Braak, 1999). Taxa with near zero species weights show either no response or one that is unrelated to the patterns represented in the PRC. Moreover, the direction of the species weights determines the direction of the response of the species to the treatments (Van den Brink and Ter Braak, 1999).

To investigate habitat-specific stressor-induced effects on macroinvertebrate communities, separate PRCs were performed for riffle and run habitats and for the normal-flow phase and the low-flow phase as the control differed between the phases. The control for the habitat-specific PRCs of the normal-flow phase was the habitat-specific (riffle or run) species composition in the channels in the last week of the pre-experimental phase, one week before the start of the normal-flow phase. For the low-flow phase, the control was the habitat-specific average of macroinvertebrate species-specific densities across all weeks of the normal-flow phase for the six channels without nutrient enrichment. An ANOVA-like permutation test (999 iterations) was used to assess the significance of the PRC model using the “anova.cca” function of the “vegan” package (Oksanen et al., 2015) in R (R Core Team, 2016). All PRC models significantly explained the data ($F > 2.8$, $p < 0.001$), except for the PRC of the run habitat during normal flow, which was only marginally significant ($F = 1.8$, $p = 0.06$), however.

To assess habitat-specific effects of low flow with and without fine sediment addition, the benthic macroinvertebrate community structure was analysed with separate permutational multivariate analyses of variance (PERMANOVA, 999 iterations, Bray-Curtis dissimilarity) (adonis function, vegan package in R; Oksanen et al., 2015) for each of the two habitats within the flumes with FS, FS + NP and without FS or NP. Here, we compared the last week of the normal-flow phase with the first week of the low-flow phase to minimize potential temporal effects interfering with the effect of low flow. Within the PERMANOVAs, the phase (normal or low flow) was used as main factor and the flumes were used as strata.

PERMANOVAs (999 iterations, Bray-Curtis dissimilarity) were also used to assess the effects of the NP treatment on the macroinvertebrate community composition during the normal-flow phase and the effects of the FS, NP, and FS + NP treatments and their interaction during the low-flow phase. Weeks were used as strata for the permutations due to the repeated nature of the sampling.

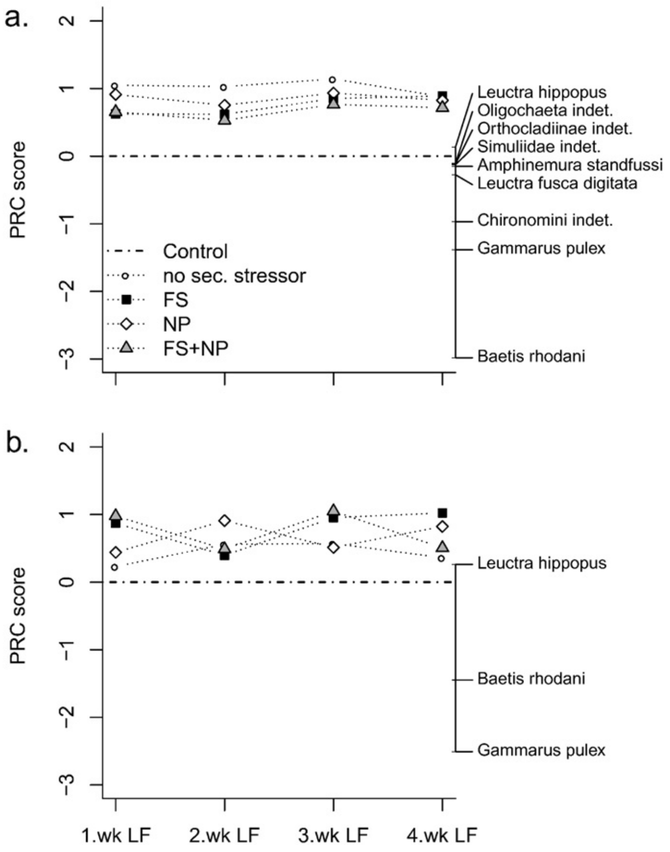

Fig. 1. Principal response curve of macroinvertebrate composition during each week of the low-flow phase in the riffle (a) and run (b) habitats with or without fine sediment (FS), the nutrient enrichment treatment (NP), the combination of FS and NP (FS + NP) or without any secondary stressor (no sec. stressor). The control is the average of taxa-specific densities during all weeks of the normal-flow phase. Only means of the treatment scores are shown for each point ($n = 3$) and only taxa with species weights > 0.1 are plotted (see the Statistics section for details on the meaning of the treatment scores and species weights).

2.4.2. Species-specific response to multiple stress

We investigated the species-specific response to the FS, NP, and FS + NP treatments within the riffle and run habitats based on the abundances of *Gammarus pulex* L. and *Baetis rhodani* Pictet. We used linear mixed-effects models with channel as random intercept (lme function, nlme package in R, Pinheiro et al., 2015) to test the effects of the NP treatment during the normal-flow phase and the FS, NP, and FS + NP treatments during the low-flow phase. We ran the linear-mixed effects models separately for the two phases and the two habitats to obtain phase- and habitat-specific responses. The above to species were selected because they constituted 73% of the macroinvertebrate density in the experiment, and their abundances thus strongly affected community statistics and assisted in their interpretation. Furthermore, *B. rhodani* is a grazer presumably influenced by the hypothesized nutrient enrichment-induced increase in algal biomass, whereas *G. pulex* is a shredder and therefore less likely to be influenced by this (Colling and Schmedtje, 1996).

3. Results

3.1. Effects of low flow and fine sediment

During the low-flow phase, we found a significant mitigating effect of fine sedimentation in the riffle habitat; hence the flumes with FS treatment were not as strongly altered in their macroinvertebrate composition relative to the control as flumes without FS treatment (Fig.1a, Table 2). Due to the mitigating effect of fine sedimentation in the riffle habitat, the change from normal to low flow was not significant in combination with the FS treatment (Table 3). Without application of the FS treatment, we detected a significant effect of the change from normal to low flow in the riffle habitat (Table 3).

In contrast, in the run habitat, the flumes with FS treatment showed the strongest deviation from the control, indicating that the FS treatment created the strongest alteration in macroinvertebrate composition (Fig. 1b, Table 2). Consequently, there was a significant effect of the change from normal to low flow in the run habitat, when this change was combined with the FS treatment (Table 3).

For *G. pulex*, we also detected habitat-specific effects of the FS treatment. Significantly higher abundances occurred with than without the FS treatment in the riffle habitats (Fig. 2a), whereas no effect of the FS treatment appeared in the run habitats (Fig. 2b). For *B. rhodani*, we found no effect of the FS treatment, but a strong habitat-specific abundance decline occurred after the flow reduction (Fig. 3), this being more pronounced in the riffle (Fig. 3a) than in the run habitats (Fig. 3b).

3.2. Effects of nutrient enrichment during normal and low flow

The NP treatment did not significantly affect the macroinvertebrate community composition during either normal or low flow (Table 3, Figs. 1, 4). However, the densities of *B. rhodani* were higher in riffle habitats in flumes with NP treatment under both normal-and low-flow conditions (Fig. 3a) which was not the case in run habitats (Fig. 3b).

4. Discussion

4.1. Habitat-specific effects of low flow and fine sediment

We found that the combined effects of low flow and fine sediment on the macroinvertebrate community were habitat dependent. This is in accordance with empirical evidence from other field studies also reporting habitat-specific effects of these two stressors (Lancaster and Hildrew, 1993; Roy et al., 2003). Furthermore, we observed that the response of the macroinvertebrate community to fine sedimentation and low flow occurred rapidly, being detectable after just one week with no or only little further development over time.

A combination of different mechanisms likely contributed to the stronger response of the macroinvertebrate community to fine sedimentation in the run habitat than in the riffle habitat. Fine sediment has been shown to affect benthic macroinvertebrates in different

Table 2
Effects of the secondary stressor treatments and their interactions on macroinvertebrate composition during the normal-flow and low-flow phase. Secondary stressor treatments were nutrient enrichment (NP) during the normal-flow phase and fine sedimentation (FS) and NP during the low-flow phase. The results from permutational multivariate analyses of variance (PERMANOVA) with sampling weeks as strata are shown ($n = 48$). $^{ns}p > 0.05$, $^{*}p < 0.05$, $^{***}p < 0.001$.

Habitat	Flow phase	NP	FS	NP × FS
Riffle	Normal flow	$F = 1.7, R^2 = 0.04^{ns}$	–	–
Riffle	Low flow	$F = 1.6, R^2 = 0.02^{ns}$	$F = 9.3, R^2 = 0.17^{***}$	$F = 0.8, R^2 = 0.01^{ns}$
Run	Normal flow	$F = 1.0, R^2 = 0.02^{ns}$	–	–
Run	Low flow	$F = 1.6, R^2 = 0.03^{ns}$	$F = 2.3, R^2 = 0.05^{*}$	$F = 1.0, R^2 = 0.02^{ns}$

ways: i) by reducing the stability and thereby the suitability of habitats, creating increased drift (Wood and Armitage, 1997) and limiting the access to food sources (Matthaei et al., 2010), ii) by clogging of interstitial spaces, reducing the availability of suitable habitats (Wood and Armitage, 1997), and iii) by increasing benthic respiration, hereby decreasing the daily minimum concentrations of oxygen (García and Pardo, 2016; Wood and Armitage, 1997). In our study, the effect of clogging of interstitial spaces was probably limited in the run habitat as we mainly used sand as original sediment to simulate typical Danish conditions (Pedersen, 2003). We found that the deployed beech leaves were partly covered with fine sediment and that the applied fine sediment was relatively rich in organic matter. Consequently, the combined effect of loss of food sources, reduced habitat stability, and increased benthic respiration probably caused the strong response of the benthic macroinvertebrates to fine sedimentation in the run habitat.

In the riffle habitats, fine sediment seemed to counteract the effects of low flow on the overall macroinvertebrate community composition. Furthermore, the abundance of *G. pulex* was higher in the riffle than in the run habitats in the flumes with fine sediment treatment. However, we did not observe cover by fine sediment, a commonly used indicator of the level of fine sedimentation (e.g. Matthaei et al., 2010; Piggott et al., 2012; Wagenhoff et al., 2012), indicating that the fine sediment may have accumulated at deeper sites, clogging of the interstitial spaces. This likely reduced the ability of *G. pulex* and other taxa to migrate vertically into the sediment (Vadher et al., 2015) and probably increased the vulnerability of *G. pulex* and other species to lower water depth (Vadher et al., 2015), and higher water temperatures (Vorste et al., 2016).

We found relatively constant effects of fine sedimentation and low flow on macroinvertebrate composition, although invertebrate drift from the source stream occurred. Therefore, despite the potential for recovery by drift, the ecosystem conditions were not sufficiently favourable to allow recovery of the macroinvertebrate community from the effects of fine sedimentation or low flow.

4.2. Habitat-specific effects of nutrient enrichment

In contrast to our second hypothesis, we found no significant overall response of macroinvertebrate community composition to nutrient enrichment. This is likely related to the already high background concentrations of dissolved inorganic nitrogen, where a further enrichment would either yield no or even negative toxic effects on benthic macroinvertebrates (Camargo et al., 2005; Camargo and Alonso, 2006; Wagenhoff et al., 2011). This may also explain why our findings contradict those obtained in earlier studies under less nitrogen-rich conditions (Bourassa and Cattaneo, 2000; Piggott et al., 2012; Townsend et al., 2008; Wagenhoff et al., 2011, 2012). Additionally, the dominant species within our experiment likely fed on sources of terrestrial organic matter, such as CPOM and fine detritus (*G. pulex*, *Leuctra fusca*, *Leuctra hippopus*, Chironomini) (Colling and Schmedtje, 1996; López-Rodríguez et al., 2012) and less on autochthonous sources, such as epibenthic algae. Therefore, their response may not have been dependent on the influence of nutrient enrichment on biofilm development. In line with this, we observed an increase in the abundance of the grazer *B. rhodani* in the riffle habitat, probably as a consequence of the increased benthic algae growth (Dudley and D'Antonio, 1991). The missing effect of nutrient enrichment on *B. rhodani* within the run habitat implies that benthic algal growth was not affected by nutrient enrichment. This is in accordance with an earlier study conducted within the same stream flumes under the same experimental conditions, which did not reveal any effect of nutrient enrichment on the benthic algae

Table 3
Effects on macroinvertebrate composition by the change from normal to low flow with or without additional fine-sediment treatment. Results of permutational multivariate analyses of variance (PERMANOVA) with stream flumes as strata are shown (n = 6).*p < 0.05, FS = fine-sediment treatment.

Habitat	FS	F	R^2
Riffle	No	4.3	0.30*
Run	No	1.1	0.10
Riffle	Yes	2.8	0.22
Run	Yes	5.9	0.37*

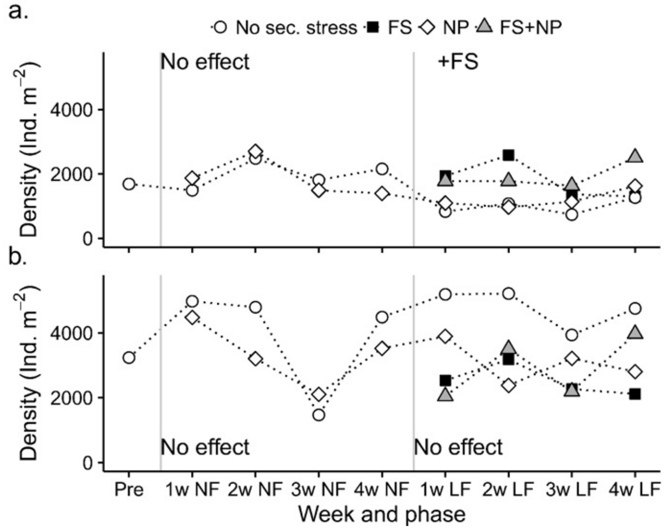

Fig. 2. Densities of *Gammarus pulex* during the normal-flow and low-flow phase in the riffle (a) and run (b) habitats. NP = nutrient-enrichment treatment, FS = fine-sediment treatment, FS + NP = both FS and NP, no sec. stressor = neither FS nor NP. Significant positive or negative effects (p < 0.05) of the secondary stressors within the phases were assessed with linear mixed-effects models and are depicted as + or − followed by the stressors, or as "No effect" if no secondary stressor effect was found. Only means are shown for each point (pre-experimental phase n = 12, normal-flow phase n = 6, low-flow phase n = 3) for clearer presentation.

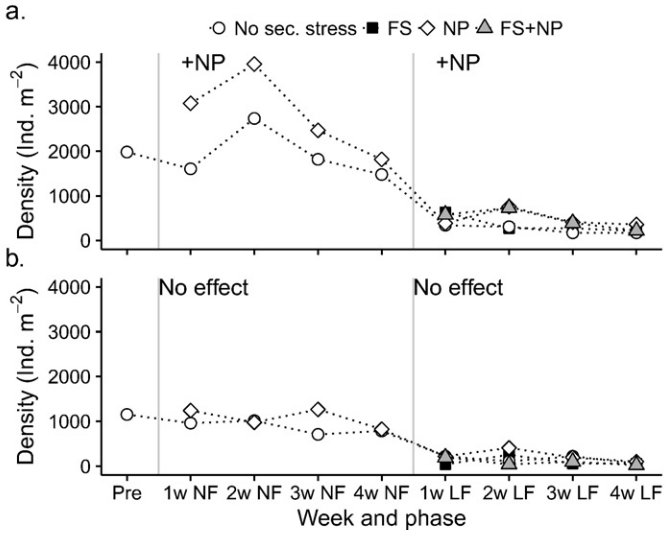

Fig. 3. Densities of *Baetis rhodani* during the normal-flow and low-flow phase in the riffle (a) and run (b) habitats. NP = nutrient-enrichment treatment, FS = fine-sediment treatment, FS + NP = both FS and NP, no sec. stressor = neither FS nor NP. Significant positive or negative effects (p < 0.05) of the secondary stressors within the phases were assessed with linear mixed-effects models and are depicted as + or − followed by the stressors, or as "No effect" if no secondary stressor effect was found. Only means are shown for each point (pre-experimental phase n = 12, normal-flow phase n = 6, low-flow phase n = 3) for clearer presentation.

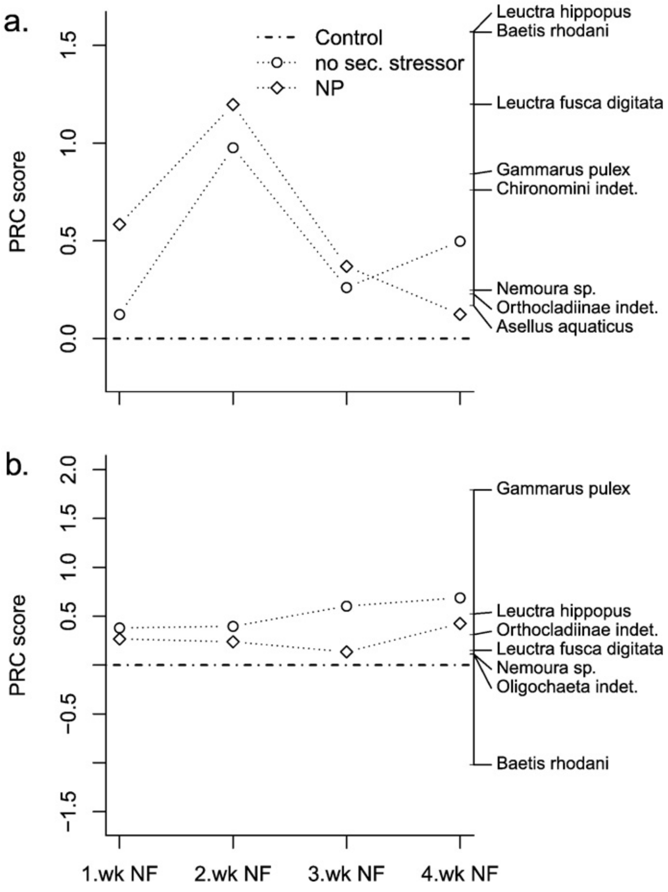

Fig. 4. Principal response curve of macroinvertebrate composition during each week of the normal-flow phase in the riffle (a) and run (b) habitats with or without the nutrient enrichment treatment (NP). The control is the macroinvertebrate composition determined for the last week of the pre-treatment phase. Only means of the treatment scores are shown for each point ($n = 6$) and only taxa with species weights > 0.1 are plotted (please see the Statistics section for details on the meaning of the treatment scores and species weights).

biovolume in the run habitat (Neif et al., 2016). However, in Neif et al. (2016) the riffle habitat was not investigated, and therefore our claim of increased benthic algae growth with nutrient enrichment in the riffle habitat remains to be supported by direct evidence.

4.3. Implications

Benthic macroinvertebrates are sensitive indicators of ecosystem status and health and are therefore used as such within monitoring programs and legislation (Friberg, 2014). Our findings showed a rapid response of the macroinvertebrate community to low flow, fine sedimentation, and nutrient enrichment, being highly dependent on habitat characteristics. This suggests a rapid ecosystem-wide response that may alter with habitat type and implies that more diverse physical stream conditions may enhance the resilience of the benthic macroinvertebrate community to multiple stress effects in streams. This notion is supported by an earlier finding in a field study with flow and sedimentation as the main stressors (Lorenz et al., 2016). Hence, maintenance or restoration of a diverse, natural range of habitats seems to be an obvious measure to apply in order to mitigate multiple stress effects in streams. Furthermore, our discovery that even short-term low-flow and fine-sedimentation events may strongly affect benthic macroinvertebrates in lowland agricultural streams clearly highlights the need for reducing the number of short multiple stress events. For example, fine sediment influx into stream ecosystems due to river bank and catchment erosion (Stutter et al., 2012) could be diminished through the use of vegetated sediment filters (buffer zones) with special focus on areas with high erosion risk (Gumiere et al., 2011). Management options to reduce the number of low-flow events created by water abstraction may be decreased cultivation of water-demanding crops and/or more efficient irrigation (e.g. droplet irrigation) in areas with intensive agriculture and dry summers (Vanneuville and Uhel, 2012). In the long term, however, the number of low-flow events can only be minimized by abating the anthropogenic climate change that not only affects stream hydrology directly via the predicted reduction in summer precipitation in coastal Europe but also increases the need for water abstraction during dry periods (Vanneuville and Uhel, 2012).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.05.102.

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