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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

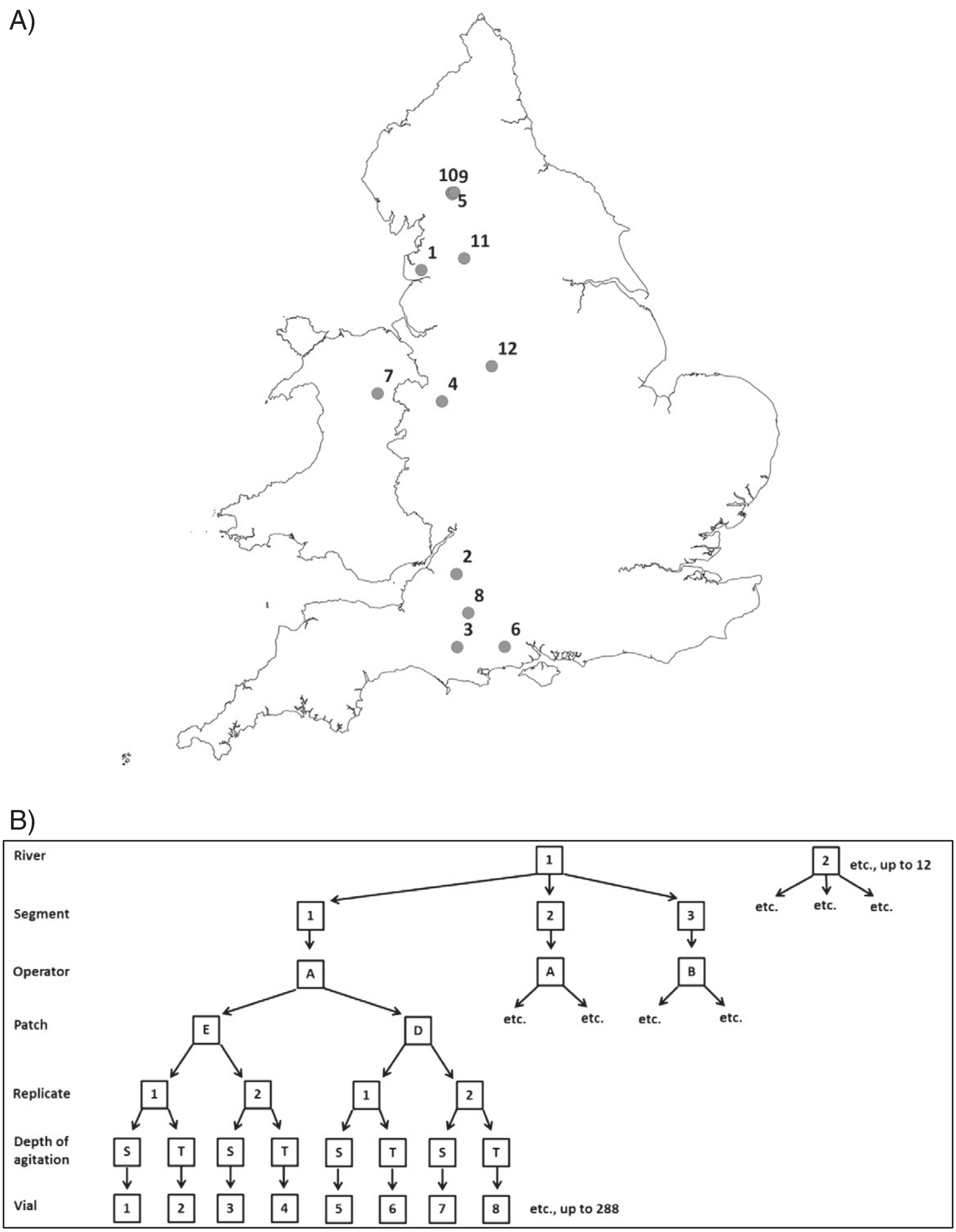



**Fig. 1.** A) Map showing the locations of the test sites. B) Schematic diagram of sampling strategy. Samples were collected from three homologous segments in 12 rivers, by either the major (indicated by A) or minor (indicated by B) operator, who sampled the surface- and total- (surface and subsurface) 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 ($\leq$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

$\mu$ overall mean value of $Y$;
$a_k$ deviation of mean value for site $k$ from the overall mean value $\mu$;
$b_{kl}$ 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

$\sigma^2_K$ variance of $a_k$, i.e. variance caused by differences in mean value between sites;
$\sigma^2_L$ variance of $b_{kl}$, i.e. variance caused by differences between operators within a site;
$\sigma^2_M$ variance of $c_{klm}$, i.e. variance caused by differences between replicate segments sampled by the same operator at the same site;
$\sigma^2_N$ 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;
$\sigma^2_O$ 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;
$\sigma^2_P$ 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
$\sigma^2_Q$ 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 $\sigma^2_L$) 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 $\sigma^2_M$ and constituents $\sigma^2_N$, $\sigma^2_O$, $\sigma^2_P$, $\sigma^2_Q$). 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 $\sigma^2_Q$), 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 ($\sigma^2_T$) in deposited fine sediment mass across all rivers is estimated by

$$\sigma^2_T = \sigma^2_K + \sigma^2_L + \sigma^2_M + \sigma^2_N + \sigma^2_O + \sigma^2_P + \sigma^2_Q. \tag{2}$$

The within-site variance ($\sigma^2_W$) in deposited fine sediment mass is estimated by

$$\sigma^2_W = \sigma^2_L + \sigma^2_M + \sigma^2_N + \sigma^2_O + \sigma^2_P + \sigma^2_Q. \tag{3}$$

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 ($\sigma^2_{Wc}$) and uncontrolled for ($\sigma^2_{Wuc}$), can be separated:

$$\sigma^2_W = \sigma^2_L + \sigma^2_{Wc} + \sigma^2_{Wuc} \tag{4}$$

where

$$\sigma^2_{Wc} = \sigma^2_N + \sigma^2_P \tag{5}$$

$$\sigma^2_{Wuc} = \sigma^2_M + \sigma^2_O + \sigma^2_Q. \tag{6}$$

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 ($\sigma^2_T$) 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:

$$P_{W/T} = 100\sigma^2_W/\sigma^2_T. \tag{7}$$

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 | $\sigma^2_K$ | 249.40*** | 262.56*** | 157.70*** | 10.13*** |
| Operator | $\sigma^2_L$ | 0.14 | 0.14 | 0.15 | 0.00 |
| Segment | $\sigma^2_M$ | 0.81 | 1.13 | 0.16 | 0.45** |
| Patch type | $\sigma^2_N$ | 24.09*** | 23.35*** | 25.31*** | 0.11 |
| Position | $\sigma^2_O$ | 0.4 | 0.37 | 0.29 | 0.02 |
| Depth | $\sigma^2_P$ | 37.88*** | 41.43*** | 18.73*** | 2.73*** |
| Water sample | $\sigma^2_Q$ | 45.53 | 48.77 | 32.28 | 7.67 |
| Total | $\sigma^2_T$ | 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

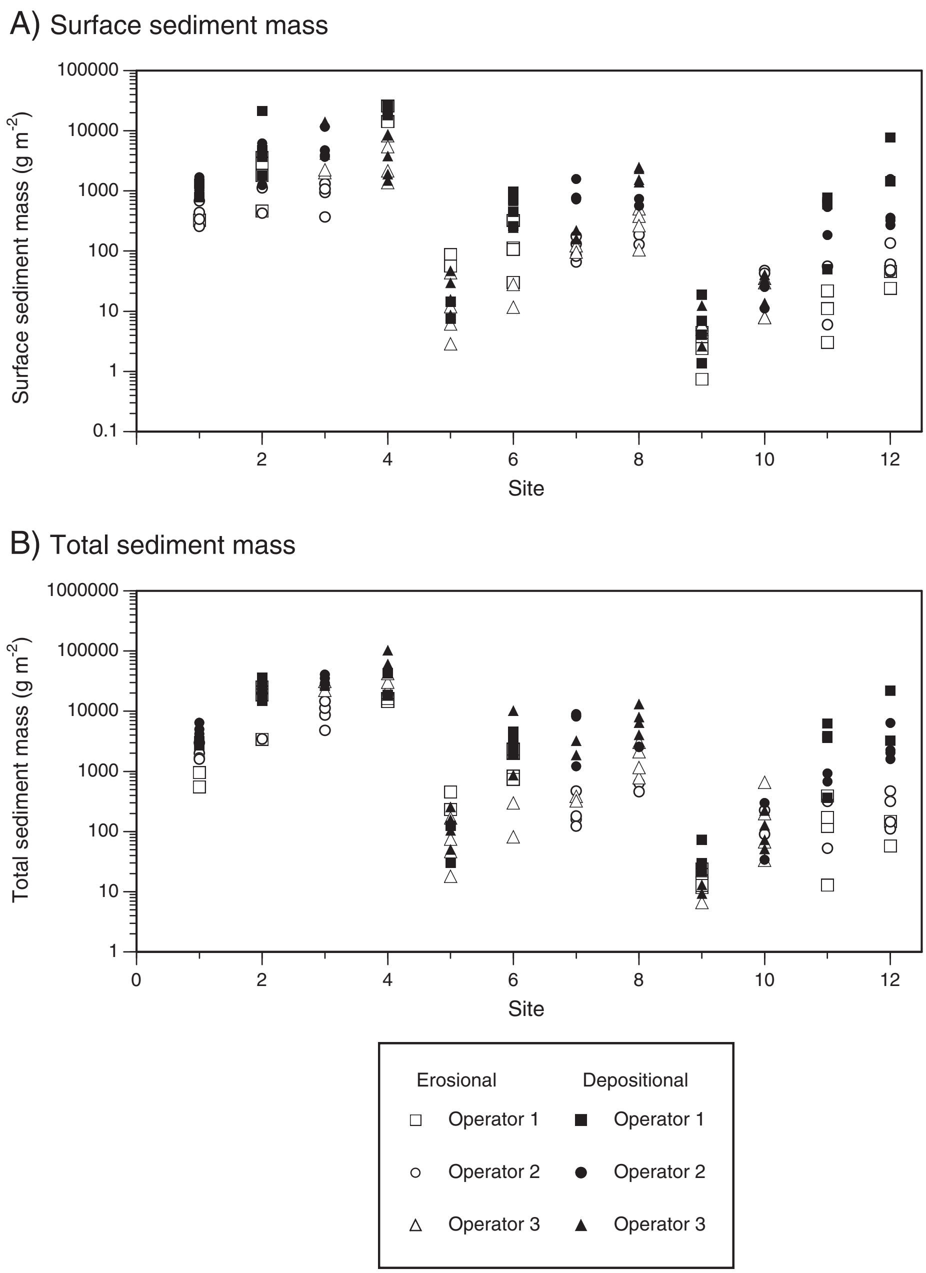



**Fig. 2.** Sampling variation in mass of A) surface- and B) total-deposited fine sediment collected from each constituent stilling well sample from the three segments within each site. The influence of different operators and different patch types (erosional or depositional) is indicated. Sites ranked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

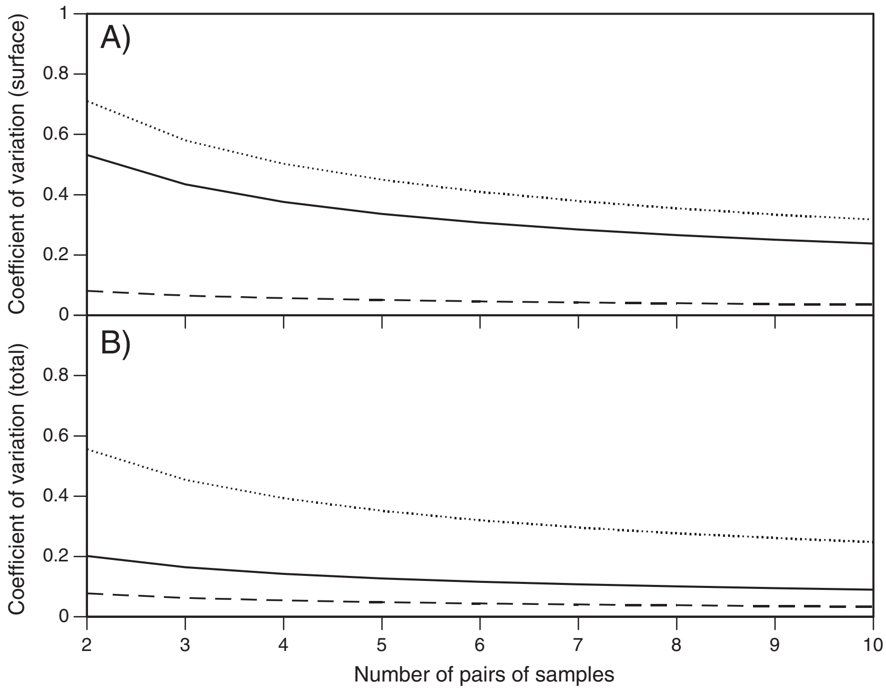



**Fig. 3.** Relationship between the number of sample pairs (one from an erosional and one from a depositional patch) and the coefficient of variation in A) surface-deposited fine sediment mass and B) total-deposited fine sediment mass for the most variable (short dash), least variable (long dash), and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

$\mu$ overall mean value of $Y$;
$a_k$ deviation of mean value for site $k$ from the overall mean value $\mu$;
$b_{kl}$ 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 | $\sigma_K^2$ | 29.52*** | 33.63*** | 31.30*** | 32.41*** | 31.3*** | 32.41*** | 19.42*** | 1.91*** |
| Operator | $\sigma_L^2$ | 0.04 | 0.05 | 0.07 | 0.07 | 0.07 | 0.07 | 0.01 | 0.01 |
| Replicate reach | $\sigma_M^2$ | 1.95 | 2.20 | 1.28 | 1.37 | 1.28 | 1.37 | 1.29 | 2.10 |
| Total | $\sigma_T^2$ | 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 |

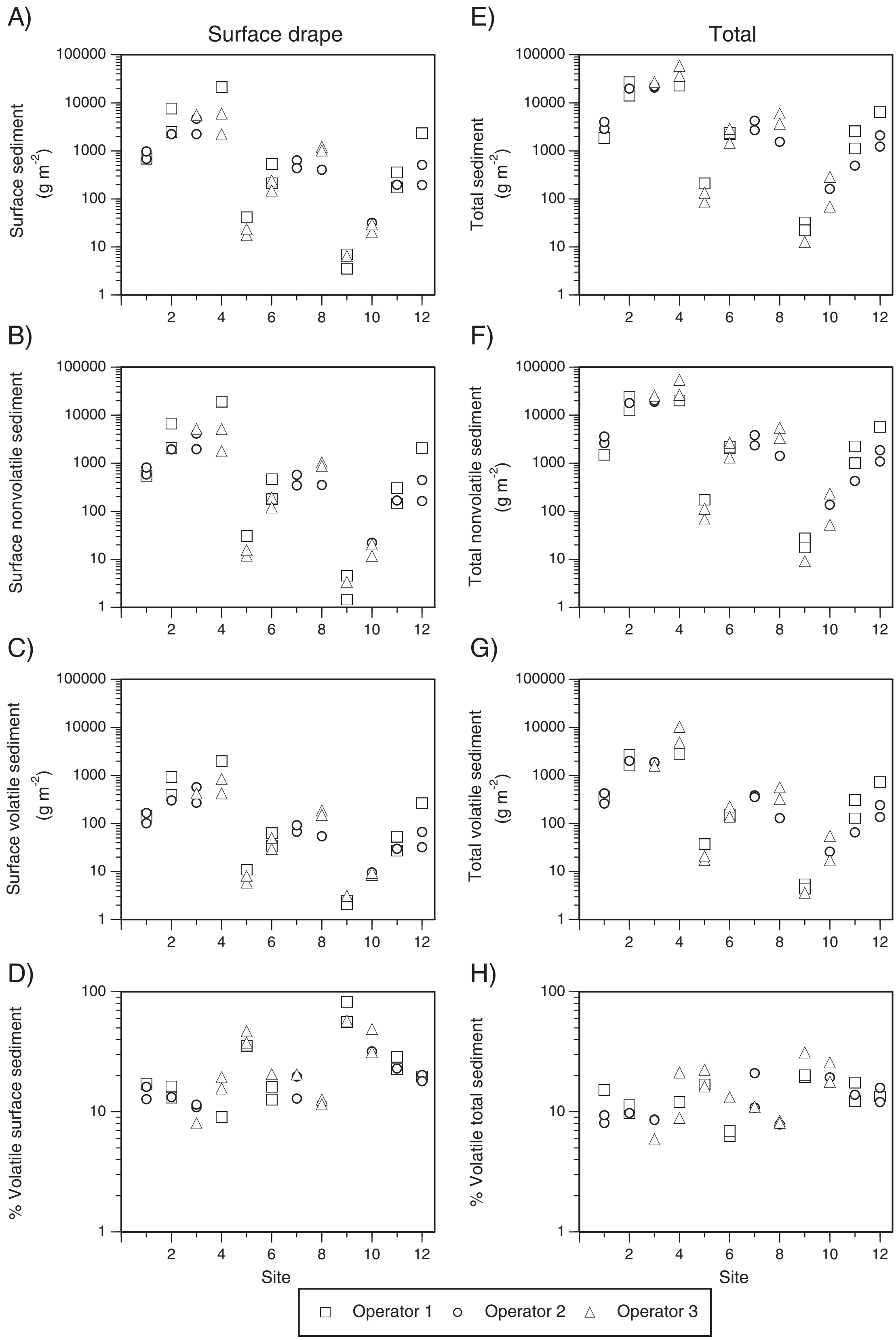



**Fig. 4.** Sampling variation in surface- (A, B, C, D) and total- (E, F, G, H) deposited fine sediment estimated by a composite sample of four stilling well samples (two from erosional and two from depositional patches): A & E) mass of deposited fine sediment, B & F) mass of deposited nonvolatile fine 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 | $\text{Log}_{10}$ sediment mass (g $\text{m}^{-2}$) | 0.549 | 0.754 |
| | $\text{Log}_{10}$ nonvolatile sediment mass (g $\text{m}^{-2}$) | 0.588 | 0.816 |
| | $\text{Log}_{10}$ volatile sediment mass (g $\text{m}^{-2}$) | 0.336 | 0.721 |
| | $\text{Log}_{10}$ percentage volatile matter | 0.113 | 0.939 |
| Total | $\text{Log}_{10}$ sediment mass (g $\text{m}^{-2}$) | 0.478 | 0.760 |
| | $\text{Log}_{10}$ nonvolatile sediment mass (g $\text{m}^{-2}$) | 0.638 | 0.826 |
| | $\text{Log}_{10}$ volatile sediment mass (g $\text{m}^{-2}$) | 0.210 | 0.675 |
| | $\text{Log}_{10}$ 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

$\sigma_K^2$ variance of $a_k$, i.e., variance caused by differences in mean value between sites;
$\sigma_L^2$ variance of $b_{kl}$, i.e., variance caused by differences between operators within a site;
$\sigma_R^2$ variance of $h_{klr}$, i.e., variance caused by differences between estimates made by the same operator at the same site; and
$\sigma_S^2$ 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 $\sigma_L^2$). 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 ($\sigma_T^2$) in percentage cover of deposited fine sediment across all rivers is estimated by

$$\sigma_T^2 = \sigma_K^2 + \sigma_L^2 + \sigma_R^2 + \sigma_S^2. \quad (9)$$

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

$$\sigma_W^2 = \sigma_L^2 + \sigma_R^2 + \sigma_S^2. \quad (10)$$

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.

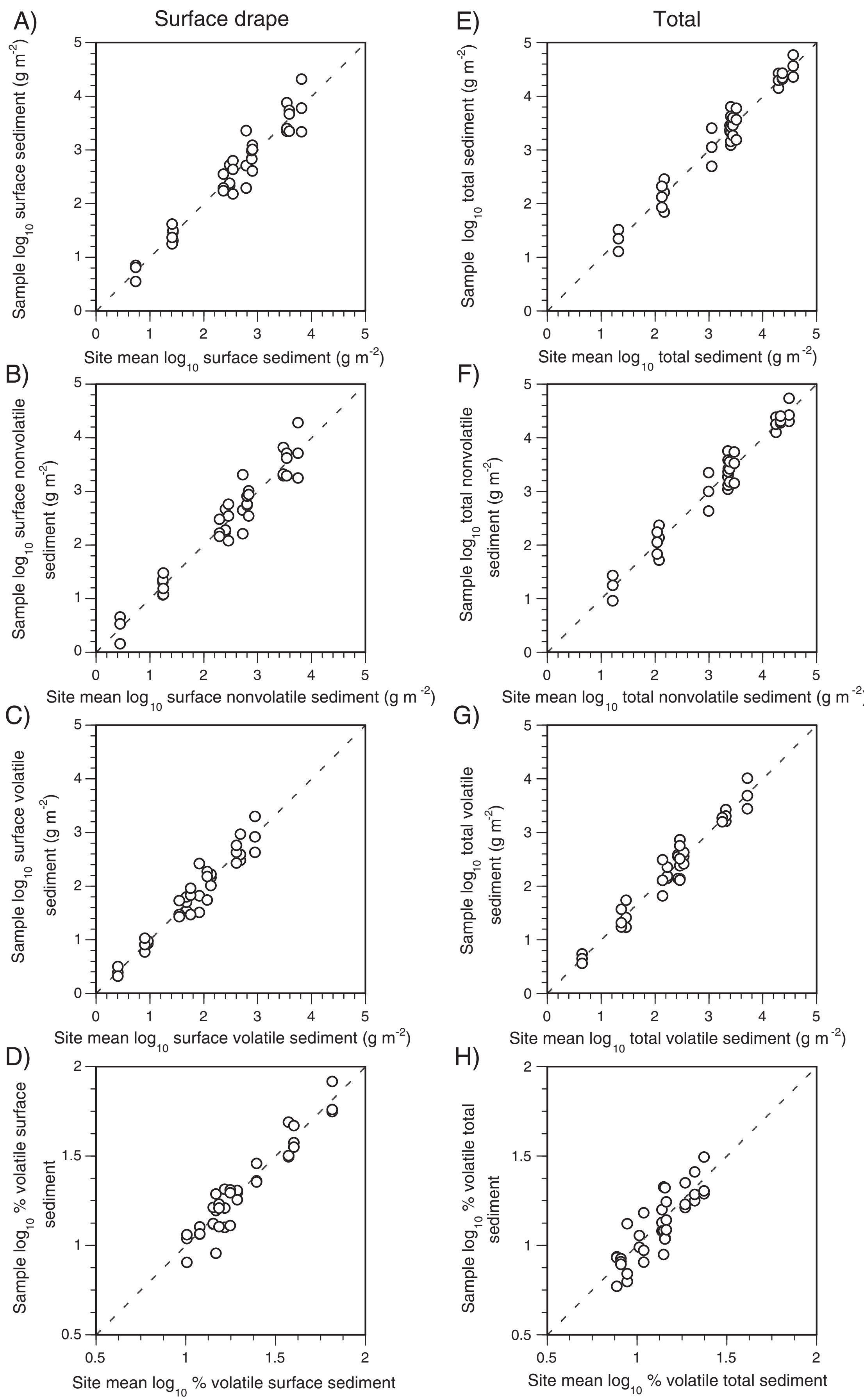
In this analysis the pertinent source of variance for comparison with the resuspension approach is that of the operator. In order for the resuspension approach to be worthy of uptake, it would need to perform at least as well as the next best single visit estimation technique available. When the components 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 log10 surface sediment (g m-2)
Site mean log10 surface sediment (g m-2)
B)
Sample log10 surface nonvolatile sediment (g m-2)
Site mean log10 surface nonvolatile sediment (g m-2)
C)
Sample log10 surface volatile sediment (g m-2)
Site mean log10 surface volatile sediment (g m-2)
D)
Sample log10 % volatile surface sediment
Site mean log10 % volatile surface sediment
E)
Total
Sample log10 total sediment (g m-2)
Site mean log10 total sediment (g m-2)
F)
Sample log10 total nonvolatile sediment (g m-2)
Site mean log10 total nonvolatile sediment (g m-2)
G)
Sample log10 total volatile sediment (g m-2)
Site mean log10 total volatile sediment (g m-2)
H)
Sample log10 % volatile total sediment
Site mean log10 % volatile total sediment

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 | $\sigma^2_K$ | 253,090*** |
| Operator | $\sigma^2_L$ | 6229*** |
| Replicate sample | $\sigma^2_R$ | 9588 |
| Season | $\sigma^2_S$ | 272 |
| Total | $\sigma^2_T$ | 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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