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Abiotic predictors of fine sediment accumulation in lowland rivers

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Abstract

The delivery of excessive fine sediment (particles <2 mm in diameter) to rivers can cause serious deleterious effects to aquatic ecosystems and is widely acknowledged to be one of the leading contributors to the degradation of rivers globally. Despite advances in using biological methods as a proxy, physical measures remain an important method through which fine sediment can be quantified. The aim of this study was to provide further insights into the environmental variables controlling sediment accumulation in lowland gravel bed rivers. We sampled 21 sites, during spring and autumn, selected to cover a gradient of excess fine sediment. Fine sediment was sampled using a range of methods including visual assessments, the disturbance method and suspended sediment concentrations. A range of abiotic predictors were measured during sampling, and hydrological and antecedent flow indices were derived from local flow gauging station data. The results show reach scale visual estimates of fine sediment to be significantly and highly correlated with fully quantitative estimates of total surface sediment. Multivariate regression analysis showed that flow variables (regime, antecedent and local flow characteristics) were strong predictors of deposited sediment metrics but poor predictors of suspended sediment. Organic content was shown to be relatively independent of total sediment quantity and is likely driven by other factors which influence the supply and breakdown of organic matter.

1. Introduction

Erosion, transport and deposition of fine sediment (defined as organic and inorganic particles <2 mm in diameter) are fundamental processes in the hydrogeomorphic cycle and river systems require a constant supply in order to function (Jones et al., 2012b). Diverse aquatic communities rely on the supply of fine sediment to provide suitable heterogeneous habitats and for delivery of particulate and dissolved organic matter (Collins et al., 2011). Increasingly intensive agricultural land management, construction, mining, deforestation, and in-channel modifications leading to bank erosion and channel incision, are some of the main sources leading to increased sediment loads in rivers (Collins et al., 2009; Owens et al., 2005; Yule et al., 2010). Excessive fine sediment delivery, when coupled with relatively low transport capacity of lowland rivers (Naden et al., 2016), results in channels choked with fine sediment causing significant impacts on aquatic communities. As a result of this, fine sediment is considered to be a significant pollutant to aquatic systems globally (Owens et al., 2005).

Fine sediment in river systems is generally classified in two main fractions: suspended or deposited. The suspended fraction is the quantity of sediment that is held within the water column. The quantity of suspended sediment is intrinsically linked to the prevailing hydraulic conditions, catchment geology and geomorphological processes acting within a river system (Walling, 2005). The deposited fraction is the quantity of sediment that settles on the river bed and can infiltrate into the substrate, a process known as colmation (Descloux et al., 2014; Wharton et al., 2017). Depending on hydraulic conditions, sediment can transfer into the stream bed either vertically via the settling or turbulent diffusion of fine sediments from the water column, or horizontally through intragravel transport (Harper et al., 2017).

Ecological effects of fine sediment are well studied across a range of trophic levels, including fish (Kemp et al., 2011), macroinvertebrates (Jones et al., 2012b; Wood & Armitage, 1997), macrophytes (Jones et al., 2012a), and diatoms (Jones et al., 2014). An increase in suspended sediment in the water column can have impacts on primary production (Klco, 2008; Nieuwenhuyse & LaPerriere, 1986), affect behaviour and activity of organisms that use visual searching cues (Breitburg, 1988; Shoup & Wahl, 2009), cause clogging effects to exposed structures such as gills and feeding apparatus

(McKenzie et al., 2020), and increase drifting behaviours of macroinvertebrates (Culp et al., 1986; Larsen & Ormerod, 2010; Magbanua et al., 2016; Suren & Jowett, 2001). Sediment deposition can affect fish directly by reducing spawning habitat, smothering eggs, and blocking fry emergence (Kemp et al., 2011; Relyea et al., 2012; Sear, 1993). Maintaining flow in aquatic environments is essential for supplying fresh nutrients, replenishing gases, and removing waste. The settling and infiltration of fine sediment by colmation clogs the spaces between gravels reducing interstitial water flow critical for the exchange of gas in these pore spaces, thereby restricting the supply of oxygen to benthic organisms and the removal of excreta (Owens et al., 2005; Wharton et al., 2017).

The impacts of soil erosion from land sources extend beyond ecological impacts on aquatic communities. Soil degradation in England and Wales has a total economic cost of an estimated £1.2 billion per year (Graves et al., 2015). ‘On-site’ costs to farmers and landowners include yield losses or costs incurred through mitigating soil erosion. Costs incurred by wider society are those which occur ‘off-site’ such as flooding of properties as a result of rapid run-off from cultivated hill-slopes or effects on drinking water quality. Increased sediment delivery to river systems can cause significant implications for river regulation. The results are serious: flooding, navigation blockages, and large build ups at weirs and dams leaving channels requiring regular maintenance, such as dredging or dam flushing which can deliver large slugs of sediment downstream (Owens et al., 2005). Effective monitoring practices can more efficiently identify areas affected by fine sediment before it becomes a significant problem. This in turn can help river regulators advise land managers to implement measures to reduce excess sediment input to rivers, thereby benefitting both river environments and sustainable land management.

A multitude of physical methods have been employed to quantify suspended or deposited fine sediment in rivers. These methods span a large gradient of cost, time, effort, and complexity. Furthermore, different techniques will measure slightly different components of fine sediment (e.g. deposition rate, organic content, turbidity, etc.) which makes comparisons between methods challenging. Suspended sediment is typically measured as a concentration per volume of water (suspended sediment concentration, SSC, e.g. mg l^{-1}). A known volume of water is sampled from a river, filtered, dried and the contents weighed to approximate the SSC (Gray et al., 2000). The light scattering properties of water measured using turbidity (in nephelometric turbidity units, NTU), is often used as a surrogate for SSC (i.e. the higher the turbidity value, the higher the SSC). However, these require site-specific calibrations as readings can be skewed by scattering of other particles including algae, plankton, organic matter, microbes, air bubbles and other fine insoluble particles and flocculated particles (Lawler et al., 2006; Rymszewicz et al., 2017).

Deposited sediment is normally measured as a volume or mass of sediment per unit area (or per unit volume for infiltration) and, depending on the method used, can be quantified over a unit of time (i.e. deposition rate). Measuring both surface and infiltrated sediment instantaneously can be done via the disturbance method. The disturbance method, also called the resuspension method, was first described by Lambert and Walling (1988) and later developed by Collins and Walling (2007a, 2007b) then Duerdoth et al. (2015). In recent assessments, this method showed low variance associated with operator or other within-site differences resulting in a precise representation of reach scale fine sediment (Conroy et al., 2016; Duerdoth et al., 2015). An alternative rapid assessment of fine sediment can be done through visual assessments. Visual estimates are an instantaneous semi-quantitative assessment method. However, this method has been found to have high inter-user variability (Murphy et al., 2015) and can be highly influenced by depth, light penetration and turbidity. Additionally, the visual estimation method only assesses the surface drape of fine sediment which may be unrelated to the ingress of fines (Murphy et al. 2015). Nonetheless, this is an assumption that has not been tested. Potential weaknesses in methodology could lead to bias in the measurement of total fine sediment at each site. In turn, this could result in poor associations between fine sediment and ecological responses potentially effecting environmental management decisions.

Given the widespread impacts of fine sediment, measuring, and monitoring its presence is required to evaluate the implementation of land management interventions and improve aquatic health. Flow is intrinsically linked with fine sediment dynamics in rivers. In the UK, most lowland rivers are transport-limited in relation to fine sediment (Naden et al. 2016). Relatively stable seasonal flow regimes and groundwater abstraction reducing river discharges, coupled with an increase in arable farming in lowland areas, results in lowland gravel rivers being most at risk of fine sediment accumulation (Collins et al., 2005). For this reason, lowland rivers in England were selected as the focus for this study. Our objectives were to: (1) compare and assess methods for quantifying suspended and deposited fine sediment in lowland gravel bed rivers and (2) determine which abiotic variables (environmental variables and antecedent flow conditions at a range of temporal scales prior to field sampling) are controlling fine sediment and how this varies between the different methods of assessment. This was achieved through a multi-site two-season field sampling regime. The results of this study will build on recent work comparing fine sediment measurements (Conroy et al., 2016; Duerdoth et al., 2015; Glendell et al., 2014; Hubler et al., 2016; Zweig & Rabeni, 2001) and extend these comparisons by understanding the abiotic variables that act as controls on fine sediment in rivers.

2. Materials and methods

2.1. Site selection

Site selection was carried out through a filtering process from existing Environment Agency (EA) monitoring locations in England, United Kingdom. All sites surveyed were classified as lowland rivers within the River Invertebrate Prediction and Classification System (RIVPACS) (Wright et al., 1998). RIVPACS uses TWINSPAN (Two Way INdicator SPecies ANalysis) to classify rivers into one of 43 end groups by their biological, physical, and chemical characterisation. The resulting output provides a broad classification of river typology through which rivers in England can be grouped. Sites pertaining to end groups 31-43 all comprise lowland characteristics. The list of national sites were screened using EA water chemistry monitoring data (Lathouri & Klaar, 2021). Sites which were failing physico-chemistry status for dissolved oxygen (DO) and ammonia for one or more seasons were removed from the data set to mitigate for any confounding effects unrelated to fine sediment. Anthropogenic physical changes to a river will inevitably affect the balance of erosion, transport, and deposition of fine sediment. Sites with any capital works (structural changes to the channel such as bank reinforcements or re-grading) or re-sectioning were therefore removed from the sites list. This is based on previous work by Dunbar et al. (2010) that showed these variables as important drivers of habitat quality based on their interaction with flow. Each site was mapped to ensure proximity (within 2 km) to an active flow gauging station. In total, 21 sites were sampled once accessibility was taken into consideration (i.e. public land or where landowner permission could be obtained) (Table A.1). The final list of sites showed a multi-region distribution throughout lowland England, with a range of RIVPACS end groups represented (Fig. 1a). In order to ensure that these sites covered a range of fine sediment conditions they were checked using the Agricultural Sediment Risk (ASR) index from Naura et al. (2016). Agriculture is the main source of fine sediment inputs to river systems, and the ASR combines sediment inputs from land-based models and predictions of fine sediment accumulation using RHS data. The ASR gives a risk category of 1-5 (very low to very high). The ASR scores were retrieved for each site which showed that the selected sites covered the whole range of risk categories (Fig. 1b).

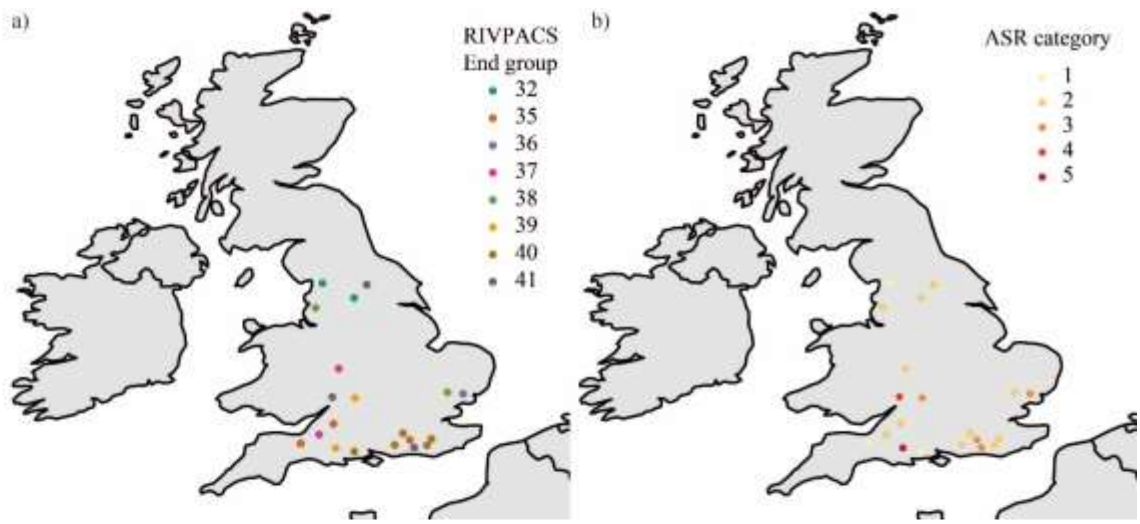

Fig. 1. Sites sampled colour coded by (a) RIVPACS end group classification and (b) Agricultural Sediment Risk Rating ranging from 1 (low risk) to 5 (high risk).

2.2. Field data collection

In order to take account of natural seasonal variation in environmental conditions, each site was sampled in spring (March – May) and autumn (September – November). This is consistent with EA methodology for seasonal ecological assessment. The sampling area was accessed from the downstream end where possible so as not to disturb the riverbed (Fig. A.1).

A 50 ml water sample was collected at each site in order to quantify the SSC at the time of sampling. Two principal methods of measuring deposited fine sediment were carried out at each site: the disturbance method and visual estimates. The disturbance method was carried out within the reach four times; twice in erosional areas (e.g. riffles, runs) and twice in depositional areas (e.g. pools, glides). The sampling reach was roughly defined as seven times the channel width up to a maximum of 50 m (Environment Agency, 2014). The method outlined in Duerdoth et al. (2015) was followed: an open-ended hollow cylinder of 0.56 m diameter was pushed into the gravel bed to achieve an adequate seal from the surrounding flow. Once a seal was achieved, water depth at three random locations within the cylinder were taken using a metre rule and the average depth of water recorded. The water within the cylinder was then vigorously agitated for 60 seconds without touching the riverbed in order to bring loose overlying sediment into suspension and the overlaying water was sampled. Immediately following the 60 second agitation, a water sample was taken by pushing an inverted 50 ml measuring cylinder into the middle of the water column within the cylinder and turned upright so it filled as it was drawn to the surface in order to collect a well-mixed sample (Fig. A.2). There is an assumption that the overlying water has a uniform concentration and thus the water sample is representative of the concentration within the cylinder (Conroy et al., 2016). An electric drill with plaster mixing attachment was used for the agitation in order to standardise the mixing and reduce the formation of a vertical gradient of sediment concentration within the cylinder (Collins et al., 2013b). The process was then repeated with 30 seconds of subsurface agitation using a metal auger to raise subsurface fine sediment into suspension, then 30 seconds of overlying water agitation using the electric drill with mixing attachment. The subsurface agitation aims to disturb the top 100 mm of the gravel bed. A further water sample was then taken to characterise the total fine sediment (from the subsurface agitation which ultimately includes both surface and subsurface fine sediment). All water samples were kept in a cool box with ice during field work and then transferred to a fridge (stored at 5°C) in the laboratory on return.

Visual estimates of fine sediment were taken at the sampling reach scale (Fig. A.1). As described in the River Habitat Field Survey Guidance Manual (Environment Agency, 2003) and the Environment Agency Operation Instruction for Freshwater Macro-invertebrate Sampling in Rivers (Environment Agency, 2014) , visual estimates involve the operator estimating the percentage substratum composition over a given reach. When taking visual estimates, the observations should represent a bird's eye view of the sampling reach and include only the particles on the surface of the stream bed. Substrate categories comprised; bedrock, boulders (>256 mm), cobbles (64 – 256 mm), pebbles (4 – 64 mm), gravel (2 – 4 mm), sand (0.0625 – 2 mm), silt (<0.0625 mm) and clay (cohesive material). The reach scale visual estimates were made by walking up the length of the reach on the riverbank observing the full width, and also by entering the reach to confirm substrate type, and recorded. Visual estimates were also taken at the patch scale within the disturbance cylinder before any agitation had occurred to allow comparisons between the quantitative and semi-quantitative methods at the patch scale. To minimise sampling error, the same operator was used for all sample collection, i.e. surface and subsurface agitation, disturbance sample collection, background sample collection, visual estimates of fine sediment.

At each site, additional abiotic variables were measured including: wetted channel width (m), channel depth (m), shading (%), in-channel macrophytes (%), filamentous algae (%), local flow types within the reach (erosional i.e. run or riffle; and depositional flow i.e. glide or pool). Additional abiotic variables were retrieved from baseline data (provided by the Environment Agency). These included altitude (m), distance from source (km), slope (m km^{-1}), discharge category (m^3 s^{-1}).

2.3. Laboratory methods

The refrigerated water samples collected from the disturbance method were processed within four days of collection. The processing method used followed that of Duerdoth et al. (2015). The samples were poured through a 2 mm sieve onto a 90 mm GF/C Whatman glass microfibre filter paper. Filter papers were pre-ashed (at 500 °C for 2 hours) and washed in deionised water prior to use in order to remove any contaminants left on the filter papers during the manufacturing process. The filter papers were weighed on a micro-balance to 0.00001 g. A wash bottle filled with deionised water was used to rinse the collection bottle into the filter paper to collect any residue. The filter papers were dried overnight in an oven at 105 °C and cooled in a desiccator for 30 minutes before weighing to determine total mass of sediment retained. The filter papers were ignited in a furnace at 500 °C for 30 minutes and again cooled in a desiccator before weighing to determine the mass of organic matter lost through ignition (loss on ignition, LOI).

2.4. Data analysis

2.4.1. Calculating sediment metrics

The SSC for each site was calculated from the background sediment samples (mg l^{-1}). Processing the surface agitation disturbance samples yielded the following metrics: total surface sediment (g m^{-2}), organic surface sediment (g m^{-2}), inorganic surface sediment (g m^{-2}). Processing the subsurface agitation samples yielded the following metrics: total sediment (g m^{-2}), total organic sediment (g m^{-2}), and total inorganic sediment (g m^{-2}). As the subsurface agitation incorporates both the surface sediment and the sediment from the top 100 mm of gravel, these metrics are described as the 'total' sediment. Following the methods as set out in Duerdoth et al. (2015), the geometric mean of the data for each of the four samples at each site (two erosional and two depositional) was calculated providing a single figure for each of the measures for each site. Disturbance samples were corrected for background SSC.

To calculate the percentage of reach scale visual fines for each site, the sum of the estimated clay, silt and sand fraction were combined. Patch scale estimates were calculated using the same aggregation of substrates using the visual estimates from within the disturbance cylinder before agitation. Patch scale estimates are specified where included in the data analysis.

2.4.2. Hydrological metrics

Mean daily flow (discharge m^3 s^{-1}) was obtained for each site for the period 01/01/2000 – 31/05/2017. Missing data were imputed using the *missForest* package (Stekhoven & Buhlmann, 2012). The *missForest* function uses a random forests regression model trained on the observed values to predict the missing values. The 'out of bag' errors (a measure of cross-validation), presented as the normalized root mean square error

(NRMSE) for continuous variables, compares the observed data with the imputed (full) data matrix. The NRMSE for the whole imputation was 0.06 (i.e. the variables are imputed with 6% error). There is no pre-determined acceptable value for NRMSE, however lower values (closer to zero) represent more robust imputations. The NRMSE for this imputation was deemed acceptable.

Two sets of hydrological metrics were calculated from the data to describe (a) the flow regime and (b) the antecedent flow. Flow data were standardized prior to analysis (using the *scale* function in R). Following standard practice (e.g. Mathers 2017), standardization was carried out by first centering by the mean and then dividing by the standard deviation to convert the data to Z-scores. This enables comparison between sites as flow will inherently vary as a function of site. The flow regime metrics were based around the five critical components of the natural flow regime as outlined by Poff et al. (1997): magnitude, frequency, duration, timing and rate of change. In total, 22 flow regime metrics (Table 1) were calculated based around these five facets and identified from previous studies reporting that these metrics are closely related to ecological structure and function (Monk et al., 2007; Olden & Poff, 2003). Ninety-six metrics were adopted to describe the antecedent flow conditions (Table 2). Lastly, stream power was calculated using the formula $\Omega = \rho g Q S$, where ρ is the density of water (1000 kg m^3), g is acceleration due to gravity (9.8 m s^2), Q is the mean daily discharge calculated from the average mean daily discharge for the entire data period for each site (m^3 s^{-1}), and S is the channel slope at each site.

Table 1. Hydrological regime metrics calculated from daily discharge data for all sites.

Flow regime metrics	Description
TOTALVOL	Total discharge for year to date
MDF	Mean daily discharge (for entire time series)
MADQ	Mean annual discharge
DAY90MAX	Average annual maximum 90-day discharge
DAY30MAX	Average annual maximum 30-day discharge
DAY7MAX	Average annual maximum 7-day discharge
MMAD	Maximum annual monthly discharge

DFMEDMAX	Median of the maximum annual monthly discharge/median annual daily discharge
STDEVDF	Standard deviation of the daily discharge
DFQ95MEAN	Q95/MDF
BASEFLOW	7-day annual minimum discharge/MADQ
DFBFI	Mean of lowest annual daily Q/mean of lowest annual daily Q
Q1090DF	Q10/Q90
CVANNQ	Covariance of MADQ
FRE1YR	Mean number of events per year over Q50
SK2	(MADQ – median annual Q)/median annual Q
Q550DF	Q5/Q50
Q10DF, Q25DF, Q20DF, Q5DF, Q1DF	The flow that is exceeded for a given percentile of time
StreamPower	Calculated as $\Omega = \rho g Q S$ for the entire data period for each site

Table 2. Antecedent flow metrics. Each metric (left) was calculated for each of the time frames (right) prior to each sampling date e.g. MDFPre7d.

Antecedent flow metrics	Description		Time frames	Description (all relative to sampling date)
MDF	Mean daily discharge		Pre7d	Previous 7 days
MAX	Maxima		Pre30d	Previous 30 days
MIN	Minima		Pre6m	Previous 6 months
SD	Standard deviation	+	Pre12m	Previous 12 months
Q1 Q5 Q10 Q20 Q25 Q50	The flow that is exceeded for a given percentile of time		PreSum	Previous summer (June, July & August)
			PreSpr	Previous spring (March, April & May)
			PreAut	Previous autumn (September, October & November)

Q90 Q95			PreWin	Previous winter (December, January & February)

When calculating a large number of hydrological metrics for both flow regime and antecedent flow, there is a high degree of redundancy. In order to reduce redundancy, existing methods developed in ecohydrology were applied (e.g. Olden and Poff 2003; Monk et al. 2007; White et al. 2017). Principal Component Analysis (PCA) (using the function *prcomp* in R) was calculated on each of the sets of indices individually. All statistical analysis was carried out using R version 4.0.2 (R Development Core Team, 2019). The purpose of PCA is to reduce dimensionality whilst still preserving variance (Jollife & Cadima, 2016) and is therefore a common method in dimensionality reduction. Unlike linear regression, PCA models are not destabilised by collinearity between variables. However, like linear models, PCA assumes a normal distribution of the data. The first two principal components (PC) contributed 92.08 % to the total variance for the flow regime indices and 82.47 % for the antecedent flow indices. Since there was a high amount of collinearity for both sets (Fig. A.3 and A.4) the 'broken stick' method was used to select non-collinear variables (Olden & Poff, 2003) which is described as follows. The contribution of each of the variables to dimensions 1 and 2 (in descending order) were calculated. The correlation coefficients of the indices were calculated using Pearson's product moment correlation (*cor* function in R). Forward selection was carried out so that the metric contributing most to the first two PCs was retained if the Pearson's correlation coefficient (*r*) between any pair of variables was higher than 0.95 (the value at which the relationship is deemed to be perfectly collinear; White et al. 2017).

2.4.3. Methods of measuring fine sediment

Early data visualisation of the variation in environmental variables between sites was carried out using PCA (using the *prcomp* function in R). Spearman's rank correlation was used to compare the different metrics of fine sediment (using *cor* function) as the data were not-normally distributed (confirmed by *shapiro.test* function with p values

<0.05). A model selection process using both linear modelling (*lm* in R) and mixed effects modelling (*lmer* in R; fitted using maximum likelihood estimation) was used to determine whether season had a significant effect on the relationship between the semi-quantitative estimates of fine sediment (derived from visual estimates) and the fully quantitative total surface sediment and total sediment (derived from the disturbance sampling). The response variables were log(x+1) transformed to reduce skewness (observed from histograms). The optimal models were determined as the most parsimonious model with the lowest Akaike's Information Criterion (AIC) value, or the next lowest if the difference was <2 AIC points (Burnham & Anderson, 2004).

Linear modelling was also used to determine which environmental variables affect each metric of fine sediment. The retained hydrological metrics after the variable reduction procedure were combined with environmental data collected during each site visit and the additional variables obtained from the RIVPACS database to derive a full list of predictors. Categorical variables from the field sheet were converted to numerical values for analysis.

Because of the high number of predictors, and the risk of overfitting in the modelling process, the variance inflation factor (VIF; using *corvif* function in R) was used to reduce the number of predictors based on their collinearity. Forward stepwise selection was carried out, the predictor with the highest VIF removed and the function run again. The recommendation given by Zuur et al. (2009) is to remove variables until all VIF values are below 3 or 5. The higher value of 5 was chosen here due to the risk of excluding ecologically relevant variables with the more stringent threshold. A full list of the original predictors and the refined list after the VIF analysis was carried out can be found in Table A.3.

The fine sediment metrics were again transformed (log or log(x+1)) prior to modelling to reduce skewness. Model selection was carried out to determine whether season should be included as a fixed effect, random effect or both (Table A.4). As before, the optimal models were determined as the most parsimonious model with the lowest Akaike's Information Criterion (AIC) value, or the next lowest if the difference was <2 AIC points (Burnham & Anderson, 2004). Stepwise selection was used to reduce the optimal models for each metric (using the *StepAIC* function in R, direction = 'both').

Earlier analyses showed a relatively strong fit among the deposited metrics of fine sediment. As the aim of this specific analysis was to determine which environmental variables affect each metric of fine sediment, the deposited metrics were not included as predictors for these sets of models. Suspended sediment appears independent of deposited sediment and therefore background SSC was offered as a predictor for each deposited sediment model.

3. Results

3.1. Data summary

The first two PCs contributed 49.2% of the total explained variance. Spring and autumn site data were well integrated and did not form distinct groups in the ordination plot (Fig. 2). The top variables contributing most to the primary PC were mostly sediment metrics whereas other physical habitat parameters contributed most to PC2. This confirms that the sampling regime captured a habitat gradient dominated by fine sediment conditions.

3.2. Comparing methods of measuring fine sediment

There was a strong correlation between reach scale visual estimates of fine sediment and total surface sediment ($\rho = 0.82$, $p < 0.001$). The relationship was stronger at the patch scale ($\rho = 0.90$, $p < 0.001$) (Fig. 3). Visual fines also correlated well with total sediment ($\rho = 0.73$, $p < 0.001$) which includes the surface and subsurface agitation. Visual fines, at both the reach and patch scales, correlated less well with organic metrics (organic surface $\rho = 0.53$, $p = 0.029$, total organic $\rho = 0.62$, $p < 0.001$) than inorganic metrics (inorganic surface $\rho = 0.82$, $p < 0.001$, total inorganics $\rho = 0.73$, $p < 0.001$). There were strong and significant correlations between most of the metrics derived from the disturbance method with the exception of organic surface sediment, which was weaker, albeit still significant. Notably, the correlation between organic surface sediment and total surface sediment was weaker ($\rho = 0.65$, $p < 0.001$) compared to the almost perfect correlation of total surface sediment with inorganic surface sediment ($\rho = 0.99$, $p < 0.001$). SSC levels were not significantly correlated with any deposited metrics.

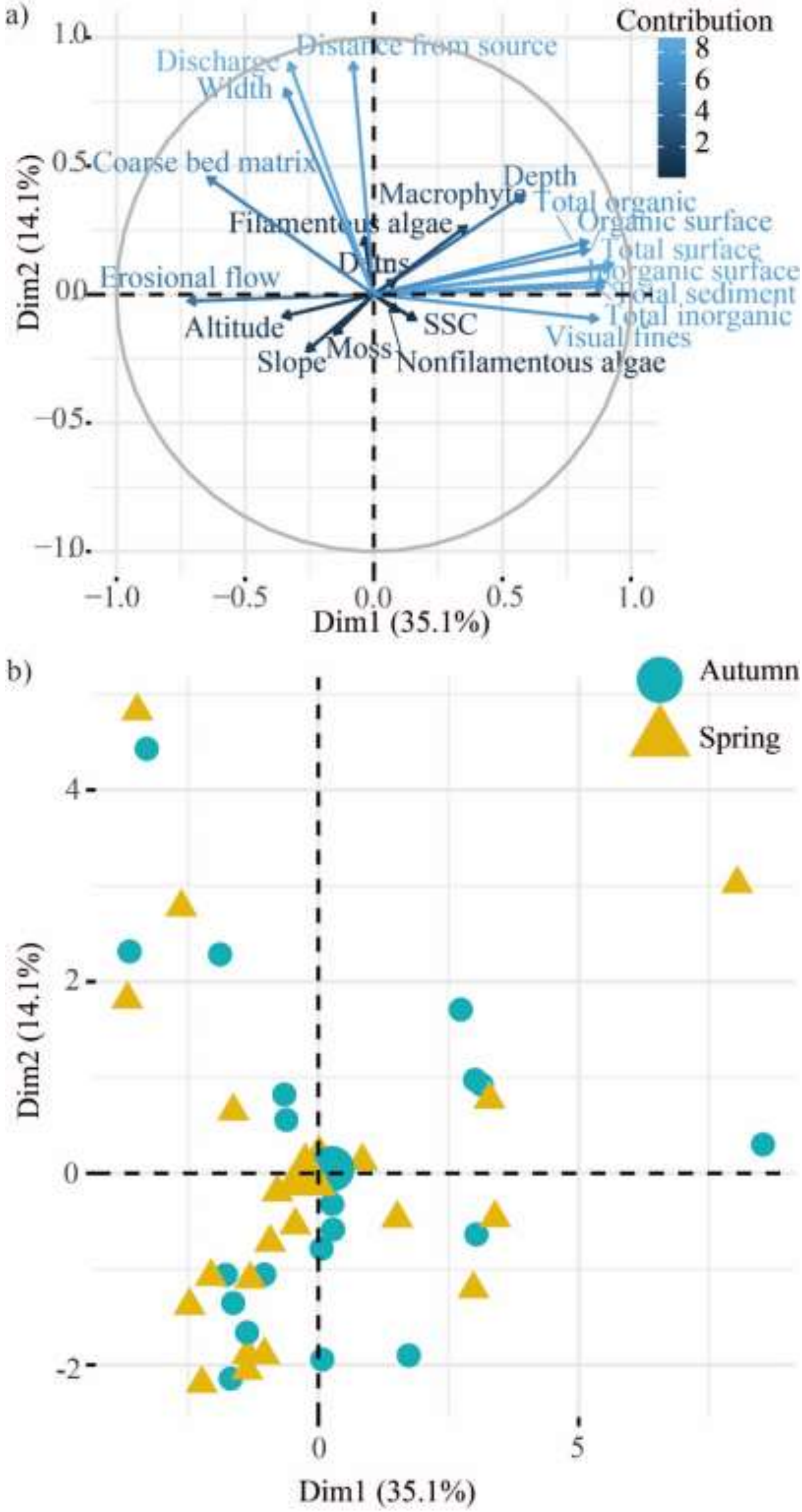

Fig. 2. Principal Component Analysis of the environmental data, plots showing as a variable contribution plot (a) and individual sites labelled by seasons (b).

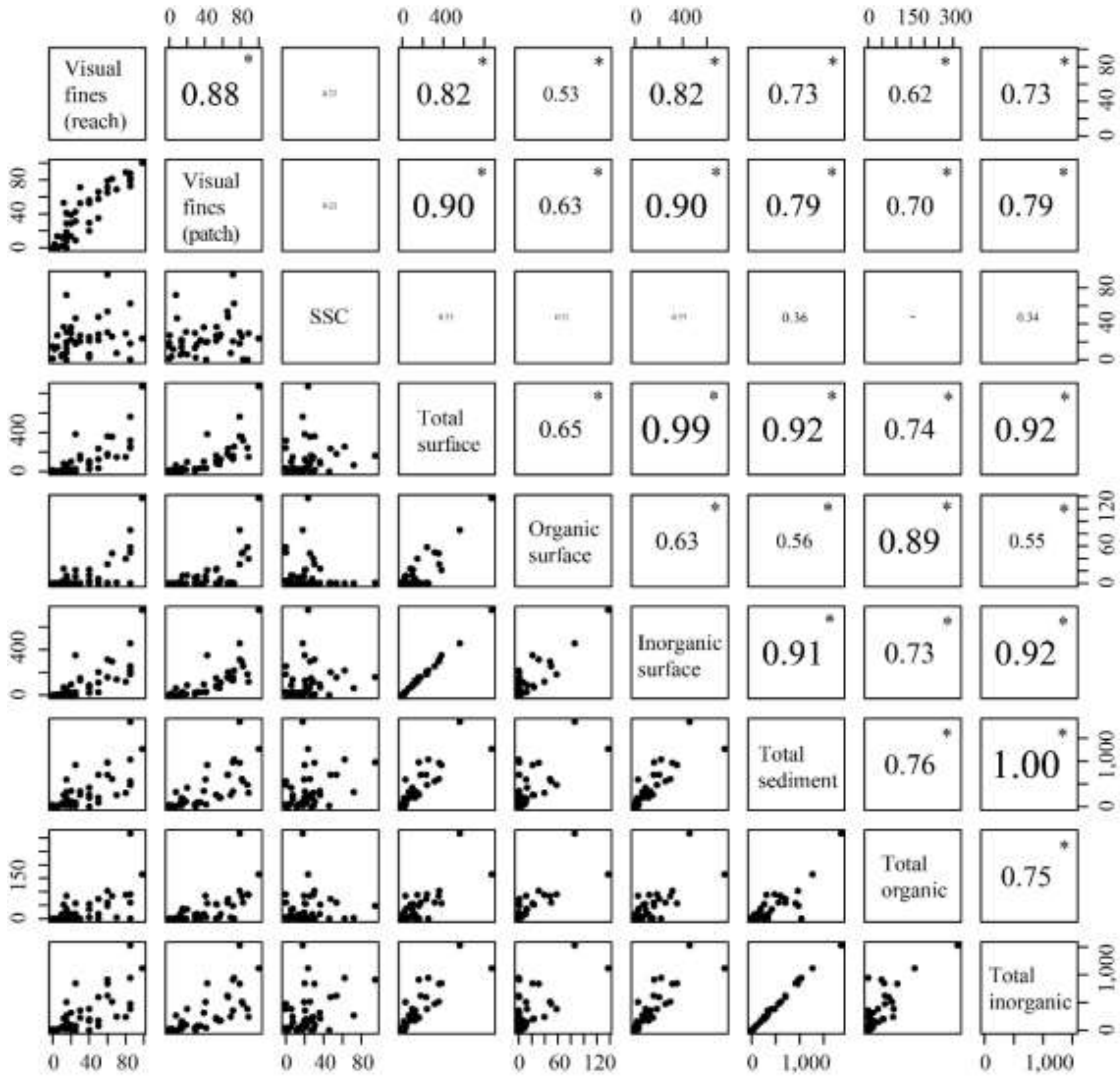

Fig. 3. Spearman's rank correlation matrix of metrics of fine sediment. Font size of the correlation coefficient is scaled to coefficient value. Significant correlations are marked with an asterisk.

The correlation between visual estimates and total surface sediment was stronger for spring ($\rho = 0.879$, $p < 0.001$) than autumn ($\rho = 0.762$, $p < 0.001$). However, model selection determined that the linear model without season as either a fixed or random effect was optimal for both total surface and total sediment (see Table A.2). Both models were significant with the model fit (R^2) of total surface higher than total sediment (Table 3).

Table 3. Linear mixed effect model results showing the relationship between total surface sediment from visual fines. Significant coefficients are marked with an asterisk.

Model	Coefficient	Estimate	Std. Error	t value	p
Total surface ~ visual fines df 40 Adj R^2 0.556 F 52.32 p <0.001*	Intercept	2.141	0.297	7.199	<0.001*
	Visual fines	0.048	0.007	7.230	<0.001*
Total sediment ~ visual fines df 40 Adj R^2 0.420 F 30.66 p <0.001*	Intercept	3.560	0.327	10.894	<0.001*
	Visual fines	0.040	0.007	5.537	<0.001*

3.3. Abiotic predictors of fine sediment metrics

When determining the significant environmental predictors of each fine sediment metric, model selection determined that the linear model with season included as a fixed effect was optimal for organic surface, total sediment, total organic and background SSC (see Table A.4). This is intuitive, at least for the organic metrics, due to seasonal changes in organic inputs. Season was not included as a fixed effect for the remaining sediment metrics. All models were significant (Table 4, full model results available in Table A.5), and the adjusted R^2 was particularly high for all deposited metrics of fine sediment, with the exception of total surface sediment for which it was more moderate. The adjusted R^2 was relatively low for background SSC. Width was a significant predictor, with a negative coefficient estimate (i.e. as width increases, the estimates of fine sediment decrease), for all metrics except organic surface and total organic. The coarse bed matrix (combined percentage of boulders, cobbles, and pebbles) was significant for all the metrics assessing deposited sediment, except for organic surface. Season was significant for the metrics where it was included as a fixed effect. The high regime flow metric, Q1, was only significant for the two organic metrics. The relatively high antecedent flow metric describing the most recent flow conditions, Q20pre7d, were not retained for any metrics. The hydrological metric Q1090DF was significant for all metrics except total sediment and inorganic surface. Notably, the coefficient was negative for background SSC but positive for all other deposited metrics. The antecedent flow metric Q50preSum was significant for visual fines, total sediment, and both inorganic metrics. The antecedent metric Q50preWin was significant for visual fines and both organic metrics only. Filamentous algae was a significant predictor with positive estimates for both of the organic metrics and background SSC.

Table 4. Refined linear model results for fine sediment metric responses. Values represent estimate sizes and significant coefficients (p <0.05) are marked with an asterisk.

	Visual fines Adj R^2 0.862 p <0.001*	Total surface Adj R^2 0.662 p <0.001*	Total sediment Adj R^2 0.779 p <0.001*	Organic surface Adj R^2 0.810 p <0.001*	Inorganic surface Adj R^2 0.726 p <0.001*	Total organic Adj R^2 0.769 p <0.001*	Total inorganic Adj R^2 0.732 p <0.001*	Background SSC Adj R^2 0.302 p 0.011*
(Intercept)	7.586*	11.437*	8.606*	9.607*	7.956*	13.980*	10.098*	-2.122
Width	-0.075*	-0.122*	-0.092*		-0.108*		-0.139*	-0.099*
Depth		0.029			0.029	-0.049*		0.050*
Bedrock	-0.009	-0.033	-0.070*	-0.025*	-0.042*	-0.062*	-0.065*	
Macrophyte	0.363*		0.379		0.442		0.617*	-0.350
Filamentous algae			0.292	0.292*		0.633*		0.550*
Altitude	-0.011*							0.009
Slope	0.067			-0.136	0.333*			
Background SSC	0.009*		0.015*	-0.025*			0.012	
Coarse bed matrix	-0.022*	-0.018*	-0.030*	-0.010	-0.026*	-0.028*	-0.026*	
Erosional flow		-0.008	-0.009*	-0.020*	-0.012*	-0.024*		0.009
Q1	-0.246	-0.463		-0.620*		-0.835*		
Q1090DF	1.146*	1.806*	1.027	1.392*	1.352	1.912*	1.420*	-1.588*
Q50preWin	0.669*			-1.631*		-1.494*		
Q50preSum	1.338*	3.456*			3.233*		3.500*	
Q20pre7d			1.397			1.492		
Q20pre6m							0.870	-1.830*
Stream power		0.346		0.690*		0.480	0.417*	
Season (spring)			0.577*	-0.904*		-0.856*		0.762*

4. Discussion

4.1. Comparing methods of measuring fine sediment

The aims of this research were to compare and assess methods for quantifying suspended and deposited fine sediment in lowland gravel bed rivers, determine which abiotic variables are controlling fine sediment quantities, and understand how this varies between the different methods of assessment. This study builds on work by Conroy et al. (2016b) who compared various methods of measuring fine sediment in laboratory-based mesocosms and recommended further comparisons under field conditions. The present study showed a strong and significant correlation between reach scale visual estimates and total surface sediment. The results of the present study support that of Zweig and Rabení (2001) and Glendell et al. (2014) who found that the measure of embeddedness and visual estimates were highly correlated with one another. Hubler et al. (2016) showed correlation coefficients of between 0.49-0.58 which is lower than the present study. However fine sediment was defined by Hubler et al. (2016) as particles <0.06 mm in diameter potentially indicating that visual observations are insufficient at accurately identifying particles at smaller sizes. Duerdoth et al. (2015), showed inter-operator variability was a significant influence accounting for up to 40% of the total variance of visual estimates. Within the present study, inter-operator variability was eliminated (as the same operator assessed fine sediment at each site) which could account for the stronger correlations between the semi-quantitative and fully quantitative metrics. The correlation between visual estimates and total surface sediment was stronger when the visual estimates were taken at the patch scale. This is expected, considering the patch scale estimates were taken of the undisturbed area of bed surface within the disturbance cylinder prior to agitation. This is perhaps confounded, and a more appropriate comparison may be to examine a set of random patches within the sampled reach. However, it provides additional support for the visual estimates, not least because of the closer relationship between the fully quantitative and semi-quantitative measures at the patch scale, but also because the accuracy of visual estimates is not drastically reduced at the reach scale.

When comparing the relationship between total surface sediment and visual estimates by season, the correlation was stronger in spring than in autumn. The weaker fit in autumn could have been a result of leaf litter and other detritus obscuring views of fine sediment and resulting in underestimates. Alternatively, high organic content on the riverbed from leaf litter breakdown could lead to overestimations. However, a linear modelling approach showed season did not significantly affect the overall relationship between visual estimates and total surface sediment. The weaker link between the organic surface and the total organic sediment with all other metrics of fine sediment suggests that the organic content is relatively independent of the total sediment content and is likely dependent on other factors which influence the supply and breakdown of organic matter.

Visual estimates correlated well with the total estimates. The subsurface agitation incorporates both the surface drape and the sediment within the top 100 mm of the gravel bed. Visual estimates are criticised on the basis that they only estimate the surface drape which may not necessarily be associated with the subsurface sediment. Subsurface sediment can be transported laterally in the subsurface of gravel bed rivers, and its retention and accumulation is an important part of the sediment transport system (Harper et al. 2017). Studies deploying sediment traps in situ within the river bed have shown lateral sediment movement to contribute between 20-46% of total surface and subsurface sediment mass (Carling, 1984; Mathers & Wood, 2016; Sear, 1996). Additionally, rivers dominated by vertical sediment ingress can lead to the formation of seals or clogs blocking further sediment movement by vertical exchange (Frostick et al., 1984). Most macroinvertebrates live in the upper layer of sediment in gravel beds (Jones et al., 2012b). Therefore, the surface sediment layer is potentially the most ecologically important metric of fine sediment that should be considered. The present study has shown that visual estimates (surface sediments) are also representative of the subsurface sediment.

4.2. Abiotic predictors of fine sediment

When modelling each sediment metric as a function of environmental variables, flow metrics, particularly antecedent metrics, appeared most important in predicting the deposited sediment metrics. Flow is intrinsically linked to sediment supply, transport and retention in rivers (Van Rijn, 1993; Wohl et al., 2015). High discharges have sufficient stream power to carry larger and greater amounts of fine sediment in suspension. This results in deposited sediments being cleared from the riverbed, and suspended sediment increasing, providing stream power is maintained. Continual or uncharacteristically low flows can result in increased deposition of fine sediment on riverbeds. This aligns with the results from the present study. With the exception of SSC and the organic metrics, the antecedent flow metrics Q50preSum and Q50preWin, and the flow regime metric Q1090DF all had positive coefficient-estimates (i.e. as they increase, the quantity of fine sediment also increases). This is intuitive for deposited sediment metrics, although no antecedent or flow regime variables were significant for total sediment. Erosional flow (proportion of erosional flow types within sampling reach) was significant for total sediment, indicating that site specific hydraulic conditions are more important than overall flow patterns in influencing subsurface infiltration. The higher antecedent flow variable, Q20pre6m was significant for background SSC with a negative coefficient, indicating a link with the effects high flows have on sediment supply in the catchment (Lawler et al., 2006). The variance explained by the linear model for SSC was particularly low compared to the deposited metrics. Thus, unsurprisingly, suspended sediment is poorly explained by the same set of environmental variables as deposited sediment. Despite large variations in deposited sediment metrics between sites, there was low variation of SSC. This is also supported by SSC contributing a low proportion of the overall variability of the PCA. This is because sampling was only carried out during low flow (high and spate flows were avoided) and therefore little variation in SSC was captured. The majority of fine sediment is transported during flood events (Grove et al., 2015; Guo et al., 2020; Woodruff et al., 2001). Therefore, when describing the factors controlling fine sediment in river environments, it is important to distinguish the fraction which is being assessed.

The two organic sediment metrics often had different sets of significant predictors, or the same predictors with a different estimate sign (positive/negative) compared to the other metrics. The presence of filamentous algae was a significant predictor for both organic metrics. Filamentous algae, and associated biofilms, can bind surface sediments preventing the resuspension into the water column (Cheng et al., 2018; Fang et al., 2017). Additionally, the quantities of algae will be affected by nutrient input to the catchment which also has a direct link with organic matter (Collins et al., 2013a). Sediments retained by macrophytes frequently contain higher organic contents (Gurnell et al., 2013), however this relationship was not shown in the present study. The quantities of organic material in sediment is likely controlled by other variables not recorded in this study, such as upwards controls from the ecological community (Wilkes et al., 2019). This supports the previous observation of poor correlations between organic sediment with the other metrics. The proportion of aquatic invertebrates (such as shredders or detritivores) and microbial organisms that breakdown leaf litter, or other organic material, into particulate organic matter (POM) will ultimately affect the quantity of organic material in the sediment (Young et al., 2008). These can be further influenced by other factors such as grain size distribution (through its influence on effective porosity) (Navel et al., 2010) or organic material type and origin (e.g. tree species, life stage etc) (Tank et al., 2010).

Season was a significant predictor where it was included as a fixed effect (total sediment and background SSC). Season was also significant for the organic metrics, further reflecting the variation in organic matter supply seasonally. Most studies to date which compare the semi-quantitative estimates with the fully quantitative disturbance method only sample a single season, missing this ecologically relevant variation. Width was a significant predictor for both the deposited metrics and background SSC, with negative coefficient estimates (i.e. as width increases, the estimates of fine sediment will decrease). Width is closely linked to both discharge and velocity and therefore the effect of width could be a proxy for these effects. Given that width is a significant predictor, this could imply that small streams are most vulnerable to fine sediment accumulation and could indicate where resources are best allocated in catchment management projects. Notably, stream power was not included in the reduced models for most of the sediment metrics. This unexpected result could be because the effects are captured by other variables (e.g. flow variables). The coarse bed matrix was a significant predictor for most metrics. In all cases the estimate was negative, therefore the quantity of fine sediment decreases with an increasingly coarse bed. The calculation of the coarse bed matrix is not completely circular with the percentage of fine sediment (as it does not include the percentage of gravel present), however this result is predictable. Additionally, flow patterns around coarse substrates can create hydrodynamic conditions which resuspend deposited sediments (Buffin-Bélanger & Roy, 1998).

5. Conclusion

The results presented in this study show that visual estimates are a reliable proxy for more labour-intensive quantifications of total surface sediment (using the disturbance method). Additionally, visual estimates were also highly representative of total sediment estimates which include the surface and subsurface agitation. Visual estimates are a quick and instantaneous method of assessing fine sediment. The disturbance method requires greater investment of both time and equipment making it unsuitable for routine monitoring. However, this method is still useful for research purposes as it has the potential to yield additional information about the mass stored and provide material to determine sediment quality and particle size. As inter-operator variability was eliminated in the current study, methods for improving accuracy could be adopted in future studies (e.g. Clapcott et al., 2011; Turley et al., 2017). When considering the environmental variables which affect fine sediment metrics, flow (regime, antecedent and local flow patterns) was particularly important. The organic metrics displayed different relationships with the predictor variables compared to the other deposited sediment metrics. Thus, implying organic sediment content can be influenced by upward controls from within the ecological community. Not surprisingly, the suspended metric, SSC, was poorly predicted by the same set of variables as the deposited metrics. We recommend further research in other river types, for example groundwater dominated rivers or those in upland areas, to determine whether the same relationships exist between abiotic predictors and sediment accumulation.

The results of this study provide further validation of the visual assessment method as a reliable proxy for fully quantitative and labour-intensive methods. This is a valuable observation for managers and researchers who regularly employ this method. Given the efficacy of visual assessments, the development of a mobile app to assess sediment accumulation in rivers could help provide more readily available data at higher resolutions. The multivariate linear regression models provide further understanding of the variables controlling fine sediment in lowland gravel bed rivers. These insights provide information to managers to guide their actions when addressing the ecological impacts of excess fine sediment.

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Appendix A. Supplementary data

Supplementary data to this article can be found online.

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