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UNDERSTANDING THE CONTROLS ON DEPOSITED FINE SEDIMENT IN THE STREAMS OF AGRICULTURAL CATCHMENTS

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Abstract

Excessive sediment pressure on aquatic habitats is of global concern. A unique dataset, comprising instantaneous measurements of deposited fine sediment in 230 agricultural streams across England and Wales, was analysed in relation to 20 potential explanatory catchment and channel variables. The most effective explanatory variable for the amount of deposited sediment was found to be stream power, calculated for bankfull flow and used to index the capacity of the stream to transport sediment. Both stream power and velocity category were highly significant ($p<<0.001$), explaining some 57% variation in total fine sediment mass. Modelled sediment pressure, predominantly from agriculture, was marginally significant ($p<0.05$) and explained a further 1% variation. The relationship was slightly stronger for erosional zones, providing 62% explanation overall. In the case of the deposited surface drape, stream power was again found to be the most effective explanatory variable ($p<0.001$) but velocity category, baseflow index and modelled sediment pressure were all significant ($p<0.01$); each provided an additional 2% explanation to an overall 50%. It is suggested that, in general, the study sites were transport-limited and the majority of stream beds were saturated by fine sediment. For sites below saturation, the upper envelope of measured fine sediment mass increased with modelled sediment pressure. The practical implications of these findings are that (i) targets for fine sediment loads need to take into account the ability of streams to transport/retain fine sediment, and (ii) where agricultural mitigation measures are implemented to reduce delivery of sediment, river management to mobilise/remove fines may also be needed in order to effect an improvement in ecological status in cases where streams are already saturated with fines and unlikely to self-cleanse.

Keywords

deposited fine sediment; agricultural streams; agricultural sediment pressure; stream power; channel substrate; saturated fine sediment fraction

1. Introduction

Excessive sediment pressure on aquatic habitats has become of increasing concern for river systems around the world (Relyea et al., 2012). In particular, intensification of agriculture has increased fine sediment loading to rivers (Wilcock, 1986; Dearing et al., 1987; Owens and Walling, 2002; Walling et al., 2003a; Foster et al., 2011; Jones and Schilling, 2011), leading to high concentrations of suspended solids and, potentially, deposition of fine sediment. Evidence has also been accumulating, from both field survey and experiments, on the deleterious effects of excessive fine sediment on biota (Waters, 1995; Wood and Armitage, 1997; Matthei et al., 2006; Bilotta and Brazier, 2008; Larsen et al., 2011; Sutherland et al., 2012; Wagenhoff et al., 2012, 2013; Chapman et al., 2014). It is clear from this evidence that the impact of excessive fine sediment on biota is more often related to deposited rather than suspended material (Kemp et al., 2011; Jones et al., 2012a, Jones et al., 2012b; Jones et al., 2014). In the light of this, attempts have been made to identify target values for both deposited fine sediment and sediment loading (Cooper et al., 2008; Collins and Anthony, 2008; Bryce et al., 2010; Collins et al., 2011; Benoy et al., 2012). Yet, the relationship between deposited fine sediment and agricultural sediment pressure is still poorly understood.

Sediment pressure has been variously quantified by catchment or local/network riparian land use (Sutherland et al., 2010), runoff-weighted percentage land use (Wagenhoff et al., 2011) and modelled sediment load apportionment (Collins and Anthony, 2008). Catchment land use has been shown to be related to deposited fine sediment in specific cases of intensification of agriculture (e.g. Nyogi et al., 2007; Sutherland et al., 2010; Wagenhoff et al., 2011). However, at a strategic level, only the approach based on modelled sediment load has potential to link fine sediment deposition with current or future projected land management and, thus, provide information on the likely effectiveness of mitigation measures for fine sediment delivery to rivers in terms of sediment deposition and its biotic impact. The ability to make this link is fundamental to supporting national policies regarding the protection of water resources and ecological status.

Representative field sampling of deposited fine sediment in agricultural streams across England and Wales, carried out as part of a wider national scientific policy support project, provided a unique opportunity to explore the relationship between an instantaneous measurement of deposited fine sediment and sediment pressure. Sampling was specifically designed to cover both the range of agricultural sediment pressure and different biological river types across England and Wales (following Davy-Bowker et al., 2008). The impact on biota is covered elsewhere (Murphy et al., 2015). The aim of this paper is to analyse the sediment data in conjunction with a range of catchment and channel descriptors in order to investigate potential linkages between agricultural sediment pressure and deposited fine sediment in streams. In particular, it is hypothesized that the mass of deposited fine sediment is directly related to the amount of sediment delivered to the channel and inversely related to the capacity of the stream to transport fine sediment.

2. Approach and methods

The approach taken was a synoptic survey of streams in agricultural catchments across England and Wales. Sampling sites were selected from the 12,447 stream sites within the Environment Agency River Habitat Survey (RHS) database. Biological river types were based on the physical attributes of catchment geology, distance from source, altitude and slope; with boundary values loosely based on those associated with RIVPACS IV super end groups (Davy-Bowker et al., 2008). Screening was undertaken to eliminate any sites with a substantial influence from urban areas or sewage effluent (see below). All sites were upstream of any lakes and reservoirs and on independent watercourses; in cases with more than one candidate site per watercourse, the most downstream site meeting the screening requirements was selected. Full details regarding the site selection process are given in Murphy et al. (2015). Some 230 sites were sampled once in either spring or autumn between May 2010 and November 2011. Most samples were collected during low to medium flows as necessitated by the technique and no samples were collected during or immediately after peak flow events. From data on water width, depth and velocity category at the time of sampling, approximately 90% samples were collected when the flow was less than 10% of the estimated median annual flood, or approximately bankfull flow. An independent dataset (Anthony et al., 2012) of 55 similar sites, sampled in both autumn and spring by the same field team and in exactly the same manner between October 2009 and May 2011, was also available for model testing and to assess temporal variability.

2.1 Deposited fine sediment

Fine sediment deposited on, or in, the river substrate to a depth of about 10 cm was collected using the disturbance technique (Duerdoth et al., 2015 adapted from Collins and Walling, 2007a,b). An open-ended, stainless steel cylinder (height 75 cm; diameter 48.5 cm) was carefully inserted into an undisturbed patch of stream bed to a depth of at least 10 cm, until an adequate seal with the substrate was achieved, and the depth of water within the cylinder was measured. To provide an instantaneous measure of the deposited surface drape, the water column was agitated vigorously for one minute using a metal pole, without touching the stream bed. This established a vortex that brought any fine sediment into suspension. This was then immediately sampled, while the water was still in vigorous motion, by plunging two inverted 50 ml tubes to the bottom of the cylinder which then filled as they were turned upright and brought to the surface. To sample the total (i.e. combined surface and sub-surface) deposited fine sediment, the stream bed was then disturbed to a depth of about 10 cm, vigorously agitated for one minute to suspend any subsurface fines and a second pair of 50 ml samples quickly taken. For each river reach sampled, four sampling locations were identified visually by the workers in the field. In broad terms, patches with a propensity to erode fine sediment (erosional) were defined as those higher velocity areas in or close to the thalweg, whereas patches with a propensity to deposit fine sediment (depositional) were in eddies or areas of lower flow velocity such as pools or backwaters. Two samples were collected from erosional and two from depositional zones of the main channel, in order to characterise the reach-scale average (derived from all 4 samples) and provide an indication of within-reach variability.

The samples were refrigerated and kept in the dark until analysed. Deposited fine sediment was characterised in terms of mass, volatile solids (i.e. organic matter derived from loss on ignition) and particle size. Fine sediment mass and volatile solids were measured within one week of return to the laboratory using one of each pair of 50 ml tubes. The samples were passed through a 2 mm sieve, to remove leaves and twigs, prior to filtration using pre-ashed, washed and dried 90 mm Whatman Glass Microfibre GF/C filters (pore size 1.2 μm). The filtered samples were dried in a pre-heated oven at 105^{o} C overnight and ashed in a pre-heated muffle furnace at 500° C for 30 minutes. Reach-average values of sediment mass were calculated using geometric means. Averaging the four samples provided an effective measure of deposited fine sediment at the reach scale (cf. Collins and Walling, 2007a,b) which has been shown to be reliable across a wide range of river types (>60% boulders/cobbles to >60% sand and silt) and not affected by operator bias (Duerdoth et al., 2015). Measurement uncertainty, in terms of 95% confidence intervals, was estimated to be ±0.27 and ±0.32

logarithmic units (i.e. factors of 1.86 and 2.09) on the average total and surface deposited fine sediment, respectively (Duerdoth et al., 2015).

Absolute particle size (< 1mm) was analysed on the second 50 ml tube of each pair using a Malvern Mastersizer 2000. In most cases, the whole sample was analysed using either a HydroS (with pump/stir speed of 2700 rpm) or HydroG (with pump speed 1600 rpm and stir speed 700 rpm) dispersion unit, dependent on the amount of sediment in the sample. For very large amounts of sediment, samples were centrifuged at 4000 rpm for 15 minutes, the supernatant carefully decanted and the sediment thoroughly mixed before subsampling. In order to give the absolute particle size distribution of the whole sample, organic material was not removed. To aid disaggregation and dispersion, 5 ml of 5% sodium hexametaphosphate was added to each sample which was then shaken and left for a minimum of 1 hr before analysis. The sample was then passed through a 1 mm sieve into the dispersion unit where maximum ultrasound was applied for 3 minutes and switched off for 1 minute prior to measurement.

For each of the sampled sites, land cover, modelled sediment pressure and other catchment and channel descriptors were derived as follows.

2.2 Land Cover

Land cover data for 2007 was derived for each of the sites in ARC-GIS Version 9.3.1 using the 25 m raster dataset LCM2007 (Morton et al., 2011) and digital catchment boundaries based on a 50 m digital terrain model (Morris and Flavin, 1990). The LCM2007 dataset was developed from satellite images and digital cartography and gives land cover information based on the UK Biodiversity Action Plan Broad Habitats. It has 23 classes. These were amalgamated into three classes considered to be most relevant to different agricultural use (i.e. arable and horticulture, improved grassland, and unimproved grassland/upland), as described in Table 1. In the case of improved grassland, land cover classes 6 and 7 (neutral and calcareous grassland, respectively) have been included with class 4 (designated improved grassland) as these have similar spectral properties and so may not be distinguishable; in practice, land cover classes 6 and 7 are only minor components, making up less than 4% of the total area in all but three of the selected catchments.

Table 1 Catchment and channel descriptors

Descriptor	**Source/derivation**
Arable (%)	% area in LCM2007 class 3 (arable and horticulture)[1]
Improved grassland (%)	% area in LCM2007 classes 4, 6 and 7 (improved, neutral and calcareous grassland)[1]
Unimproved grass and upland (%)	% area in LCM2007 classes 5, 10, 11, 12 and 13 (rough grassland, heather, heather grassland, bog and montane habitats)[1]
Sediment pressure (T/yr)	Derived from updated PSYCHIC model (see text)
Sediment yield (T/km^2/yr)	Derived from sediment pressure and catchment area
Catchment area (km^2)	Digital terrain model (50m resolution)
Altitude (m)	RHS database from maps[2]
Distance to source (km)	RHS database from maps[2]
Stahler stream order	RHS database from maps[2]
Channel slope (m/km)	RHS database from maps[2]
MSUB (phi units)	Mean substratum size derived from field measurement at time of sampling using RIVPACS protocol[3]
Bankfull width (m)	RHS database from field survey[2]
Water width (m)	Field measurement at time of sampling (RIVPACS protocol)[3]
Water depth (m)	Field measurement at time of sampling (RIVPACS protocol)[3]
Velocity category	Field measurement at time of sampling (RIVPACS protocol)[3] 1: ≤ 10 cm/s; 2: 10 to ≤ 25 cm/s; 3: 25 to ≤ 50 cm/s; 4: 50 to ≤ 100 cm/s; 5: > 100 cm/s
Habitat Modification Class	RHS database from field survey[2]
Median annual flood (m^3/s)	Flood Estimation Handbook method using digital data (see text)
Stream power (W/m)	Derived from median annual flood and channel slope
Unit stream power (W/m^2)	Derived from stream power and bankfull width
Baseflow index	Estimated from Hydrology of Soil Types[4]

[1] Morton et al. (2011)
[2] Environment Agency (2003)
[3] Murray-Bligh et al. (1997)
[4] Boorman et al. (1995)

2.3 Sediment pressure

Agricultural sediment delivery to streams was modelled using a national pressure layer generated by a new policy-support framework based on updates and refinements to the process-based Phosphorus and Sediment Yield CHaracterisation In Catchments (PSYCHIC) model (Collins et al., 2007, 2009a,b; Davison et al., 2008; Stromqvist et al., 2008) and the June agricultural census returns for 2010 as model input for crop areas and livestock numbers. This is a generic model based on national datasets relating to climate, soils and farm types which is designed to capture the variation in sediment pressure across England and Wales. The original PSYCHIC framework has been shown to perform satisfactorily at field (Collins et al., 2009a) and national (Collins et al., 2009b) scale. The agricultural sediment pressure modelling framework used in this work has been tested and shown to perform satisfactorily at a range of scales including plot, field, catchment (Collins et al., 2012a) and national (Zhang et al., 2014) scale. The calculation of cross-sector sediment pressures is fully described in Collins et al. (2009a). Sediment pressure from urban sources was calculated on the basis of published data for event mean concentrations following Mitchell et al. (2001) and Mitchell (2005). Inputs from sewage treatment works were based on consented discharges and a correction for the relationship between observed and consented suspended solids concentrations. Sediment pressure from bank erosion was calculated as a function of the duration of excess bank shear stress and channel density, calibrated against the results from sediment fingerprinting studies (Collins and Anthony, 2008; Collins et al., 2009a). The modelled cross-sector data were used to ensure that no site had urban inputs >2 kg/ha/yr or STW inputs >0.5 kg/ha/yr, thereby permitting an assessment of the potential relationship between agricultural fine sediment loss and instantaneous measurements of deposited fine sediment on stream beds.

2.4 Other catchment and channel descriptors

In addition to the land cover statistics and modelled sediment pressure for each of the sampled sites, a range of catchment and channel descriptors were available from maps or associated databases (Table 1). They included those RIVPACS channel descriptors (substrate size, water width, water depth and velocity category) collected during the field campaigns, thus characterising hydromorphological conditions at the time of sampling, and descriptors from the RHS database.

In addition, stream power has been used to index the capacity of a stream to transport sediment (Bagnold, 1966; Knighton, 1999; Gurnell et al., 2010). It is well-known that most of the annual load of suspended sediment is carried during high flows so stream power was calculated using the median annual flood (similar in return period to bankfull flow) which can be estimated from catchment characteristics. A revised unbiased equation for the median annual flood, based on a study of 602 rural catchments across the UK, is given by Kjeldsen and Jones (2010) as:

$$Q_{MED} = 8.3062\ AREA^{0.8510}\ 0.1536^{(1000/SAAR)}\ FARL^{3.4451}\ 0.0460^{\ BFIHOST2}$$

where Q_{MED} is median annual flood (m^3/s), $AREA$ is catchment area (km^2), $SAAR$ is standard average annual rainfall 1961-90 (mm), $FARL$ is an index of flood attenuation due to reservoirs and lakes, $BFIHOST2$ is the square of the baseflow index derived from Hydrology of Soil Types (HOST) data (Boorman et al., 1995).

Stream power and specific, or unit, stream power (Bagnold, 1966) are then given by:

$$\Omega = \rho g\ Q_{MED}\ S$$

$$\omega = \Omega\ /\ W_{BF}$$

where Ω is stream power (W/m), ρ is density of water (kg/m^3), g is acceleration due to gravity (m/s^2), Q_{MED} is median annual flood (m^3/s), S is channel slope (m/m), ω is specific or unit stream power (W/m^2), W_{BF} is bankfull width (m). Both channel slope and bankfull width were taken from the RHS database.

Flow regime is also relevant to fine sediment deposition in that it indicates the overall balance between potentially depositing and flushing flows. This may be effectively represented by the baseflow index (BFI) or proportion of the flow which occurs as baseflow. Low values of BFI represent flashy responsive catchments, while high values represent slowly-responding groundwater-fed catchments with a propensity for excessive deposition of fine sediment (Sear et al., 1999). BFI was estimated directly from the proportion of HOST soil types in the catchment. The HOST classification of soils (Boorman et al., 1995) is based on conceptual models of the hydrological processes taking place in the soil and, where appropriate, the underlying geology. These models take into account the physical properties of the soil, permeability of the underlying geology and depth of the water table. BFI coefficients for each of the soil classes were derived from measured BFI for 575 catchments across the UK using bounded multiple regression analysis by Boorman et al. (1995); the overall standard error of the estimate across all soil classes is quoted as 0.09.

2.5 Statistical Analysis

Analysis was carried out in the R language. The amount of deposited fine sediment, as well as many of the variables included in the analysis, were log-normally distributed. Consequently, a logarithmic transformation was applied to all continuous variables. This implies that the model developed to explain the deposited fine sediment will be multiplicative in form which seemed appropriate. Categorical variables were treated as factors. The Habitat Modification Score class (an indicator of anthropomorphic alteration of the river channel and available from the River Habitat Survey database) was subsequently dropped from the analysis as individual subscores could be interpreted as either enhancing or reducing deposition of fines, sometimes dependent on whether samples were upstream or downstream of a particular feature, leading to inconsistency of impact. Preliminary regression tree analysis suggested that interaction terms were not important.

3. Results

The sampled sites were strongly biased towards the north and west of England and Wales (Figure 1). This was due to the process of site screening to ensure that the sediment pressure was mostly derived from agriculture as described by the cross-sector model. Missing catchment or channel characteristics meant that 26 sites were dropped from the analysis. Modelled sediment pressure, expressed as sediment yield, ranged from 1.4 to 190 tonnes/km^2/yr, with a median value of 28 tonnes/km^2/yr. The majority of these values were well above empirical target values proposed for the sediment yields of different river types (Cooper et al., 2008) and alternative targets derived from palaeo-limnological reconstruction to represent modern background sediment delivery to river channels, prior to post-war agricultural intensification (Foster et al., 2011). Thus, it is highly plausible that most of the sites were heavily impacted by agricultural sediment (cf. Collins et al., 2012b).

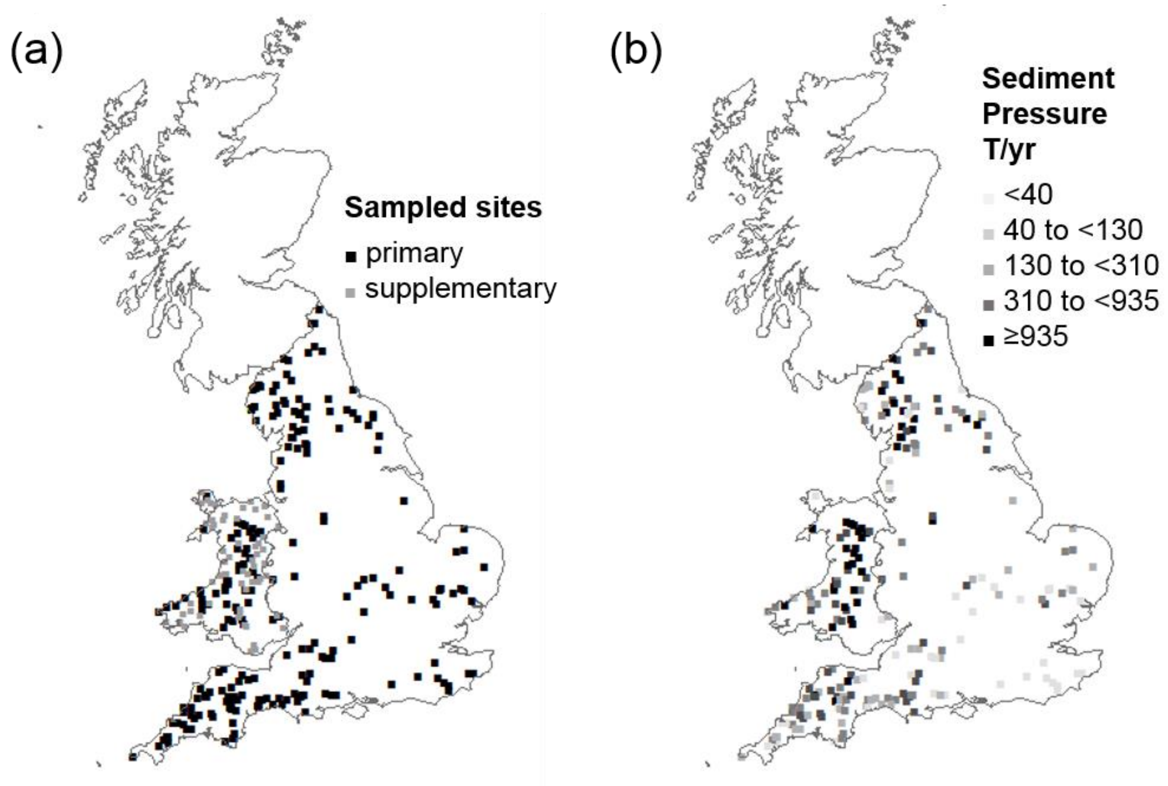

Figure 1 (a) Location of sampled sites; (b) sediment pressure class based on quintiles from an updated version of the PSYCHIC model using agricultural data for 2010.

3.1 Deposited fine sediment

The reach-averaged instantaneous mass of fine sediment in the surface drape ranged from 6 to 4,562 g/m^2 with a median value of 181 g/m^2; the reach-averaged mass of total fine sediment (i.e. surface plus subsurface down to *circa* 10 cm depth) ranged from 8 to 69,664 g/m^2 with a median value of 906 g/m^2 (Table 2). Volatile solids (i.e. organic fraction determined by loss on ignition) ranged from 2 to 497 g/m^2 in the surface drape and 4 to 3,492 g/m^2 in the total. The median percentage volatile solids was 16% for the surface drape and 11% for the total, with the surface drape having a higher percentage content of volatile matter, as might be expected. There was close correlation between surface and total sediment mass (Spearman rank correlation $\rho = 0.92$; $p << 0.001$).

Table 2 Selected percentiles for reach-averaged instantaneous measures of sediment mass and particle size for surface drape and total

Surface drape: reach-averaged values primary sites

%ile	sediment mass g/m^2	volatile solids g/m^2	volatile solids %	median grain size μ	span grain size[1]	sand % by volume	silt % by volume	clay % by volume
10	25.58	6.48	9.54	15.95	3.80	16.04	47.62	6.97
25	58.04	10.99	12.62	19.31	4.28	20.29	55.84	8.95
50	180.86	25.17	16.44	25.44	5.07	26.10	61.90	11.81
75	454.13	60.37	22.17	35.09	6.00	34.70	66.33	13.96
90	988.22	132.52	34.45	45.09	6.97	42.32	69.44	16.27
Surface drape: reach-averaged values supplementary sites								
10	35.91	10.34	9.51	14.64	4.06	14.89	58.07	7.59
25	83.62	15.69	13.15	18.53	4.45	18.06	60.73	9.53
50	196.73	33.97	18.39	23.23	5.15	23.81	64.74	11.44
75	383.31	51.99	24.41	27.19	5.81	27.45	67.76	14.73
90	1074.82	125.80	35.92	33.18	6.64	32.42	70.59	17.20

Total (surface and subsurface to *circa* 10 cm): reach-averaged values primary sites

%ile	sediment mass g/m^2	volatile solids g/m^2	volatile solids %	median grain size μ	span grain size[1]	sand % by volume	silt % by volume	clay % by volume
10	107.47	16.04	6.39	16.45	4.11	18.37	42.05	6.22
25	301.89	33.22	8.51	20.43	4.74	23.01	49.64	8.40
50	906.01	82.82	11.12	27.21	5.80	30.36	57.88	11.12
75	2452.09	241.54	14.91	40.13	7.22	39.73	63.54	14.10
90	7720.38	550.33	19.35	64.61	8.51	49.52	67.21	16.66
Total (surface and subsurface to *circa* 10 cm): reach-averaged values supplementary sites								
10	175.79	20.41	6.83	15.57	4.44	17.11	52.06	7.10
25	397.46	45.84	8.98	19.13	5.06	20.75	58.43	8.62
50	961.42	103.01	12.06	23.70	6.08	24.97	63.17	10.76
75	2187.51	181.45	15.99	33.00	6.98	33.10	65.85	13.85
90	7567.31	573.01	20.50	39.16	8.03	38.70	69.16	16.62

[1] span of grain size given by $(D_{90}-D_{10})/D_{50}$ where D_i is the absolute grain size with i% finer by volume

The reach-averaged median absolute particle size (Table 2) varied between 10 and 176 μm in the surface drape; 95% sites had a median grain size in the silt range (i.e. between 4 and <63 μm). The median grain size of the total sediment was, in general, slightly coarser with 89% sites in the silt range. The span of the grain size distribution of most samples was broad; with a number of samples having a bimodal distribution. The reach-averaged percentage of clay sizes (<4 µm) was always less than 22%, but the percentage sand-sized material (≥63 µm and <1mm) ranged between 5 and 70% in the surface drape and between 10 and 81% in the total sediment (Figure 2). As with the sediment mass variables, there was a close correlation between measures of absolute particle size in the surface drape and total sediment.

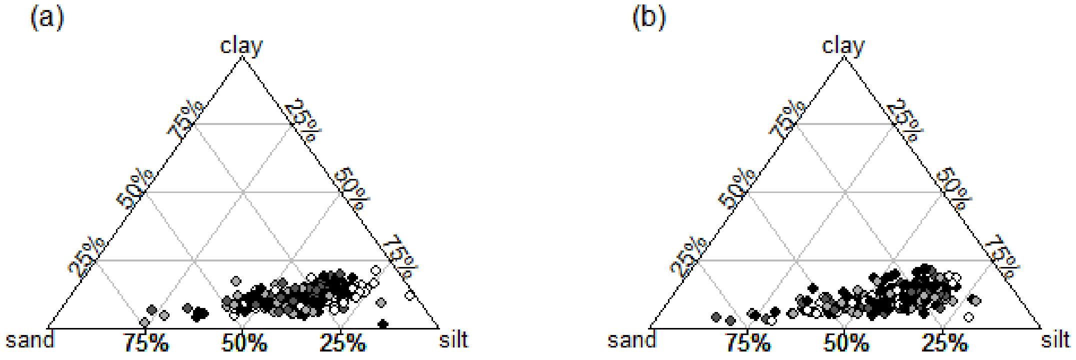

Figure 2 Ternary diagrams giving percentage sand, silt and clay in (a) reach-averaged surface and (b) reach-averaged total bed sediments (grey scale indicates the number of samples on which the reach average is based from 4 (black) to 1 (white)).

3.2 Temporal variability

The primary sites were sampled only once, with 73% sites being sampled in autumn 2010 or spring 2011. The sites in the supplementary dataset were each sampled twice – first in autumn and then in spring of the following year – and these sites were used to assess the influence of temporal variation in the deposited fine sediment which may be related to the timing of the sampling with respect to the flow regime. In general, the deposited fine sediment in the supplementary sites had a similar distribution of sediment mass and sediment characteristics to those of the primary sites. However, they did not include sites with extremely low sediment mass. There was also a tendency for more volatile solids and a slightly finer calibre of material (Table 2). All the supplementary sites were located in Wales and, as none of the sampled streams had flow data, the pattern of daily mean flows on the

River Teifi at Llanfair in south-west Wales is used to illustrate the possible variation in river flows during the various sampling periods (Figure 3).

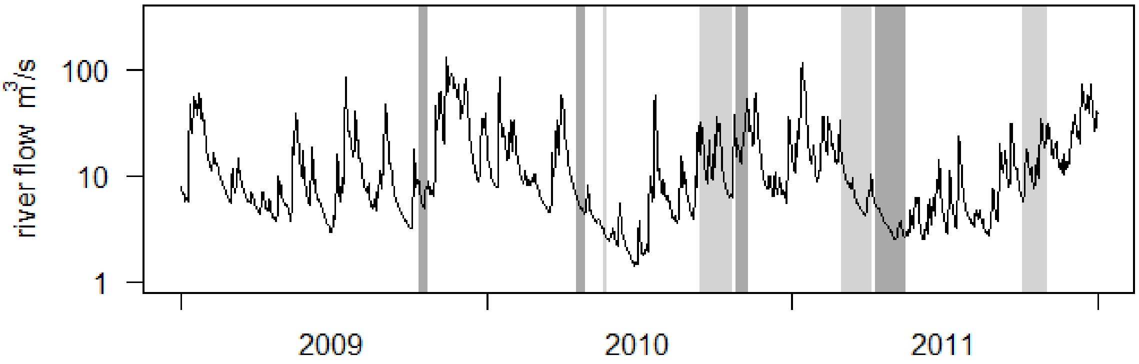

Figure 3 Sampling periods overlain on mean daily flows (note logarithmic scale) for the River Teifi at Llanfair, south-west Wales. Light grey bars relate to primary sites; dark grey bars to the supplementary dataset.

Short-term temporal variability was assessed in two ways. First, the difference in logged values of sediment mass and volatile solids from autumn to spring was compared to the 95% confidence intervals derived from the uncertainty study of Duerdoth et al. (2015). For the total sediment, the observed difference in the reach-scale sediment mass for 50 of the 55 (91%) sites and in volatile solids for 48 of the 55 sites lay within the measurement error. For the surface drape, observed differences were greater but, for both the sediment mass and the volatile solids, observed differences in over 82% sites still lay within the measurement error. Those sites with significant changes in measured values (i.e. differences greater than measurement error) showed both loss and gain of sediment in both the total and the surface drape even though all comparisons were between samples taken in autumn and the following spring, after a relatively wet winter (Figure 3). A second assessment of change was provided by looking at the correlation between pairs of measurements (i.e. measurement in autumn correlated with the equivalent measurement in spring). In all cases, the correlation was highly significant (total: sediment mass $\rho = 0.75$, volatile solids $\rho = 0.71$; surface: sediment mass ρ

= 0.67, volatile solids ρ = 0.66; p < 0.001). Thus, it may be argued that taking single instantaneous samples may add scatter but it is unlikely to fundamentally change the relationships found. It is assumed that this finding from the supplementary dataset applies to the single instantaneous measurements from the primary sites.

3.3 Relationship to land cover

Deposited fine sediment mass in both the surface drape alone and the subsurface to a depth of approximately 10 cm was significantly (p < 0.001) related to land cover (Figure 4). In particular, sediment mass was positively related to the percentage of the catchment (above zero) of arable and horticultural land and negatively related to unimproved grassland and upland. There was no relationship with improved grassland, and amalgamating this class with either of the other two simply degraded those relationships. While these results were highly significant, there was a large degree of scatter, with arable land cover explaining only 25 to 31% of the total variance in deposited fine sediment (Table 3).

Table 3 Significant relationships between deposited fine sediment and land cover

Regression model	**adjusted R^2**	**residual standard error**	***n******
reach-averaged total sediment			
$\log TS = 2.718 + 0.0118\ AH$	0.308	0.479	163
$\log TS = 3.238 - 0.0113\ UGU$	0.365	0.501	194
reach-averaged surface sediment			
$\log SS = 2.077 + 0.0096\ AH$	0.257	0.441	163
$\log SS = 2.552 - 0.0114\ UGU$	0.420	0.453	194

* number of catchments (zero % land cover omitted from relationships)

where *TS* is average sediment mass in surface drape and subsurface to a depth of approximately 10 cm (g/m^2), *SS* is average surface sediment mass (g/m^2), *AH* is percentage catchment area in LCM2007 class 3 (arable and horticulture) and *UGU* is percentage catchment area in LCM2007 classes 5,8,10-13 (unimproved grassland and upland).

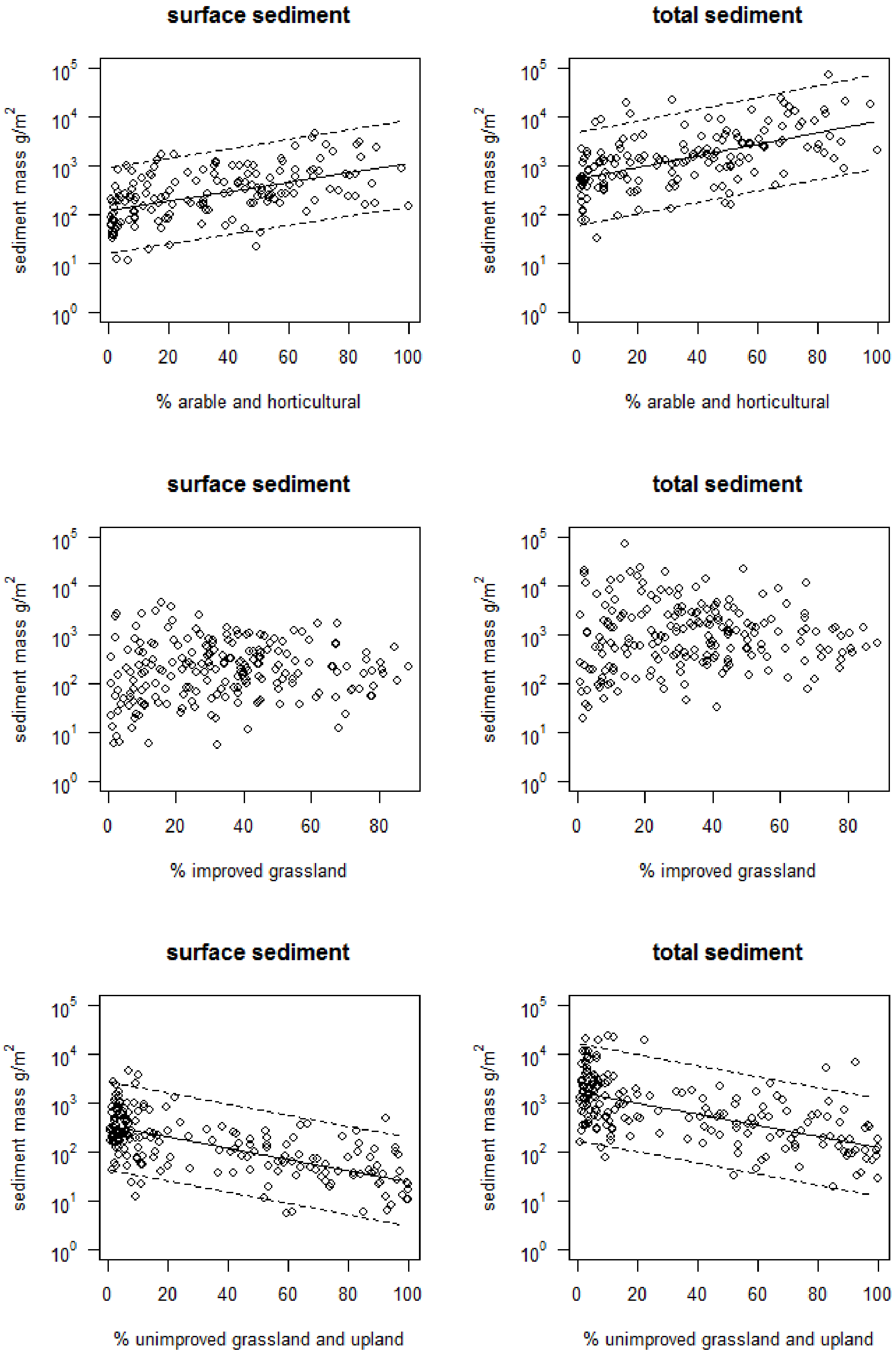

Figure 4 Deposited fine sediment and catchment land cover: significant regression lines ($p<0.001$) and 95% prediction intervals shown by solid and dashed lines, respectively.

3.4 Relationship to other variables

Initial exploration of the available data showed a very high degree of cross-correlation amongst the selected catchment and channel descriptors (Table 4). Many of the high correlations simply revealed where different variables were indexing the same attribute e.g. catchment scale appears in catchment area, channel width, river discharge, stream power and modelled sediment pressure. Land cover variables were consistently highly correlated with other catchment descriptors – in particular, altitude, median annual flood and stream power; arable and horticultural land cover was the mirror image of unimproved grassland and upland. This implies that land cover, at this scale of analysis, may simply be a reflection of the fact that arable agriculture is found in the drier, low altitude parts of England and Wales while grassland is found in the wetter, upland areas. Percentage arable land cover was also inversely related to sediment pressure, despite its positive relation to deposited fine sediment.

In seeking to explain the mass of deposited fine sediment on the channel bed, it is therefore vital to understand how it varies with other catchment and channel descriptors. The highest correlation found was with channel substrate (*MSUB*) itself – a visual assessment which included the percentage of fines but which is not designed to address the issue of siltation, i.e. infiltration of fines into a gravel substrate or thin layers of silt covering coarser substrates (Murray-Bligh et al., 1997). In particular, the relationship with *MSUB* was found to be curvilinear, flattening off at a value of around 1200 g/m^2 for the surface sediment and 10,000 g/m^2 for the total (Figure 5). Stream power showed the second highest correlation with deposited fine sediment, implying that the capacity of a stream to transport sediment is fundamental, although strongly linked to many other catchment descriptors including some of those used to model sediment pressure. The negative relationship between deposited fine sediment and modelled sediment pressure (Table 4) is counter-intuitive and implies the importance of other factors in mediating this relationship.

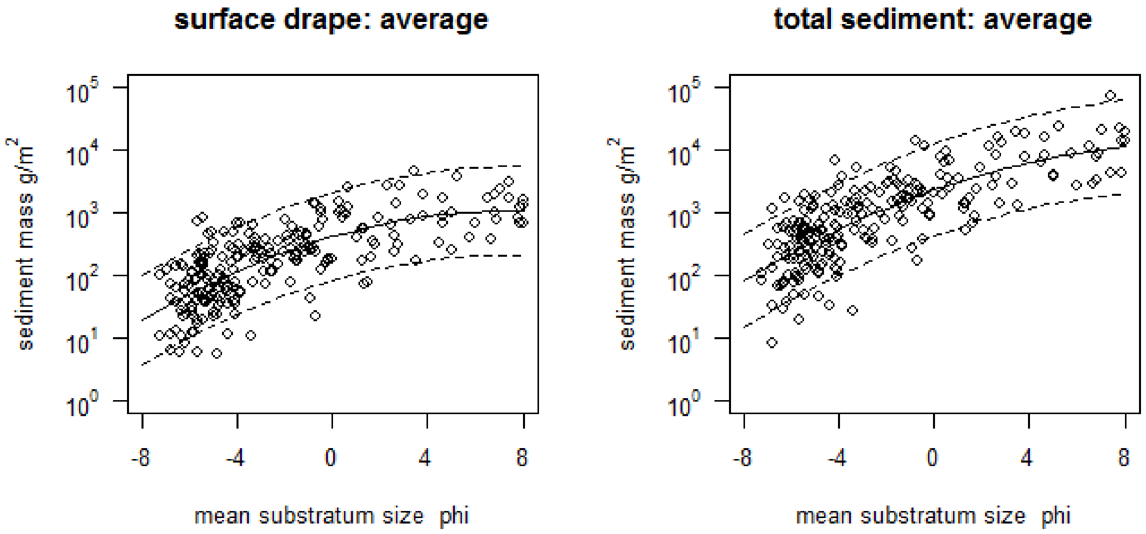

Figure 5 Relationship between reach-averaged measured fine sediment and mean substratum size derived from visual assessment following protocol for RIVPACS environmental variables (Murray-Bligh et al., 1997); best fit polynomial regression lines and 90% prediction intervals shown.

Table 4 Spearman cross-correlation between reach-averaged mass of deposited fine sediment and potential explanatory variables (values with significance level $p<0.001$ based on t test where $t=\rho\sqrt{[(n-2)/(1-\rho^2)]}$ with $(n-2)$ degrees of freedom (Siegel, 1956); only sites with no missing data used $n=204$).

	Total sediment mass kg/m^2	Surface drape kg/m^2	Arable %	Improved grassland %	Unimproved/upland %	Sediment pressure T/yr	Sediment yield T/km^2/yr	Catchment area km^2	Altitude m	Distance to source km	Strahler stream order	Channel slope m/km	MSUB phi	Bankfull width m	Water width m	Velocity category	HMS class	Median annual flood m^3/s	Stream power W/m
Surface drape kg/m^2	0.90																		
Arable %	0.68	0.67																	
Improved grassland %																			
Unimproved/upland %	-0.59	-0.60	-0.84	-0.37															
Sediment pressure T/yr	-0.46	-0.40	-0.57		0.60														
Sediment yield T/km^2/yr	-0.62	-0.60	-0.69		0.64	0.74													
Catchment area km^2			-0.22		0.31	0.80	0.23												
Altitude m	-0.53	-0.52	-0.70		0.67	0.51	0.69												
Distance to source km	-0.28	-0.23	-0.37		0.44	0.84	0.36	0.93	0.24										
Strahler stream order	-0.34	-0.30	-0.48		0.48	0.77	0.42	0.77	0.34	0.78									
Channel slope m/km	-0.43	-0.45	-0.41		0.32		0.33	-0.47	0.43	-0.37									
MSUB phi	0.76	0.72	0.73		-0.65	-0.56	-0.60	-0.30	-0.58	-0.44	-0.48	-0.37							
Bankfull width m	-0.32	-0.26	-0.40		0.41	0.65	0.35	0.63	0.35	0.65	0.65		-0.50						
Water width m	-0.43	-0.36	-0.58		0.59	0.81	0.48	0.76	0.43	0.78	0.74		-0.59	0.70					
Velocity category	-0.52	-0.45	-0.49		0.45	0.44	0.39	0.28	0.40	0.33	0.32		-0.58	0.35	0.54				
HMS class	0.27	0.26	0.38		-0.30	-0.34	-0.34		-0.28	-0.23	-0.33		0.33		-0.34	-0.17			
Median annual flood m^3/s	-0.54	-0.48	-0.66		0.62	0.90	0.61	0.78	0.48	0.84	0.84		-0.66	0.69	0.86	0.48	-0.39		
Stream power W/m	-0.73	-0.68	-0.79		0.73	0.71	0.71	0.41	0.69	0.52	0.61	0.48	-0.80	0.54	0.68	0.51	-0.43	0.80	
Unit stream power W/m2	-0.69	-0.67	-0.73		0.66	0.52	0.66		0.65	0.31	0.41	0.61	-0.69		0.49	0.42	-0.42	0.61	0.90
Baseflow index	0.43	0.51	0.57	0.31	-0.52	-0.47	-0.55	-0.22	-0.48	-0.35	-0.41		0.49	-0.26	-0.41	-0.24	0.26	-0.56	-0.57

3.5 Hydromorphological controls on substrate composition

The capacity of a stream to transport sediment may be characterised by its hydromorphology. Accordingly, the river typology developed by Orr et al. (2008) was applied. No data were available which indicated floodplain extent so there was no discrimination between some river types. This is not a serious limitation as the focus here is on relatively small streams. Based on stream order, specific stream power and slope, the sampled sites fell into six categories (Table 5). There were no sites in type 3/4 which are small streams with lower stream power but steeper slope and only one site with a stream order of 5.

Table 5 River types based on hydromorphology (following Orr et al., 2008)

River type	River type Orr et al. 2008	Strahler stream order	Unit Stream power Wm^{-2}	Slope %	No. sites
1	1/2	1 and 2	<20	<2.5	30
2	3/4	1 and 2	<20	>2.5	0
3	5/6	1 and 2	>20	<7.5	65
4	7/8	1 and 2	>20	>7.5	2
5	9	3 and 4	<50	-	25
6	10	3 and 4	>50	-	85
7	11	5	-	-	1

Substrate (*MSUB*) varied significantly between hydromorphological river types. Ignoring river types with few sites, type 1 (low stream power and low slope) had significantly finer substrate than other types and type 6 (high stream power) significantly coarser substrate (Tukey HSD test; $p<0.01$). Deposited fine sediment also varied with river type (Figure 6). For the surface drape, there were significant differences (AOV; $p<<0.001$) in sediment mass; type 1 rivers had more fine sediment than types 3, 4, and 6, and type 6 rivers had less fine sediment than types 1, 3 and 5. Neither % volatile solids nor % sand-sized material in the surface drape differed significantly across river types. In the case of the total sediment (surface drape plus depth to approximately 10 cm), both mass of sediment and % sand-sized material showed significant differences between river types but only to the extent that type 1 had higher sediment mass and higher % sand-sized material than types 3 and 6. There was no significant difference in % volatile solids. The pattern of differences in fine sediment across hydromorphological types emphasises both the higher sediment mass found in lower order streams and the importance of unit stream power – specifically, the link between low unit stream power and larger mass of deposited fine sediment.

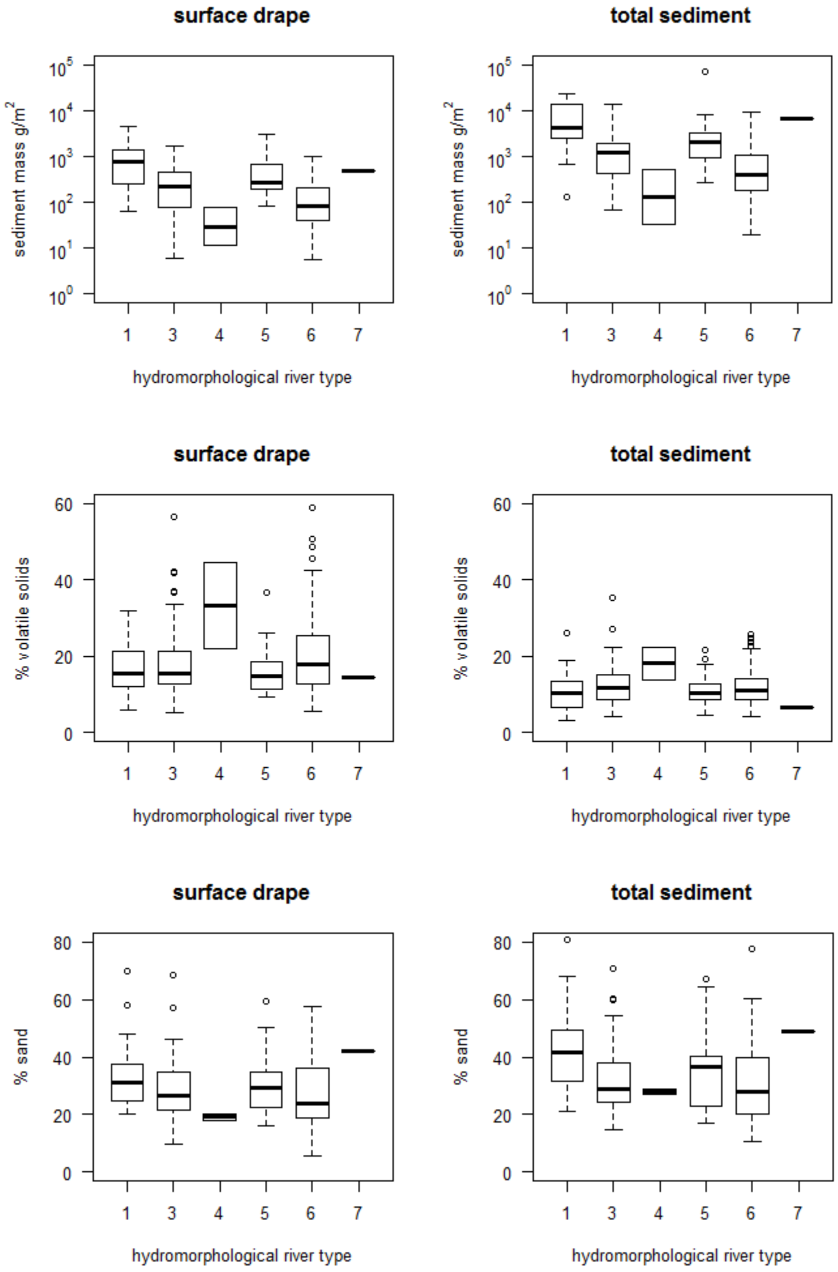

Figure 6 Deposited fine sediment characteristics by hydromorphological river type; see Table 5 for definition of river types following Orr et al. (2008).

3.6 Relationship of deposited fine sediment to modelled sediment pressure

To understand the link between deposited fine sediment and modelled sediment pressure, it was hypothesized that the mass of deposited fine sediment was (i) inversely related to the capacity of the stream to transport fine sediment, (ii) directly related to the amount of sediment delivered to the channel system, (iii) mediated by channel geometry, and (iv) influenced by flow regime, insofar as this describes the balance between potentially depositing and flushing flows, or the potential, in ground-water dominated systems, for fine sediment to be delivered to the channel during times of low flow. The measured sediment mass at any one site may also have been influenced by the time since the last flood event but it was not possible to index this dynamic temporal variation by the available national-scale data considered here. Given the degree of cross-correlation between variables (Table 4), model identification proceeded by selecting, in turn, alternative descriptors of transport capacity with modelled sediment pressure and other potential explanatory variables. The primary sites (Figure 1) were used to derive the models; the supplementary sites (Figure 1) were used for model assessment.

3.6.1 Total sediment

The most effective linear models for describing the reach-averaged total sediment mass are given in Table 6. Each of these models satisfied the diagnostics for constancy of variance and normality of residuals, and each of the retained terms was significant ($p<0.05$). If categorical variables were included, the number of factors has been simplified such that individual parameter values were more than one standard error apart. Based on the Akaike Information Criterion (AIC), the first two models given for total sediment mass were not distinguishable from each other (relative likelihood given by $\exp(AIC_{min}-AIC_i)/2 = 0.64$; Burnham and Anderson, 2002). The third alternative, based on specific stream power, was a poorer fit. Only the regression model based on stream power, calculated using the estimated median annual flood or approximately bankfull flow, included the modelled agricultural sediment pressure. In this model (Figure 7a), total fine bed sediment had a highly significant relationship with stream power ($p<<0.001$) and velocity category ($p<<0.001$). Velocity category was taken as a very broad indication of the relative turbulence intensity of the flowing water, assuming that measurements were taken at roughly similar flow stages (low to medium flows rather than in spate as necessitated by the deployment of the disturbance technique used for sediment sampling). As turbulence intensity controls the ease with which sediment is maintained in suspension, it was expected that higher velocity categories would be associated with smaller amounts of deposited fine sediment as shown here. Only the two lowest categories were distinguishable from the rest of the data. The residual relationship between reach-averaged total sediment mass and modelled agricultural sediment pressure, although positive, was weak (Figure 7b). This may be partly due to the fact that some of the variables used to calculate stream power are also instrumental in the modelling of sediment load. Analysis showed that 15% of the variance in modelled sediment load was not explained by these variables with catchment area contributing some 71% of the total variance in modelled sediment load but only 49% of the total variance in stream power. The predicted versus measured values of total sediment mass (Figure 7c) gives an indication of the overall model fit for the primary sites; residual standard error was considerably higher than the measurement error (Duerdoth et al., 2015).

Table 6 Best-fit linear models for explaining instantaneous data on deposited fine sediment

Regression model	**adjusted R^2**	**Akaike inform^{n} criterion**	**residual standard error**
Average total sediment			
$\log TS = 4.714 - 0.614 \log(\Omega) + 0.128 \log(TL) - 0.456\,(vc=2) - 0.624\,(vc>2)$	0.578	242.0	0.428
$\log TS = 4.379 - 0.473 \log(Q_{MED}) - 0.658 \log(S) - 0.472\,(vc=2) - 0.639\,(vc>2)$	0.580	241.1	0.427
$\log TS = 4.535 - 0.544 \log(\omega) - 0.477\,(vc=2) - 0.734\,(vc>2)$	0.553	253.0	0.441
Average total sediment – erosional zones			
$\log ETS = 4.622 - 0.690 \log(\Omega) + 0.147 \log(TL) - 0.525\,(vc=2) - 0.752\,(vc>2)$	0.617	265.9	0.454
$\log ETS = 4.255 - 0.526 \log(\Omega) - 0.741 \log(S) - 0.543\,(vc=2) - 0.770\,(vc>2)$	0.619	264.8	0.452
$\log ETS = 4.416 - 0.602 \log(\omega) - 0.549\,(vc=2) - 0.878\,(vc>2)$	0.585	281.4	0.472
Average total sediment – depositional zones			
$\log DTS = 4.922 - 0.492 \log(\Omega) - 0.428\,(vc\geq 2)$	0.402	317.1	0.516
$\log DTS = 4.703 - 0.350 \log(Q_{MED}) - 0.551 \log(S) + 0.704 \log(BFI) - 0.477\,(vc\geq 2)$	0.417	313.8	0.510
$\log DTS = 4.751 - 0.404 \log(\omega) + 0.669 \log(BFI) - 0.418\,(vc=2) - 0.602\,(vc>2)$	0.408	317.1	0.514
Average surface sediment			
$\log SS = 3.750 - 0.520 \log(\Omega) + 0.164 \log(TL) + 0.736 \log(BFI) - 0.344\,(vc\geq 2)$	0.500	234.4	0.420
Average surface sediment – erosional zones			
$\log ESS = 3.520 - 0.655 \log(\Omega) + 0.185 \log(TL) - 0.447\,(vc\geq 2)$	0.483	284.3	0.476
$\log ESS = 3.377 - 0.383 \log(Q_{MED}) - 0.641 \log(S) + 0.599 \log(BFI) - 0.484\,(vc\geq 2)$	0.486	284.1	0.474
$\log ESS = 3.353 - 0.533 \log(\omega) - 0.432\,(vc=2) - 0.587\,(vc>2)$	0.453	295.7	0.489
Average surface sediment – depositional zones			
$\log DSS = 3.885 - 0.375 \log(\Omega) + 0.949 \log(BFI)$	0.343	319.8	0.520
$\log DSS = 3.587 - 0.472 \log(\omega) - 0.161\,(vc=3) - 0.376\,(vc>3)$	0.333	324.1	0.524

where TS, ETS and DTS are averaged sediment mass (surface and subsurface to a depth of approximately 10 cm) for total, erosional and depositional zones respectively (g/m^2), SS, ESS and DSS are averaged surface sediment mass for total, erosional and depositional zones respectively (g/m^2), Ω is stream power (W/m), TL is modelled sediment pressure (tonnes/year), vc is velocity category, Q_{MED} is median annual flood (m^3/s), S is channel slope (m/km) and ω is specific stream power (W/m^2).

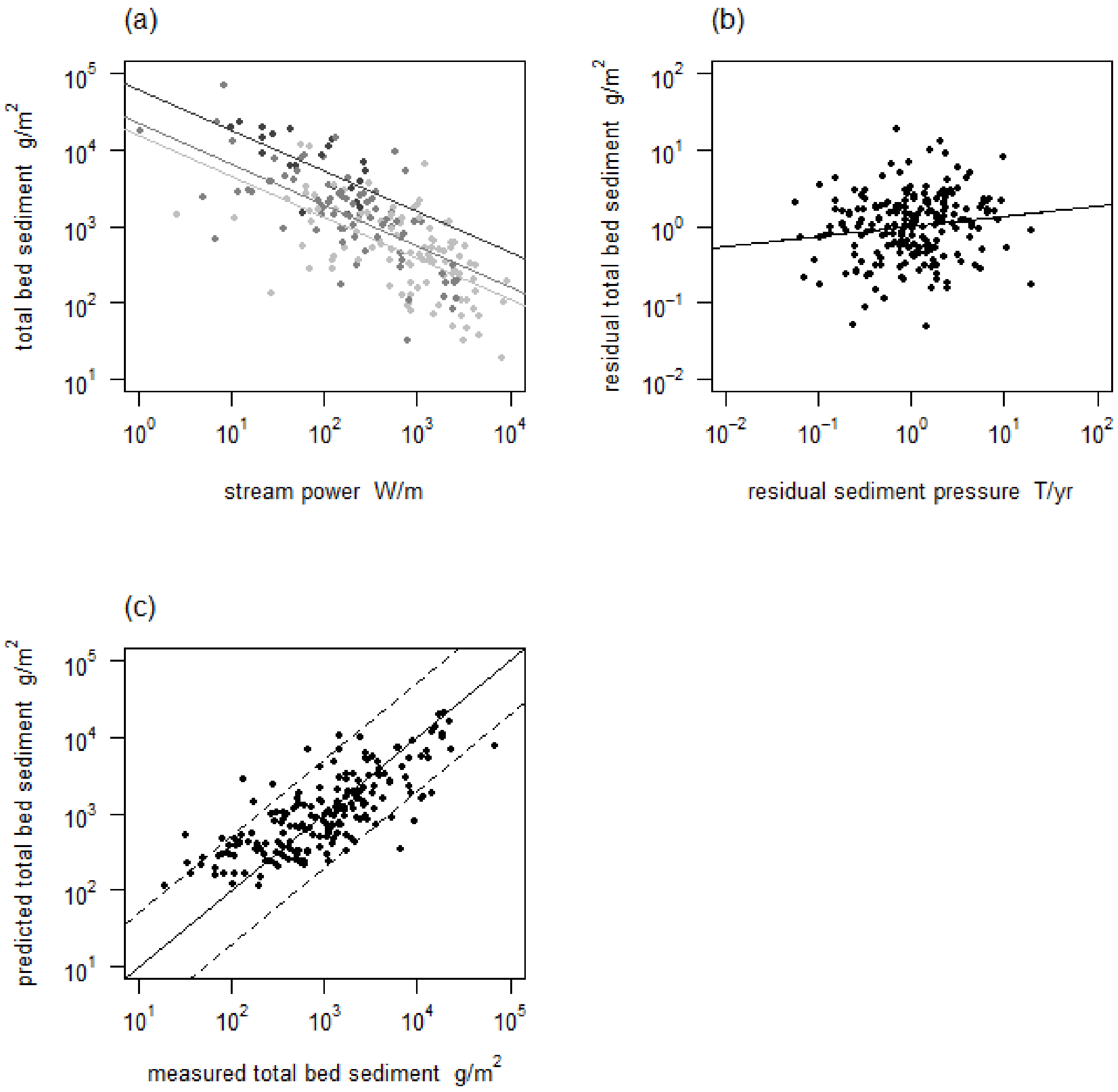

Figure 7 Regression analysis for total fine sediment mass (primary sites): (a) relationship with stream power and velocity category (black: *vc*=1; dark grey: *vc*=2; light grey: *vc*≥3); (b) residual relationship with modelled sediment pressure, predominantly from agriculture; (c) predicted versus measured total fine sediment mass showing 1:1 line and 90% confidence intervals.

A similar analysis was undertaken using the mass of total sediment in erosional and depositional zones of the main channel separately. The relationships for erosional zones were similar to those for the reach average, although they were slightly stronger (Table 6), implying that these zones may be more indicative of modelled sediment pressure. In the case of depositional zones, the fitted models explained much less of the variability in total fine sediment and diagnostics revealed some pattern in the plot of residuals versus fitted values. Modelled sediment pressure was not a significant variable and the baseflow index, included in two of the relationships, was only marginally significant. Using the mass of non-volatile solids or the mass of the non-volatile silt-clay size fraction (assuming equivalence of fraction by volume and by mass) did not improve the relationship with modelled sediment pressure.

3.6.2 Surface drape

For the reach-averaged surface sediment mass, there was only one regression model which satisfied the diagnostics for acceptability and explained some 50% of the variation in the measured fine sediment mass (Table 6). Again, the most effective explanatory variable was stream power, calculated from the estimated median annual flood, (Figure 8a) but four other variables were also significant: velocity category (p=0.0006), baseflow index (p=0.004) and modelled agricultural sediment pressure (p=0.007). Each of these variables added about 2% explanation to the variation in surface fine sediment mass. Only the lowest velocity category was distinguishable from the others; with more fine sediment being associated with the lowest velocity category, as expected. There was a positive relationship with baseflow index as again might be expected; large amounts of fine sediment were associated with a high baseflow index indicative of steady seasonal variation in flow. A high baseflow index is associated with relatively few large flow events which might flush out fine sediment, and there is the potential for sediment delivery, from local impermeable areas or autochthonous production by instream biota, during times of low flow (Sear et al., 2008). There was also a highly significant positive residual relationship with modelled agricultural sediment pressure (Figure 8b). The overall model for the primary sites (Figure 8c) had a residual standard error higher than the measurement error (Duerdoth et al., 2015).

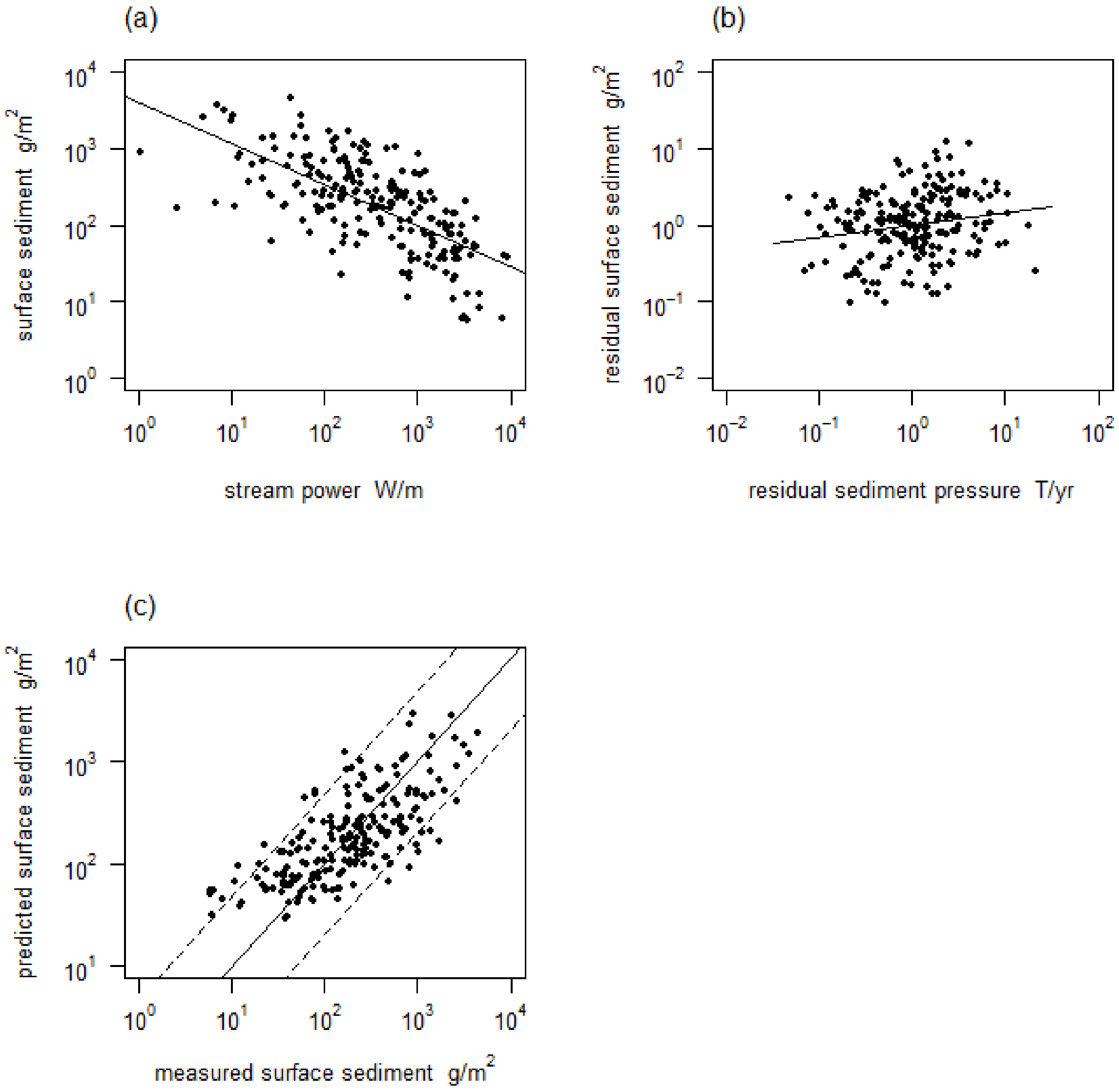

Figure 8 Regression analysis for surface fine sediment mass (primary sites): (a) relationship with stream power; (b) residual relationship with modelled sediment pressure, predominantly from agriculture, taking account of stream power, velocity category and baseflow index (see Table VI); (c) predicted versus measured surface fine sediment mass showing 1:1 line and 90% confidence intervals.

Separate analyses for erosional and depositional zones were less strong than the reach-averaged values for the surface drape (Table 6). The relationship with the baseflow index was less clear and, in depositional areas, the surface sediment mass showed no significant relationship with modelled sediment pressure. Again, the relationships were not improved by using the mass of non-volatile solids or the mass of the non-volatile silt-clay fraction.

3.6.3 Independent model assessment

The dataset relating to the supplementary sites (Figure 1) was used as an independent assessment of the fitted model for the reach-averaged deposited fine sediment. The total sediment mass showed a somewhat wider scatter of values compared with the original dataset (Figure 9a). In particular, several of the autumn measurements fell outside the 90% confidence band, with the model overestimating the amount of deposited fine sediment. Most of the spring measurements fell within the 90% confidence band but here there was a tendency for the model to underestimate the measured values. By contrast, the reach-averaged surface sediment mass showed a similar spread of values compared with the original dataset (Figure 9b). However, there were a few outliers where the model seriously underestimated very high values of measured deposited sediment. These were equally present in the autumn and spring samples. For the supplementary sites, the relationship between measured deposited fine sediment mass and stream power showed a similar fit to that of the primary sites for both the surface and total sediment, with little or no discrimination between seasons (Figure 9c, 9d).

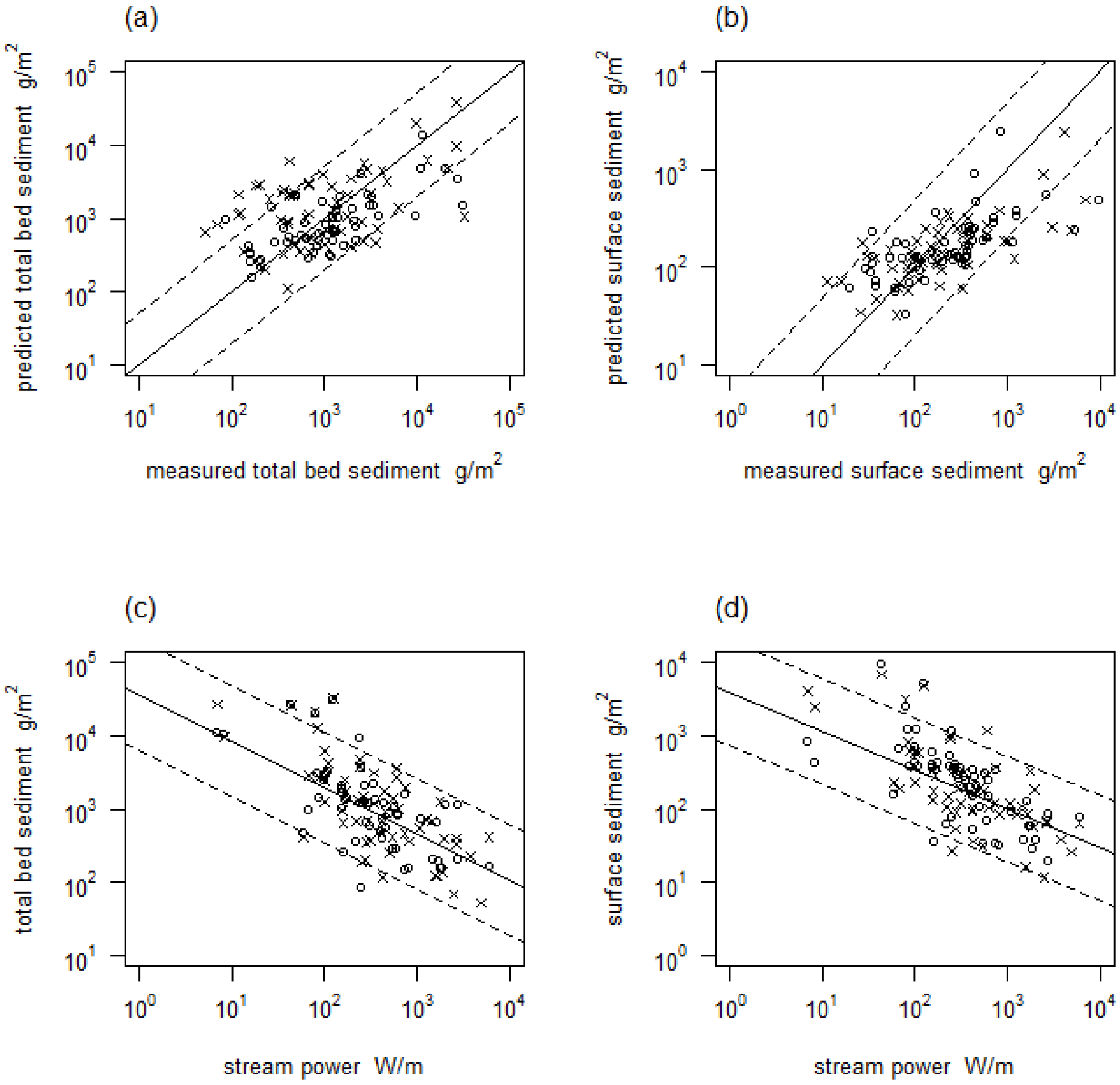

Figure 9 Assessment of regression relationships using independent dataset from supplementary sites (measurements taken in autumn × and spring ○): (a) measured and predicted reach-averaged total bed sediment; (b) measured and predicted reach-averaged surface sediment; (c) relationship between total bed sediment and stream power; (d) relationship between surface sediment and stream power. In all cases, relationship from analysis of primary dataset with 90% prediction intervals is shown.

4. Discussion

The data presented in this paper provide improved spatial coverage in the quantification of instantaneous fine sediment storage within streams across England and Wales and offer a unique baseline snapshot of substrate condition for assessment of future change at the sampled sites. Previously published data for the UK has mostly focused on large rivers with moorland headwaters (Owens et al., 1999; Walling et al., 1998) and lowland groundwater-dominated rivers (Collins and Walling, 2007b,c), albeit that these more spatially constrained datasets provide better temporal coverage (typically two years of monthly or every other month sampling).

The data presented also extend the characterisation of deposited fine sediment by including both non-volatile solids and measures of absolute particle size. The percentage of volatile solids is an important measure for linking to biota as this relates to availability of nutrients through decomposition and a food source for aquatic organisms. Critically, decomposition of organic matter can lead to reduced interstitial oxygen concentration, a key stressor on aquatic organisms (Jones et al., 2012a; Jones et al., 2012b; Sear et al., 2014), and crucially important for nutrient transformation pathways and the production of ammonia (e.g. Pretty et al., 2006; Trimmer et al., 2009). The organic component of deposited fine sediment is a critical, yet with notable exceptions (e.g. Marttila and Kløve, 2014; 2015) often overlooked, determinant of biological response to fine sediment pressure (Collins et al., 2009c; Murphy et al., 2015). Indeed, Von Bertrab et al. (2013) go further to suggest that the chemical composition of deposited sediment is more important to benthic macroinvertebrate assemblages than the amount of sediment. The percentage organic matter and associated sediment oxygen demand are also recognised as important parameters for fish egg survival (Olsson and Pearson, 1988; Greig et al., 2005; Greig et al., 2007; Sear et al., 2014; Sear et al., 2016).

Data on the absolute particle size of fines (<1 mm) indicate that, although the silt/clay size fraction was most associated with agricultural runoff, there was a large variation in the percentage sand-sized particles present. This is an interesting finding in the context of the clogging of gravel substrates. Sand can more easily bridge pore spaces within gravels such that finer and, critically, organic material is more easily trapped (Warren et al., 2009), thus reducing flow through the gravel and the exchange of oxygen-rich waters. For river management, it is therefore important to understand the source of the sand-sized material and its transport regime (Collins et al., 2009c), in addition to the more usual source apportionment of the finer size fractions (e.g. Walling et al., 2003b; Collins et al., 2012c,d). The relatively large amounts of sand-sized particles are consistent with previously published findings (Milan et al., 2000; Julien and Bergeron, 2006). Intuitively, on the basis of limited transport distances, eroding channel banks may be a key contributor to the sand-sized particles, thus, driving important process linkages in the river substrate that impact on aquatic ecology.

4.1 Relationship with land cover

A number of studies have found strong positive relationships between deposited fine sediment and percentage of land use under agriculture in small to medium catchments (Table 7). However, those studies which have reported a high correlation between fine sediment and land use are generally those where sites range from near-pristine to highly impacted, where sediment pressure from agriculture is high, e.g. potato production (Sutherland et al., 2010) or intensive pasture (Niyogi et al., 2007), and where the range of geomorphological variation is relatively small. In our study, while there is a significant relationship between deposited fine sediment and % arable and horticultural land, the latter is highly correlated with other catchment descriptors and negatively correlated with modelled sediment pressure, suggesting a more complex linkage to deposited fine sediment. Indeed, both Anlauf and Moffitt (2010) and Sutherland et al. (2010) report that variation in fines was almost equally explained by *either* percentage agriculture *or* stream slope. Hence, it is important to develop a more process-based understanding of what controls the amount of deposited fine sediment sequestered in stream beds.

4.2 Dominant drivers and relationship to modelled sediment pressure

In our study, the most effective explanatory variable for the amount of deposited fine sediment was found to be stream power, calculated from the estimated median annual flood or approximately bankfull flow. This is a measure of the ability of a stream to transport sediment, but it is also correlated with many other factors. Other variables which had a statistically significant, but small, contribution were stream velocity category, modelled agricultural sediment pressure and, in the case of channel bed surface deposition, flow regime indexed by BFI. The identified model structure (Table 6) accorded with expectations and explained 50-60% of the variation in the measured deposited fine sediment.

Table 7 Published relationships between deposited fine sediment and land use

Source	Measure of fine sediment	Measure of land use	R^2 (%)	No. sites	Location
Walser and Bart (1999)	sediment index based on fine sediment depth	% agricultural land	43	14	Chattahoochee River Georgia, USA
Niyogi et al. (2007)	mass of suspendable inorganic sediment (depth 5cm)	% pasture land	59	21	Otago Province New Zealand
Sutherland et al. (2010)	% fines <2mm by mass from shovel cores	% land under potato production	67	15	New Brunswick Canada
Anlauf and Moffitt (2010)	% bed area classed as fines <2mm	% agricultural land	75	56	Salmon River Idaho, USA
Wagenhoff et al. (2011)	mass of suspendable inorganic sediment (depth 5cm)	% catchment runoff from pasture	27	43	Southland Province New Zealand
This study	mass of total suspendable sediment (depth *ca.* 10cm)	% arable and horticultural land	31	163[#]	England and Wales

[#] excludes catchments with no arable land cover.

Other studies have also consistently identified stream slope (a contributor to stream power) to be a dominant geomorphic factor (Walters et al., 2003; Anlauf and Moffitt, 2010; Sutherland et al., 2010; Relyea et al., 2012). Anlauf and Moffitt (2010) also found slow water habitat to be a significant predictor of deposited fine sediment alongside the percentage of agricultural land in the catchment. Stream order has also previously been identified as an important contributory factor, which suggests a need to understand how the balance between sediment supply and transport capacity changes downstream. For example, Relyea et al. (2012) reported that first order streams had more fine sediment than all other Strahler orders, and that 4th and 5th order streams had less fine sediment that lower orders. Similarly, Wagenhoff et al. (2011) found positive relationships between suspendable inorganic sediment (SIS) and % catchment runoff from pasture, an indication of sediment delivery, for all stream orders except the lowest in their study (third order). A similar tendency was seen in our data, suggesting that it is the lower order streams which are more likely to be impacted by deposited fine sediment; perhaps partly as a result of the strong coupling between low-order streams and their catchment.

The spatial scale of any analysis is fundamental to understanding the controls on fine sediment deposition, as is due recognition of the co-variation within the dataset. Despite sampling agricultural streams across a gradient of modelled sediment pressure, this was not found to be a key driver of deposited fine sediment. One reason for this was the substantial variation in catchment hydrogeomorphology across the sites. This is a driver of *both* sediment pressure and in-stream transport, as indexed by stream power at approximately bankfull flow. Sites with high modelled agricultural sediment pressure also had high stream power and relatively small amounts of deposition, implying that these streams could carry much of the delivered sediment. Sites with low modelled sediment pressure had low stream power and large amounts of deposited fine sediment, implying that these streams were limited in their transport capacity with respect to even relatively low sediment pressure. Clearly these linkages need to be interpreted in the context of stream power being a function of other physical factors (e.g. slope), correlated with other variables including land use, and the longer-term temporal basis of the modelled agricultural sediment pressure. Despite these limitations, the findings have important implications with respect to setting sediment load targets to avoid excessive deposition as it suggests that, at least for small catchments, such targets should be dependent on the transport capacity of the receiving channel. The approach to target-setting based on measured in-stream sediment loads developed by Cooper et al. (2008) partly takes this into account by default. As a result, Cooper et al. proposed a much more stringent target for chalk streams than other river types. However, Cooper et al.'s empirical approach cannot distinguish those streams with low sediment load due to limited sediment supply from those with a low transport capacity. Thus, it is clear that target-setting for sediment loads demands a much more robust approach taking into account sediment delivery, transport capacity, bed mobility and biological sensitivity (Sear et al., 2008; Collins et al., 2011; Bilotta et al., 2012).

4.3 Another potential explanation

Another aspect of the relationship between deposited fine sediment and modelled agricultural sediment pressure can be explored by considering the capacity of the substrate to sequester fine sediment. It is clear that different substrates can accommodate different amounts of fines dependent on their pore space and ease of ingress. Wooster et al. (2008) defined the saturated fine sediment fraction (FSF) as a function of the geometric standard deviation of the grain size of both the substrate framework and the fine sediment matrix, and their relative grain sizes. A rough conversion of the saturated FSF into mass of fine sediment per unit area can be achieved using our measurement depth of approximately 10 cm and an assumed particle density of fine sediment. For the purposes of this argument, a particle density of 2485 kg/m^3 has been assumed. For the coarser range of mean substratum size (2 to 256 mm i.e. coarse sand to cobbles), the calculated mass of fine sediment at saturation varied between about 100 and 1000 g/m^2 (Figure 10a) dependent on the assumed grain size of the fines and the uniformity of the substrate. Assuming that the fine material is silt-sized (0.063 mm) and that the substrate is highly non-uniform (geometric standard deviation 4), the shading in Figure 10a indicates the substrate which was most likely to be below saturation.

By comparing this with the measured total sediment mass for a given mean substratum size (Figure 10b), it appeared highly likely that the majority of the sampled sites were saturated with fines. This may help to explain the weak relationship with modelled sediment pressure, although other potential factors may be at play here, including the much longer temporal basis of the modelled sediment pressure. Based on the analysis above, there were 42 sites with a mean substratum size coarser than -3 phi units (i.e. >8 mm) and measured total fine sediment mass less than 300 g/m^2 which were unlikely to be saturated with fines. The scatterplot of measured total fine sediment mass and modelled sediment pressure for these sites had a wedge-shaped distribution (Figure 10c). The upper limit of deposited fines clearly increased with the modelled sediment pressure. Below the upper limit, smaller amounts of deposited sediment were then perhaps a reflection of the temporal dynamics of the siltation process, such as the sequence of recent flow events leading to disturbance or washout of fines and the local rate of siltation coupled with the elapsed time since disturbance. Thus, this subset of sites appeared not only to be unsaturated with respect to deposited fines but also supply-limited; the dominant driver for the envelope curve was modelled sediment pressure, predominantly from agriculture, and there was no relationship between deposited fine sediment and stream power (Figure 10d).

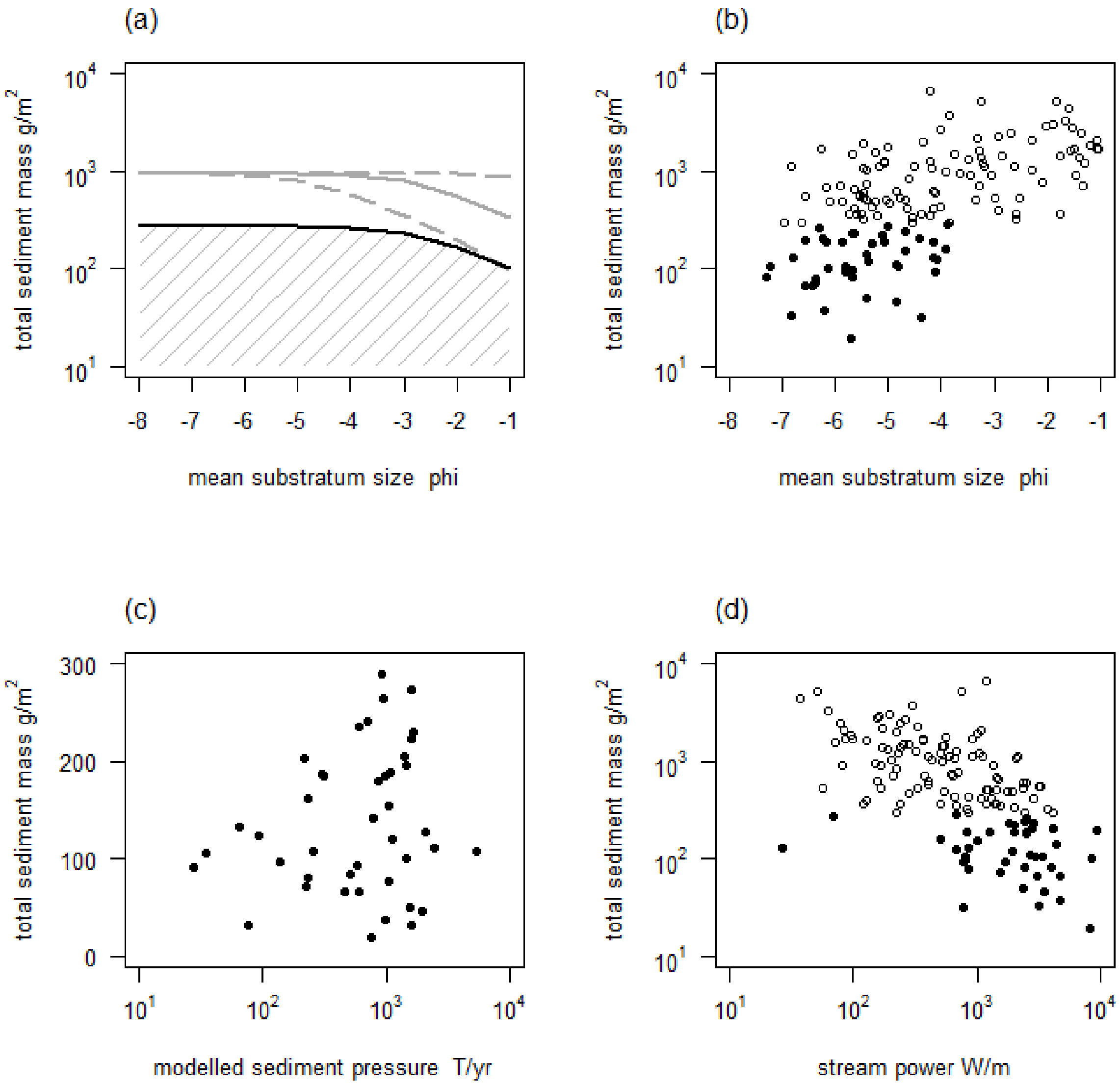

Figure 10 Analysis of unsaturated substrate for sites with *MSUB* ≤ -1: (a) calculated saturation following Wooster et al. (2008): grey shows uniform substrate with silt-sized fines (solid line) and with maximum and minimum measured D_{50} of fines (dashed lines); solid black line shows saturation level for silt in highly non-uniform substrate, shading below this identifies most likely unsaturated substrate; (b) measured total sediment mass versus mean substratum size with solid circles indicating those likely to be unsaturated; (c) measured total sediment mass against modelled sediment pressure for sites likely to be unsaturated by fines; (d) measured total sediment mass versus stream power with solid circles indicating those likely to be unsaturated.

The hypothesis that the majority of the sampled sites may be saturated with deposited fines requires further work – particularly with respect to field testing and proper evaluation of the parameters required in the model proposed by Wooster et al. (2008). However, the possibility of splitting sites into saturated and unsaturated substrates does provide a useful new perspective for understanding the controls on deposited fine sediment in agricultural streams. It was only in unsaturated sites that modelled sediment pressure, predominantly from agriculture, seemed to dictate the amount of deposited fine sediment. This has important implications with respect to the implementation of agricultural mitigation measures to reduce sediment pressure in that, if most agricultural streams are saturated with fines, then simply reducing sediment delivery may have little immediate impact on deposited stream sediment. Additional river management may be needed to mobilise or extract the existing fines, especially in cases where bed material is not naturally mobilised during bankfull or larger events.

Traditionally chalk stream management has included regular gravel cleaning (Shackle et al., 1999) and there have been a number of recent studies which have explored the effectiveness of substrate restoration by either cleaning or addition of clean gravels (Merz and Setka, 2004; Meyer at al., 2008; Geist and Sternecker, 2013; Pulg et al., 2013). In these studies, improvements to physical habitat, in terms of both fine sediment content and compaction of the substrate; hyporheic water quality, including increased oxygen supply and reduced concentrations of nitrite and ammonium; and biota have all been reported. However, the length of time over which improvement in habitat was maintained varied from 5 months to 5 years. Presumably, this is a function of fine sediment delivery and reinforces the need to implement mitigation measures to reduce sediment pressure in tandem with river channel management (Greig et al., 2005). Another important consideration is the potential for negative impacts in downstream sites; for example, Geist and Sternecker (2013) reported significantly increased sediment deposition for 1 km downstream of a restored site. An understanding of the controls on siltation and how these change downstream is, therefore, vital to effective holistic management of river systems.

5. Conclusion

Deposited fine sediment was characterised in 230 streams, representative of different biological stream types, across a gradient of modelled agricultural sediment pressure, thus providing a systematic survey of deposited fine sediment across England and Wales. The data offer a unique snapshot of substrate condition, across a wider range of river types than hitherto reported, for the assessment of biotic impact and future change.

Deposited fine sediment was found to be predominantly related to stream power, calculated from the estimated median annual flood, rather than modelled sediment pressure, which, for the measured sites, is largely from agriculture. These results are consistent with previously published studies in so far as they relate to small streams of low Strahler stream order which are impacted by agriculture and have a high variation in their hydrogeomorphology – a driver of *both* sediment pressure and in-stream transport. Thus, it is suggested that the majority of the sites were essentially transport-limited and, an analysis in terms of substrate capacity to hold fine sediment, implied that most of the sites were saturated with respect to fine sediment. Below the level of saturation, there was some indication of a positive relationship between the maximum amount of deposited fine sediment and modelled sediment pressure which provided an upper envelope for those sites which may be considered to be supply-limited. Further work is needed to develop and test this idea in the field.

There are two important implications of these findings:

- future proposed targets for sediment loads need to take into account channel hydromorphology – specifically, the ability of streams to transport/retain fine sediment;
- river management to mobilise/remove fines from the bed should be considered in conjunction with mitigation measures for reducing delivery of fine sediments for those streams identified as being already saturated with fines and unlikely to self-cleanse. In this case, due care will need to be exercised with respect to potential downstream impacts.

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