

Spatial and temporal variations in the erosion threshold of fine riverbed sediments

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Abstract

Purpose Lowland chalk streams in the UK are experiencing increased deposition of fine sediment due to changes in land-use practices, channel modifications, and groundwater abstraction. The excessive fine sediment deposits have been linked to benthic habitat degradation, the obstruction of surface–groundwater flow, and the storage of contaminants, such as nutrients and pesticides. While research has been conducted on the provenance, transport, deposition, and storage of fine sediment in chalk streams, none has expressly investigated the erosion of fine sediment deposits.

Materials and methods A year-long field survey was conducted in two reaches of the Frome-Piddle catchment (Dorset, UK) to quantify spatial and temporal variations in the erosion thresholds of surficial fine sediment deposits. Erosion thresholds were measured at randomly located points within areas of sediment accumulation using a cohesive strength meter (CSM). The threshold measurements were paired with sediment cores for analysis of the physical, chemical, and biological properties of the sediment. Spatial and temporal patterns in the erosion thresholds of fine sediment were analyzed using nonparametric statistical tests and visualized with GIS. The sediment properties underlying the

variations in erosion thresholds were examined through correlation and linear regression analyses.

Results and discussion Erosion thresholds varied significantly over space and time within the stream reaches. Erosion thresholds were greater for fine sediment deposits found in the center of the channel than in the margins. Thresholds were highest in September 2008 and declined substantially to a minimum in May 2009, with a small peak in March 2009, indicating an annual cycle in erosion thresholds. Effective particle size was identified statistically as the most important sediment property influencing erosion thresholds and was probably underlying much of the spatial variation within the reaches. None of the measured sediment properties adequately characterized the temporal variation in erosion thresholds, however, the results suggest that biological sediment properties and water geochemistry (i.e., cation content) may play a role.

Conclusions By identifying significant spatial and temporal variations in erosion thresholds, this study provides valuable information on the stability of fine sediment deposits, and sediment-bound contaminants, in lowland river systems. This is a crucial step in assessing their local environmental impacts and developing models of fine sediment transport for the effective management of catchment sediment budgets and water resources.

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1 Introduction

Fine sediment is an essential component of riverine systems, and plays a crucial role in many geomorphological and ecological processes. However, society has altered the quantity,

transport dynamics, and quality of fine sediment in many aquatic environments, requiring us to monitor and manage sediment for environmental, human health, and engineering reasons (European Parliament 2002; Owens et al. 2005). To accurately predict the transport dynamics of fine sediment, though, we need to better understand how and why a key parameter in sediment transport models, erosion threshold, varies in riverine systems (Grabowski et al. 2011).

1.1 Sediment erosion thresholds

The stability of fine sediment deposits within river channels is determined by a balance between erosive and resistive forces. The principal erosive forces are shear stress and turbulence imparted onto the sediment surface by flowing water, as well as solid transmitted stress from particles moving along the bed (Amos et al. 2004; Winterwerp and Van Kesteren 2004). These are countered by the forces within the sediment that resist erosion, which include gravity, friction, cohesion and adhesion. Erodibility is a measure of the resistive forces, and is most commonly represented as an erosion threshold or erosion rate (Sanford 2008).

The erosion threshold of sediment is defined as the force required to initiate surface erosion. Although it is typically expressed in terms of water velocity or shear stress, it is actually an attribute of the sediment itself. Erosion thresholds are dictated by the characteristics of the surficial layer of the sediment. A broad range of sediment properties are known to influence erosion thresholds, including particle size distribution, bulk density, water content, water geochemistry, organic content, and extracellular polymeric substances (EPS) produced by sediment inhabitants, such as bacteria and diatoms (for a review, see Grabowski et al. 2011). These properties can vary over space and time to produce significant variations in erosion thresholds (Paterson and Black 2000; Hanson and Simon 2001; Friend et al. 2003, 2005; Bale et al. 2006; Tolhurst et al. 2006a)

While the hydrodynamics related to fine sediment transport in rivers have been well-studied and modeled (e.g., Naden et al. 2006), there is a paucity of empirical data on the erodibility of fine sediment in riverine systems (Hanson and Simon 2001; McNeil and Lick 2004; Gerbersdorf et al. 2005, 2007, 2008). This is compounded by an inability to accurately predict erosion thresholds from first principles due to the large number of sediment properties that interact to determine erodibility (Black et al. 2002). Consequently, field investigations are essential to understanding how and why erosion thresholds vary in nature, and to develop accurate models of fine sediment transport dynamics.

1.2 Fine sediment in lowland rivers

Lowland rivers have experienced increased fluxes of fine sediment worldwide (Owens et al. 2005). This increase is

caused by soil erosion induced by human activity, such as agriculture, mining, and deforestation. Evidence has shown that this excess of fine sediment can impact the geomorphology, hydrology and ecology of the rivers due to higher turbidity levels and increased sedimentation.

In the UK, the impact of fine sediment on lowland, groundwater-dominated rivers has been a particular concern. Chalk rivers are characterized by their crystal clear waters and clean gravel beds, which support diverse aquatic communities and productive fisheries. They have low stream powers due to their relatively constant discharges and high width/depth ratios. Consequently, chalk streams are dependent on low sediment loads, but because of their low stream power are less able to transport fine sediment or erode it once it deposits on the channel bed.

Fine sediment deposition has increased over recent decades in lowland chalk rivers. This change has been attributed to shifts in land-use practices, specifically an increase in tilled agriculture and more intensive grazing (Walling and Amos 1999; Collins and Walling 2007a), and reduced base-flows due to water extraction (Bickerton et al. 1993). The fine sediment, defined as material finer than the gravel bed (<2 mm) (Wood and Armitage 1997; Heppell et al. 2009), ingresses into the bed and also forms substantial surficial deposits. These sediment deposits negatively impact the hydrology and ecology of rivers by obstructing hyporheic flow (Boulton et al. 1998; Packman and Salehin 2003), altering interstitial communities and nutrient processing (Hancock 2002; Pretty et al. 2006), choking salmonid nesting grounds (Acornley and Sear 1999), and storing sediment-bound contaminants, such as heavy metals, pesticides, nutrients, and pathogenic bacteria (Bowes et al. 2005; Luoma and Rainbow 2008; Droppo et al. 2009). Consequently, assessments of the stability of the fine sediment deposits are essential to the holistic management of lowland rivers, including restoration efforts to improve ecosystem health and ecological status.

Substantial quantities of fine sediment are deposited and stored within UK chalk river channels. Colmation (fine sediment ingress into the gravel bed), accounts for a significant amount of fine sediment storage: 0.92 kg m⁻² for the River Frome, 1.29 kg m⁻² for the River Lambourn, and 1.59 kg m⁻² for the River Piddle (Collins and Walling 2007a, b). These represent 19–57 % of the annual fine sediment loads of the rivers. Surficial deposits constitute even greater stores of fine sediment, particularly along channel margins and within aquatic macrophyte stands (Clarke 2002; Cotton et al. 2006; Gurnell et al. 2006). Estimates of fine sediment storage within surficial deposits range between 11.6 and 66.8 kg m⁻² for the Bere Stream and between 0.9 and 23.5 kg m⁻² in the River Frome (Heppell et al. 2009). Furthermore, evidence that these deposits persist longer than a year suggests that they may have longer-term

ecological and hydrological impacts on the streams (Heppell et al. 2009), although to date no study has quantified the stability of the sediment deposits.

1.3 Study aim

The aim of this study was to improve our understanding of fine sediment transport dynamics in lowland river systems. This study reports on a year-long field survey that investigated how erosion thresholds for fine riverbed sediments varied spatially and temporally within chalk river reaches, and the key sediment properties responsible for the variations.

2 Materials and methods

2.1 Study location

A year-long field investigation of fine sediment erodibility was conducted in two stream reaches within the Frome-Piddle catchment (Dorset, UK); the Bere Stream (UK Grid Reference 385563, 93009) and the River Frome (UK Grid Reference 359790, 97390). The Frome-Piddle catchment has been the focus of several recent studies on sediment dynamics due to concerns about the sources and impacts of fine sediment on the chalk stream ecosystems (Walling and Amos 1999; Cotton et al. 2006; Wharton et al. 2006; Collins and Walling 2007a; Heppell et al. 2009).

The study reaches were single thread and relatively straight in planform (30 m long \times 7–9 m wide). They were largely unshaded by riparian trees, permitting the growth of in-stream macrophytes. The dominant in-channel aquatic macrophyte in both streams was *Ranunculus penicillatus* subsp. *pseudofluitans* (water crowfoot), a submerged macrophyte that forms discreet patches in the higher flow sections of the reaches. *Nasturtium officinale* (watercress), an emergent macrophyte found primarily along stream margins, was seasonally abundant in the Bere Stream (Wharton et al. 2006). The bed is composed of flinty gravels, with fine sediment (silt and sand) accumulating along the margins, within macrophyte beds, and within unvegetated areas in the center of the channel at times of low flow (Heppell et al. 2009).

2.2 Field sampling design

Bimonthly site visits were conducted from September 2008 to July 2009. During each visit, a survey was conducted to map fine sediment accumulation, macrophyte distribution and hydrodynamic conditions. Transects were laid across the stream channel, at 1-m intervals, and point estimates were taken of water depth, surficial fine sediment depth (where present), macrophyte presence and species, and

water velocity at 60 % depth (Valeport Model 801 flat flow meter), at 0.5 m intervals.

The survey served two functions: (1) it provided important environmental information on the reach and (2) it was used to create a stratified random sampling design for the measurement of fine sediment erodibility. The measurement locations from the initial survey were stratified based on the depth of fine sediment accumulation using a threshold of 5 cm, which was the minimum depth of sediment required for the extraction of an intact core with an undisturbed sediment surface. Sampling locations for erodibility measurements were chosen randomly from the >5-cm deep fine sediment strata ($n=20$), and sorted so that sampling progressed in the upstream direction to minimize disturbance during the sampling process.

2.3 Measurement of sediment erosion threshold

Erosion thresholds were quantified using a cohesive strength meter (CSM; MK4, Partrac), which is a portable jet test device that has been used extensively in estuarine environments (Yallop et al. 1994; Paterson 1989; Defew et al. 2002; Friend et al. 2005; Tolhurst et al. 2003, 2006b). The CSM fires a jet of water at the sediment surface within a test chamber, and incrementally increases jet pressure until the erosion threshold is reached, identified by the occurrence of sediment resuspension using a transmissometer. Water depths in the stream exceeded the manufacturer's guidelines, so the CSM could not be used in situ. Therefore, sediment cores were taken by hand using an acrylic core tube (Φ 6.6 cm I.D.), ensuring an undisturbed sediment surface and a consistent depth of overlying water, and erodibility was measured within the sediment core tubes. Preliminary trials indicated that the Sand 1 setting on the CSM produced the most precise estimates of erodibility for the riverine sediment, so it was used for the entire field survey. The setting has a low starting pressure (0.3 PSI), short jet pulse duration (0.3 s), and small pressure steps (0.3 PSI). The erosion threshold was defined, as is common for the device, as the pressure at which average transmission within the test chamber drops below 90 % of the maximum. Erosion thresholds are reported as critical stagnation pressure (P_{stag}), which is the pressure of the impinging jet at the sediment surface (Vardy et al. 2007). P_{stag} was calculated based on P_1 for the specific CSM unit following the methods of Vardy et al. (2007) ($n=3$). P_{stag} is reported in SI units for pressure (Pa) and for the MK4 CSM model is calculated according to the following equation,

$$P_{\text{stag}} = 3.71(6.89P_1)^{1.37} \quad \left(R_{\text{adj}}^2 = 0.94, P < 0.001\right) \quad (1)$$

for P_1 up to 4.8 PSI, for CSM measurements from September 2008 to May 2009. In July 2009, a different CSM MK 4 unit

was used, while the usual unit was being serviced, and the calibration was:

$$P_{\text{stag}} = 1.23(6.89P_1)^{1.78} \quad (R_{\text{adj}}^2 = 0.93, P < 0.001) \quad (2)$$

for P_1 up to 4.8 PSI. The calculation of P_{stag} allows erosion thresholds to be compared between CSM models and individual units. Until recently, CSM-derived erosion thresholds were relative because a calibration had not been successfully developed to convert the vertical forces generated by the CSM to horizontal shear stress (Vardy et al. 2007; Widdows et al. 2007). However, Grabowski et al. (2010) have recently proposed an empirical calibration between P_{stag} and critical shear stress based on a comparison of erosion thresholds measured using the CSM and a laboratory flume,

$$\tau_c = 0.0013P_{\text{stag}} + 0.047 \quad (3)$$

(For 40 Pa < P_{stag} < 90 Pa) ($R_{\text{adj}}^2 = 0.87, P < 0.01$)

which allows CSM-derived erosion thresholds to be compared with hydrodynamic conditions to assess the stability of the surficial fine sediment deposits. Erosion thresholds are presented principally as P_{stag} because the observed range in P_{stag} was wider than the empirical calibration, but critical shear stress is included on figures to facilitate comparison.

2.4 Analysis of sediment properties

The sediment cores used to measure erosion threshold were extruded in the field, and the top 3-cm layer retained for laboratory analyses. The sediment was stored at 4°C for a maximum of 12 h before processing and analysis. The following physical, chemical and biological properties were quantified for the sediment samples: effective and absolute particle size; bulk density; water content; cation concentrations; organic content; water-soluble carbohydrate fraction of EPS; and chlorophyll *a*. Effective particle size was measured using fresh sediment, and all other properties were quantified using freeze-dried (lyophilized) sediment.

Particle size was measured using a Beckman Coulter LS 13 320 Laser Diffraction Particle Size analyzer. Effective particle size is the diameter of natural sediment aggregates, which includes inorganic and organic components. Absolute particle size is the diameter of the inorganic mineral grains, quantified following treatment of the sediment with hydrogen peroxide (30 %) to remove organics and with hexametaphosphate to disperse particles (Cotton et al. 2006). Particle size is reported as a median particle size (d_{50}) and is based on sediment volume. Dry bulk density and water content were measured gravimetrically, based on the loss of

water due to freeze-drying. Particle size distribution and water content data were used to calculate the bed solids volume fraction, mud volume fraction, and sand volume fraction according to Sanford (2008), as they have been shown to be significantly correlated with erosion threshold in recent studies (e.g., Dickhudt et al. 2011). These properties were included in all analyses, but are not presented in the results section because they were not identified as significant in this study. A measure similar to mud volume fraction, mud density, was calculated as the dry mass of fine sediment (<63 μm) divided by the volume of fines and water. Cation content has a significant impact on soil erodibility, and its possible role in governing sediment erodibility was recently highlighted by Grabowski et al. (2011). Cations (Na^+ , Ca^{2+} , and Mg^{2+}) were extracted using a weak acid digest (Tipping et al. 2003), and measured with an Inductive coupled plasma—OES (ICP-OES) using matrix-matched multi-element standard. To correct for the strong correlation between grain size and cation content, a granulometric normalization was applied, in which cation contents were divided by the absolute mud content (<63 μm) for the sample (Loring 1991; Luoma and Rainbow 2008). Cations are reported as content (in micrograms per gram sediment) and as the ratio of monovalent to divalent cations ($\text{Na}^+ / (\text{Mg}^{2+} + \text{Ca}^{2+})$). Organic matter content was measured using loss-on-ignition (550°C for 4 h) (Cotton et al. 2006; Heppell et al. 2009). EPS are produced by diatoms and bacteria living in the sediment and have been shown to have a significant impact on sediment erosion thresholds (Widdows et al. 2006; Droppo et al. 2007; Gerbersdorf et al. 2007). The water-soluble carbohydrate fraction of EPS (i.e., colloidal carbohydrates) was quantified using a phenol/sulfuric acid assay and spectrophotometry (485 nm wavelength), and reported as content (in micrograms per sediment) (Underwood et al. 1995). Chlorophyll *a* content is a measure of the photoautotrophic community in the sediment and has been shown to correlate with sediment erodibility (Tolhurst et al. 2003; Gerbersdorf et al. 2008). Chlorophyll *a* was extracted using acetone, and quantified using a spectrophotometer and the Lorenzen Pheopigment correction (US EPA Method 46; USEPA 1997).

2.5 Data processing and analysis

As CSM erosion thresholds are estimated based on sediment resuspension, the sediment must have a minimum mud content (<63 μm) so that erosion is equivalent to resuspension (Grabowski et al. 2010). For the fine riverbed sediment, laboratory trials indicated a minimum mud content of 10 % (v/v ; for more information, see Grabowski et al. 2010). Particle size analyses were conducted for all sediment samples collected during the survey, and samples with less than 10 % mud content were excluded from the analysis. A total of 185 samples were included in the analysis; 98 from the Bere Stream and 87 from the River Frome. Null erosion

threshold values, in which the sediment was too weak to be measured by the CSM, were included in the analysis, but were corrected to half the minimum erosion threshold measured by the CSM.

Statistical analyses were conducted using the software R, and included non-parametric statistical tests to examine spatial and temporal differences in erodibility (Kruskal–Wallis and Mann–Whitney U tests), and Spearman's rank correlation and linear regression analysis to examine the relationships between sediment properties and erosion threshold (R Development Core Team 2009). The linear regression model was developed using a square root transformed erosion threshold, and the optimal model was selected using a combination of: (1) forward/backward selection using the Akaike information criterion and (2) best subsets regression using the Bayesian information criterion (Gotelli and Ellison 2004; Zuur et al. 2007). Spatial representations of erosion thresholds were created in ArcGIS using the natural neighbor's interpolation.

3 Results

Surficial fine sediment deposits up to 40 cm deep were identified in the Bere Stream and River Frome during the study. The deposits were located predominantly within macrophyte stands, both in the center and margins of the channel. The sediment texture varied within the reach, from silt in the margins to sandy silt and silty sand in the channel center (Fig. 1).

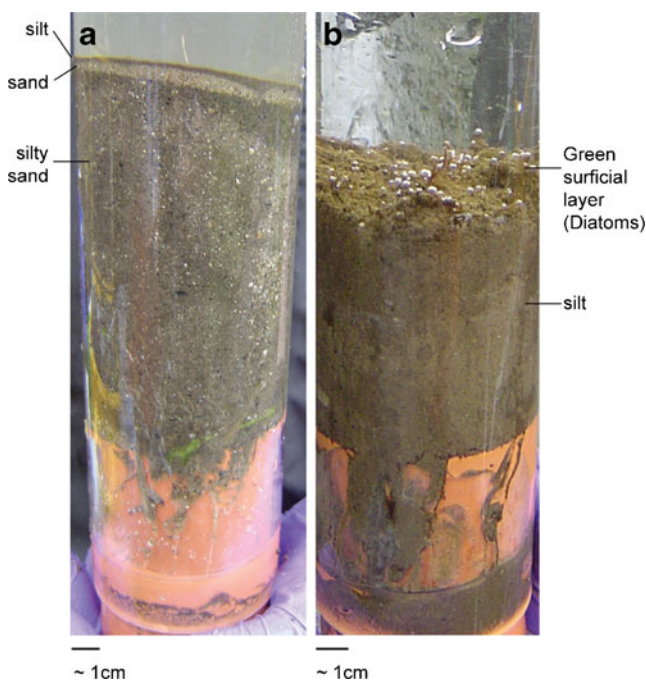


Fig. 1 Examples of sediment cores taken from the Bere Stream in **a** the center of the channel and **b** the margins. Note: the channel sediment is sandier than the marginal sediment, and an abundant autotrophic microbial community is visible at the surface of the marginal sediment (March 2009)

3.1 Spatial and temporal variations in erodibility

Fine sediment erosion thresholds varied significantly over space and time in the study reaches. Overall, erosion thresholds were significantly greater in the channel centers than in the margins in the Bere Stream (median thresholds 117 and 37 Pa, respectively) but not in the River Frome (median thresholds 91 and 72 Pa, respectively; Mann–Whitney, $P < 0.05$). As stated above, CSM-derived erosion thresholds are reported as P_{stag} ; a recent study found that a stagnation pressure range of 40–90 Pa is equivalent to a critical shear stress range of 0.10–0.16 Pa (Grabowski et al. 2010). This cross-stream spatial pattern in erosion thresholds was not consistent over time (Fig. 2). For example, the Bere Stream exhibited a large range in erosion thresholds in November 2008 with the highest values found in the channel center (see Fig. 2a). This spatial pattern, though, was not present in May 2009 when erosion thresholds were considerably lower (see Fig. 2c). In the River Frome, erosion thresholds were not greater on average in the channel center than margins for

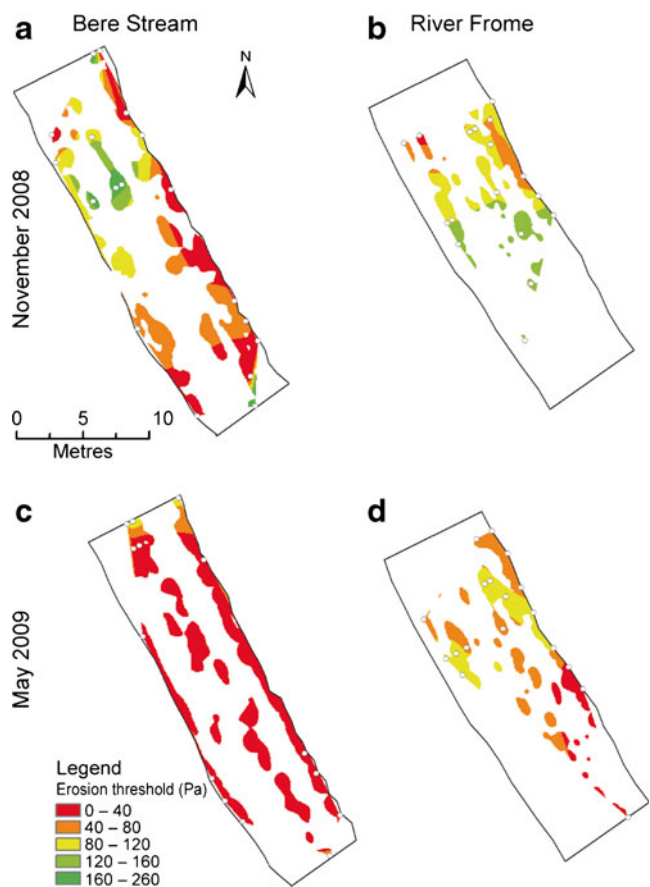


Fig. 2 Visualizations of spatial patterns in surficial sediment accumulation (>2 cm depth) and CSM-derived erosion thresholds (P_{stag}) for the Bere Stream (**a, c**) and River Frome (**b, d**) in November 2008 (**a, b**) and May 2009 (**c, d**). Open circles mark the locations of erosion threshold measurements

either month; however, they did increase in the downstream direction in November 2008 (see Fig. 2b, d).

The erodibility of the surficial fine sediment varied markedly over the year-long survey. Overall, there was a general declining trend in erosion thresholds from September 2008 to May 2009 (−97 % for the Bere Stream and −45 % for the River Frome), which was followed by a modest increase in July 2009 (Fig. 3). This temporal trend was statistically significant in the Bere Stream (see Fig 3a), but not in the River Frome (see Fig 3b) (Kruskal–Wallis, $P < 0.05$). The variation in erosion threshold was high for each sampling date, perhaps reflecting the high spatial variability in erosion thresholds (e.g., November 2008, see Fig. 2a). The sediments found in the margins and channel centers differed substantially in their physical characteristics (see Fig. 1), and by examining temporal trends separately by location within the channel it was possible to partition some of the variance and identify unique temporal responses.

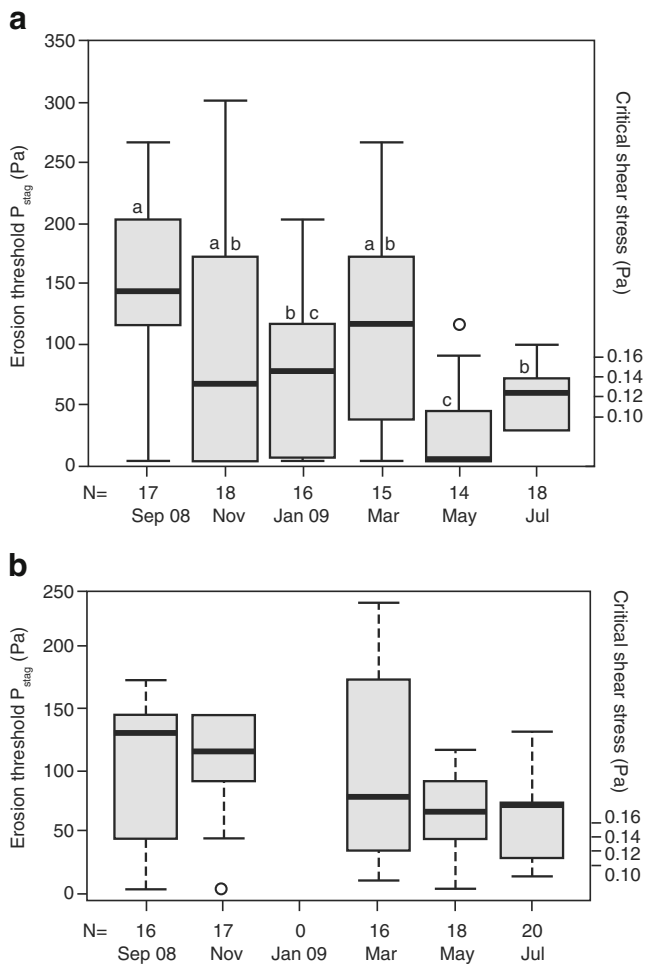


Fig. 3 Erosion thresholds for fine riverbed sediments in **a** the Bere Stream and **b** River Frome by sampling date. CSM-derived erosion thresholds are represented as critical stagnation pressure (P_{stag}). Critical shear stress equivalent derived from empirical calibration by Grabowski et al. (2010). Months marked with the same letter have erosion thresholds that are not significantly different (Kruskal–Wallis, Mann–Whitney, $P < 0.05$)

Statistically, the temporal trends in erosion threshold were similar for sediment in the center and margins of the Bere Stream, with both displaying significant decreases between September 2008 and May 2009 (Fig. 4). However, other temporal trends are apparent, although not statistically significant. Marginal sediment exhibited an earlier and more substantial decline in erosion thresholds at the start of the survey, dropping from 144 to 28 Pa from September to November (−80 %) (Fig. 5b). In contrast, erosion thresholds remained high for this same period in the channel center, and then dropped from 188 to 104 Pa between November 2008 and January 2009 (−45 %) (see Fig. 5a). In both the channel center and margins, erosion thresholds for fine

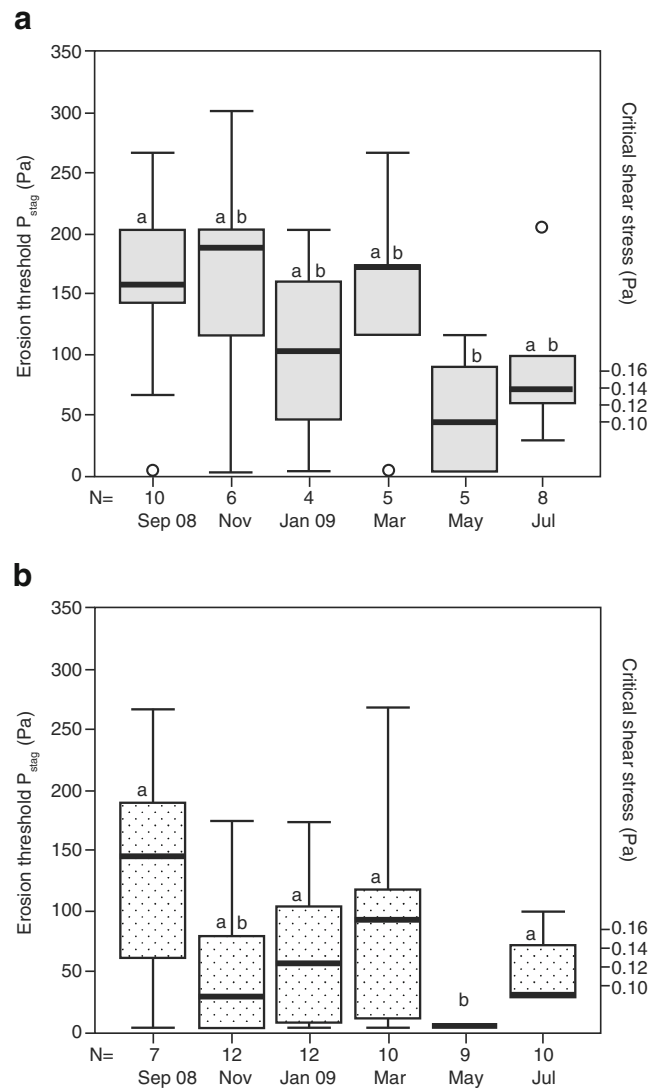


Fig. 4 Erosion thresholds for fine riverbed sediment in the Bere Stream by sampling date for **a** sediment in the channel center and **b** margins. CSM-derived erosion thresholds are represented as critical stagnation pressure (P_{stag}). Critical shear stress equivalent derived from empirical calibration by Grabowski et al. (2010). Months marked with the same letter have erosion thresholds that are not significantly different (Kruskal–Wallis, Mann–Whitney, $P < 0.05$)

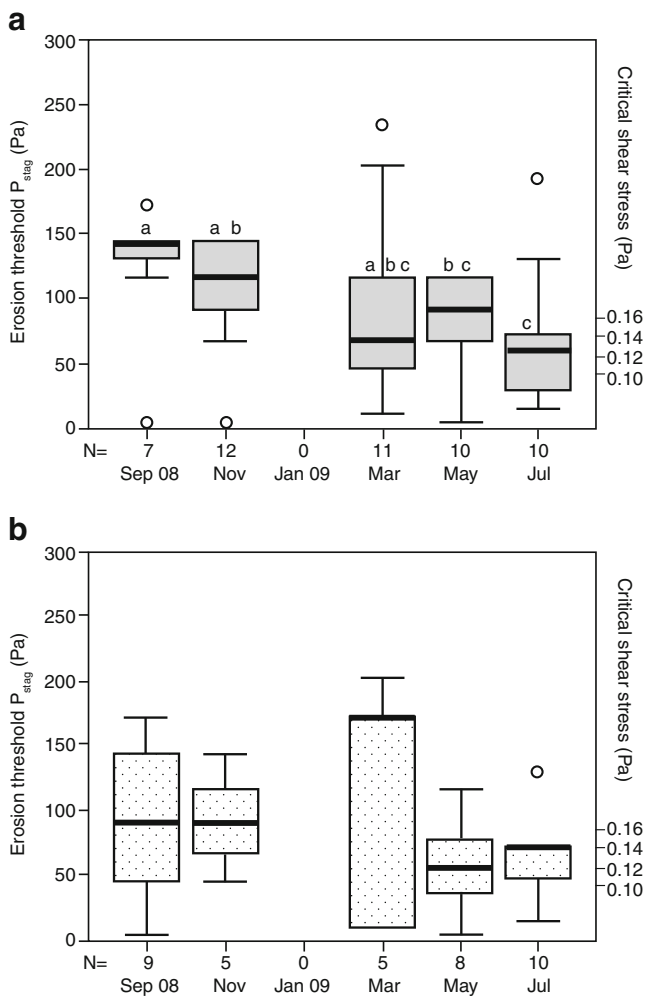


Fig. 5 Erosion thresholds for fine riverbed sediment in the River Frome by sampling date for sediment in **a** the channel center and **b** margins. CSM-derived erosion thresholds are represented as critical stagnation pressure (P_{stag}). Critical shear stress equivalent derived from empirical calibration by Grabowski et al. (2010). Months marked with the same letter have erosion thresholds that are not significantly different (Kruskal–Wallis, Mann–Whitney, $P < 0.05$)

surficial sediment increased over the middle of the survey, reaching local maxima in March 2009 (see Fig. 5). In the River Frome, erosion thresholds decreased significantly over the study period for sediment in the channel center (−58 %) (see Fig. 5a). Erosion thresholds decreased over the study period for sediment in the margins, but this was not supported statistically, possibly due to the extremely high erosion thresholds in March 2009 (see Fig. 5b).

3.2 Spatial and temporal variation in sediment properties

The sediment properties that control the erosion thresholds of fine sediment showed considerable spatial and temporal variation. The dry bulk density of the sediment was much greater in the channel centers than margins (Fig. 6a, b), which was probably caused by the greater particle sizes found in the

channel center (see Fig. 6c–f). Dry bulk density, effective particle size and absolute particle size showed similar temporal patterns; they increased over most of the study period for channel sediment and marginal sediment in the Bere Stream (see Fig. 6a, c, e), but were variable or largely unchanged for sediment in the River Frome (see Fig. 6b, d, f).

Normalized calcium, magnesium and sodium contents were greater and more variable in the Bere Stream than in the River Frome (Fig. 7a, c, e). They were higher in the channel centers than margins, and for the Bere Stream, peaked from November 2008 to January 2009 and then declined to July 2009 (see Fig. 7a, c, e). Major cation contents decreased slightly for the River Frome over time (see Fig. 7b, d, f). Monovalent-divalent cation ratio showed strong declining trends in the Bere Stream, reaching a minimum in March 2009 (see Fig. 7g). The pattern was similar for the River Frome, except that the range was reduced (see Fig. 7h).

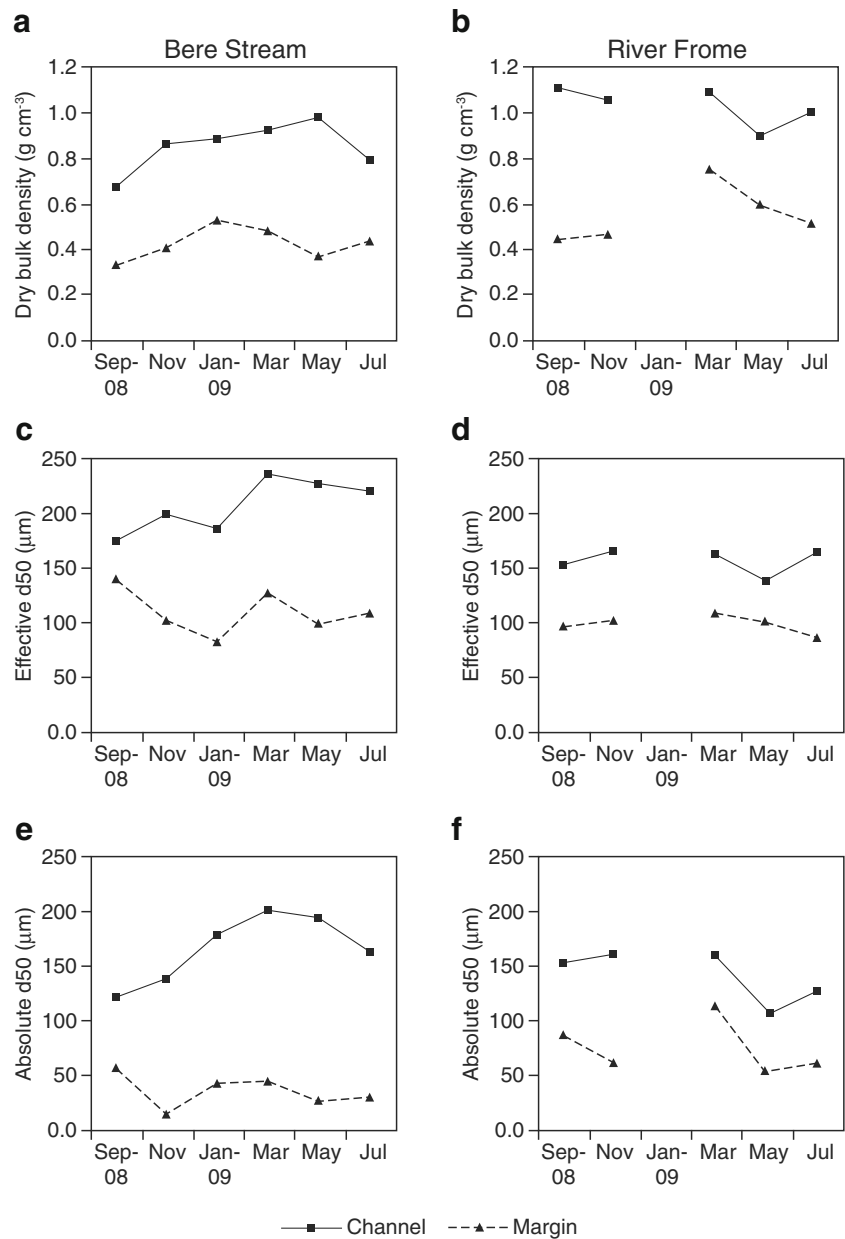
Biological sediment properties demonstrated marked variations over space and time. Organic content, colloidal carbohydrate content, and chlorophyll *a* content were greater for sediment in the margins than channel centers, with the exception of chlorophyll *a* in the Bere Stream. All three biological parameters decreased over the study period in the Bere Stream for fine sediment in the channel center and margins, with local peaks present in May 2009 in the margins and in March 2009 for colloidal carbohydrate content in the channel center (Fig. 8a, c, e).

Temporal trends were less consistent in the River Frome. Organic content decreased initially from September 2008 to March 2009, but then increased to July for both channel and marginal sediment (see Fig. 8b). Colloidal carbohydrate content peaked in March 2009 for the channel center sediments but in November 2008 and May 2009 for the marginal sediments (see Fig. 8d, f). Chlorophyll *a* content was low in channel center sediments and increased to a maximum in May 2009 (see Fig. 8f). It was greater and more variable in marginal sediments with peaks in November 2008 and July 2009 (see Fig. 8f).

3.3 Relationship between erosion threshold and sediment properties

Spearman's rank correlation analysis identified significant correlations between erosion threshold and many of the measured sediment properties, particularly the physical and chemical properties. In the Bere Stream, all of the measured sediment properties, except colloidal carbohydrate and chlorophyll *a* content, were significantly correlated with erosion threshold (Table 1). Median effective particle size had the highest level of correlation ($r_s = 0.40$, $P < 0.01$). In the River Frome, fewer sediment properties were significantly correlated with erosion threshold, and correlation coefficients were lower; only median effective particle size, median

Fig. 6 Temporal variations in physical sediment properties for channel and marginal sediment in the Bere Stream and River Frome: **a, b** dry bulk density, **c, d** median effective particle size, and **e, f** absolute particle size



absolute particle size and sodium content were significantly correlated with erosion threshold (Table 2). High levels of covariation were evident amongst most of the sediment properties, so caution must be exercised in the interpretation of the correlations. For example, organic content was negatively correlated with erosion threshold in the Bere Stream (see Table 1). Organic content is generally considered to have a stabilizing impact on fine sediment (Aberle et al. 2004; Gerbersdorf et al. 2007), particularly when dissolved cation levels are as high as they are in chalk streams (Ravisangar et al. 2005). The negative correlation was most likely caused by the decrease in bulk density that often accompanies an increase in organic content (Avnimelech et al. 2001).

Linear regression analysis identified median effective particle size (d_{50e}) as the sole significant predictor variable

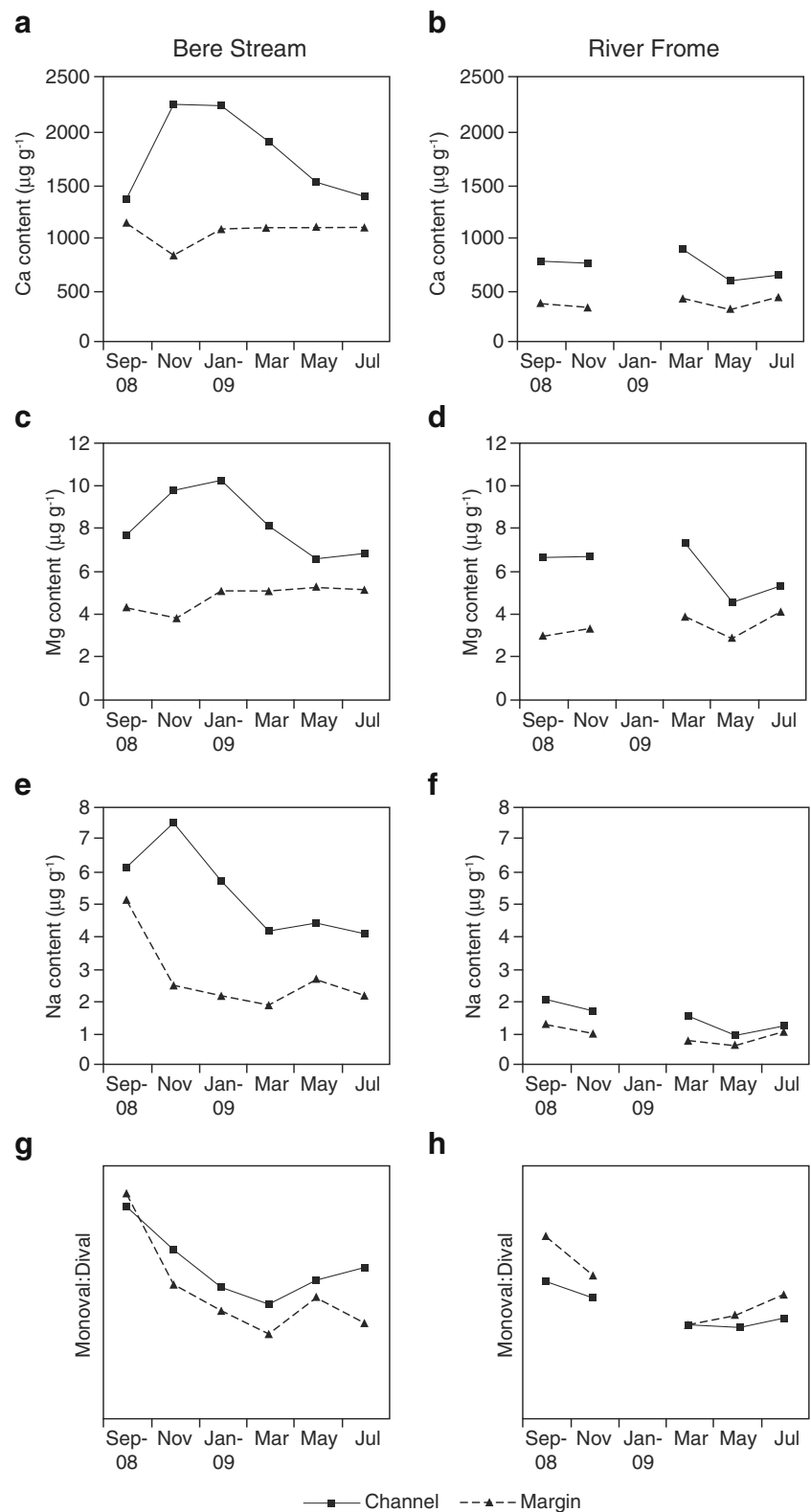
for erosion threshold in the Bere Stream:

$$P_{stag}^{0.5} = 0.029(d_{50e}) + 3.84 \quad (R_{adj}^2 = 0.16, P < 0.001) \quad (4)$$

Median effective particle size, though, poorly captured the significant temporal variation in erosion threshold, which can only be modeled using month as a dummy variable in the regression ($R^2=0.34, R_{adj}^2=0.29, P<0.001$). Median erosion threshold was one of three significant predictor variables for erosion threshold identified in the River Frome,

$$P_{stag}^{0.5} = 0.030(d_{50e}) - 0.74(Mg) + 2.76(Na) + 5.09 \quad (R_{adj}^2 = 0.12, P < 0.001) \quad (5)$$

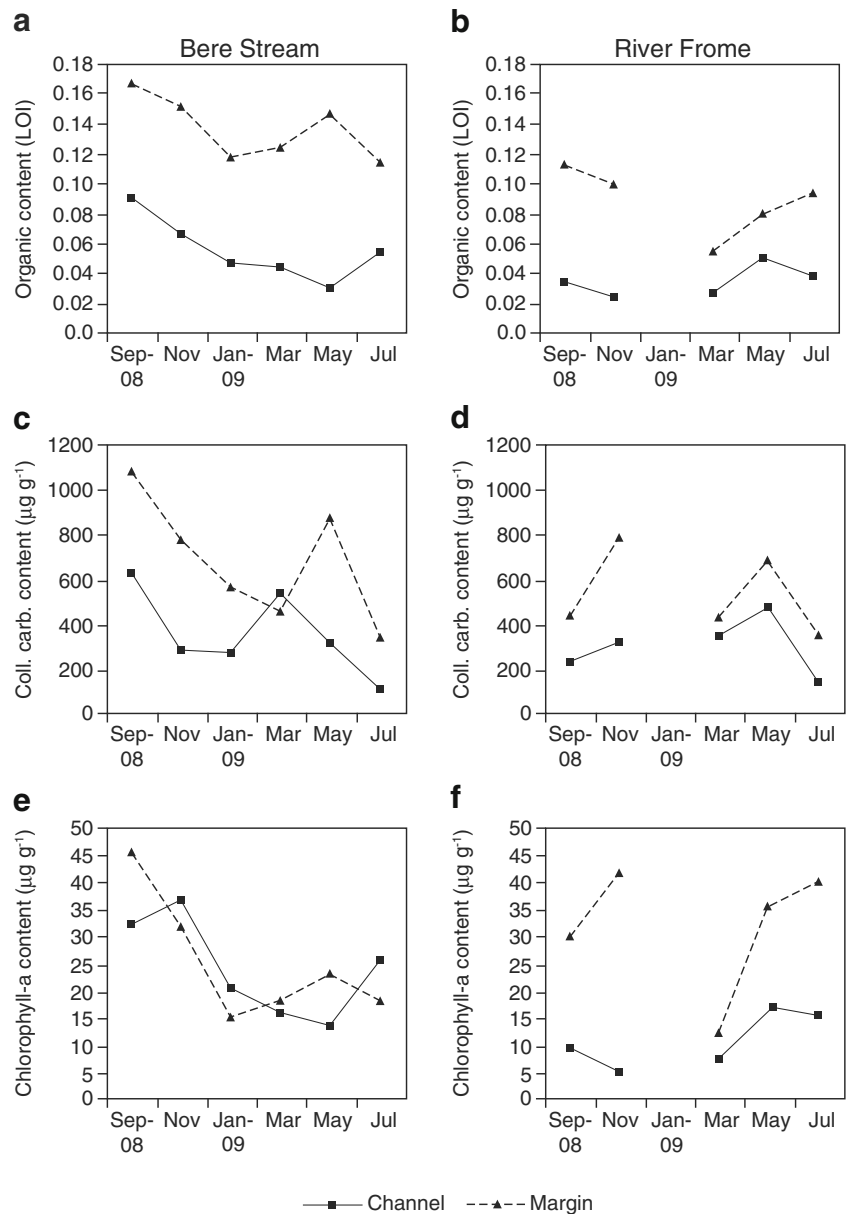
Fig. 7 Temporal variations in cation contents by stream and location within the channel for the Bere Stream and River Frome; **a, b** calcium, **c, d** magnesium, **e, f** sodium (in micrograms per gram sediment, normalized by absolute mud content), and **g, h** the ratio of monovalent (Na) to divalent cations (Ca and Mg)



where Mg is magnesium content and Na is sodium content. The negative relationship between magnesium content and erosion threshold is not supported by the theory of clay particle coagulation (Partheniades 2007), and may relate to

another sediment property. If magnesium content is removed from the linear regression model, sodium content is no longer significant, thereby producing a one-variable model with median effective particle size ($R_{adj}^2=0.06$, $P<0.05$). While the

Fig. 8 Temporal variations in biological sediment properties for channel and marginal sediment in the Bere Stream and River Frome: **a, b** organic content, **c, d** colloidal carbohydrate content (in micrograms per gram sediment), and **e, f** chlorophyll *a* content (in micrograms per gram sediment)



linear regression models are significant for both streams, they do not account for much of the observed variance inherent in the dataset.

When linear regression analysis was conducted independently for each sampling period, coefficients of determination were greater and additional predictor variables were identified (Table 3). For example in the Bere Stream, dry bulk density and organic content accounted for over 50 % of the variation in erosion threshold in November 2008, but median effective particle size was the sole significant predictor variable in May 2009 ($R_{adj}^2=0.34, P<0.05$) (see Table 3). In the River Frome, mud density was the only significant predictor variable in November 2008 ($R_{adj}^2=0.26, P<0.05$), but organic content and colloidal carbohydrate content accounted for the greatest variation in erosion

threshold ($R_{adj}^2=0.25, P<0.05$). Overall, dry bulk density, median effective particle size, mud density and organic content were the sediment properties identified most frequently in the analysis. However, as with the correlation analysis, caution should be exercised in the interpretation, due to high levels of covariation in the dataset.

4 Discussion

The purpose of this year-long field survey was to quantify the erosion threshold of fine sediment over space and time in lowland river reaches with recent histories of siltation. Erosion threshold is an attribute of the sediment that is determined by several key sediment properties (Mehta et al.

Table 1 Spearman's rank correlation coefficients for erosion threshold and sediment properties for the Bere Stream, $n=98$

	Erosion threshold	Dry bulk density	Effective d_{50}	Absolute d_{50}	Ca ²⁺ content	Mg ²⁺ content	Na ⁺ content	Monovalent/divalent cation	Organic content	Colloidal carbohydrate content	Chl-a content
Erosion threshold	–										
Dry bulk density	0.27 ^a	–									
Effective d_{50}	0.40 ^a	0.58 ^a	–								
Absolute d_{50}	0.38 ^a	0.80 ^a	0.73 ^a	–							
Ca ²⁺ content	0.26 ^b	0.23 ^a	0.55 ^a	0.52 ^a	–						
Mg ²⁺ content	0.28 ^a	0.34 ^a	0.54 ^a	0.55 ^a	0.77 ^a	–					
Na ⁺ content	0.31 ^a	0.18	0.57 ^a	0.51 ^a	0.83 ^a	0.66 ^a	–				
Monovalent/divalent cation	0.25 ^b	–0.012	0.28 ^b	0.24 ^b	0.20	0.19	0.67 ^a	–			
Organic content	–0.24 ^b	–0.95 ^a	–0.65 ^a	–0.82 ^a	–0.27 ^a	0.37 ^a	–0.018	0.01	–		
Colloidal carbohydrate content	–0.17	–0.67 ^a	–0.41 ^a	–0.048 ^a	–0.17	–0.16	0.01	0.21 ^b	0.68 ^a	–	
Chl-a content	0.13	–0.51 ^a	0.18	–0.18	0.41 ^a	0.28 ^a	0.60 ^a	0.51 ^a	0.46 ^a	0.36 ^a	–

^a Level of significance, 0.01 (two tailed)

^b Level of significance, 0.05 (two tailed)

1989; Winterwerp and Van Kesteren 2004; Sanford 2008), and is an important parameter in transport dynamic models for sediment and sediment-bound contaminants. This study found that erosion thresholds for fine riverine sediment varied significantly within stream reaches and over time. To the authors' knowledge, this is the first empirical study to identify significant seasonal differences in erosion thresholds for riverine sediment, and one of only a few to report spatial variations (Hanson and Simon 2001; McNeil and Lick 2004).

Spatially, erosion thresholds varied substantially within the 30-m-long stream reaches, ranging by up to three orders of magnitude in a single sampling date. While spatial patterns differed by stream and sampling date, erosion thresholds were greater on average for fine sediment located in the channel center compared with the margins, particularly in the Bere Stream (see Figs. 4 and 5). This difference was

caused by spatial patterns in the particle size of river bed sediment, which resulted from an interaction between aquatic macrophytes and water flow.

Chalk streams support abundant in-channel macrophyte growth, which alters flow and sedimentation patterns to produce distinct hydromorphological and sedimentological zones. Dense macrophyte patches growing in the center of channels deflect the flowing water, producing a low flow, low turbulence environment within the patches that is conducive to the accumulation of fine sediment (Clarke 2002; Cotton et al. 2006; Wharton et al. 2006; Heppell et al. 2009). The margins are naturally low flow, depositional environments in straight channels, due to the effects of bed and wall friction on water flow velocities. The width of this marginal zone is determined by the channel dimensions, flow characteristics, and the presence of obstructions or marginal aquatic macrophytes (Gurnell

Table 2 Spearman's rank correlation coefficients for erosion threshold and sediment properties for the River Frome, $n=87$

	Erosion threshold	Dry bulk density	Effective d_{50}	Absolute d_{50}	Ca ²⁺ content	Mg ²⁺ content	Na ⁺ content	Monovalent/divalent cation	Organic content	Colloidal carbohydrate content	Chl-a content
Erosion threshold	–										
Dry bulk density	0.11	–									
Effective d_{50}	0.23 ^b	0.86 ^a	–								
Absolute d_{50}	0.22 ^b	0.88 ^a	0.88 ^a	–							
Ca ²⁺ content	0.15	0.70 ^a	0.72 ^a	0.80 ^a	–						
Mg ²⁺ content	0.14	0.68 ^a	0.66 ^a	0.78 ^a	0.95 ^a	–					
Na ⁺ content	0.22 ^b	0.35 ^a	0.44 ^a	0.58 ^a	0.78 ^a	0.75 ^a	–				
Monovalent/divalent cation	0.18	–0.56 ^a	–0.48 ^a	–0.37 ^a	–0.35 ^a	–0.29 ^a	0.27 ^b	–			
Organic content	–0.14	–0.95 ^a	–0.87 ^a	–0.88 ^a	–0.69 ^a	–0.67 ^a	–0.34 ^a	0.56 ^a	–		
Colloidal carbohydrate content	–0.01	–0.57 ^a	–0.48 ^a	–0.48 ^a	–0.31 ^a	–0.30 ^a	–0.09	0.34 ^a	0.54 ^a	–	
Chl-a content	–0.014	–0.86 ^a	–0.71 ^a	–0.79 ^a	–0.53 ^a	–0.53 ^a	–0.25 ^b	0.47 ^a	0.88 ^a	0.54 ^a	–

^a Level of significance, 0.01 (two tailed)

^b Level of significance, 0.05 (two tailed)

Table 3 Linear regression models by sampling date and river

	Bere Stream	River Frome
Sep 2008		
Intercept	-8.76	1.58
Chlorophyll <i>a</i>	0.1582 ^a	
Dry bulk density		-12.57 ^a
Mud density	56.82 ^a	
Absolute <i>d</i> ₅₀		0.149 ^b
<i>R</i> _{adj} ²	0.30	0.48
<i>P</i> value	<0.05	<0.01
Nov 2008		
Intercept	-17.437 ^a	0.757
Dry bulk density	27.66 ^b	
Mud density		32.54 ^a
Organic content	82.301 ^a	
<i>R</i> _{adj} ²	0.53	0.26
<i>P</i> value	<0.01	<0.05
Jan 2009		
Intercept	5.06 ^a	
Dry bulk density	-10.25 ^a	
Effective <i>d</i> ₅₀	0.107 ^b	
Chlorophyll <i>a</i> (normalized by mud content)	-0.0607 ^a	
<i>R</i> _{adj} ²	0.41	
<i>P</i> value	<0.05	
Mar 2009		
Intercept	27.20 ^c	-32.69 ^a
Organic content	-80.46 ^a	
Dry bulk density		-16.58 ^a
Magnesium content	-1.6 ^a	
Sodium content		12.42 ^b
Mud density		149.65 ^b
<i>R</i> _{adj} ²	0.32	0.48
<i>P</i> value	<0.05	<0.05
May 2009		
Intercept	-0.213	-0.213
Effective <i>d</i> ₅₀	0.029 ^a	
Organic content		-80.81 ^a
Colloidal carbohydrate content		0.0076 (<i>P</i> =0.06)
<i>R</i> _{adj} ²	0.34	0.25
<i>P</i> value	<0.05	<0.05
Jul 2009		
Intercept	4.36 ^b	3.962
Effective <i>d</i> ₅₀	0.021 ^b	
Monovalent/divalent Calcium content		3.791e3 ^c
		6.508e-3 ^b

Table 3 (continued)

	Bere Stream	River Frome
<i>R</i> _{adj} ²	0.36	0.52
<i>P</i> value	<0.001	<0.01
Stream		
Intercept	3.84 ^c	5.09 ^c
Effective <i>d</i> ₅₀	0.029 ^c	0.030 ^b
Magnesium content		-0.74 ^b
Sodium content		2.76 ^b
<i>R</i> _{adj} ²	0.17	0.12
<i>P</i> value	<0.001	<0.001
Total		
Intercept	4.89 ^c	
Effective <i>d</i> ₅₀	0.025 ^c	
<i>R</i> _{adj} ²	0.12	
<i>P</i> value	<0.001	

^a Level of significance, 0.05

^b Level of significance, 0.01

^c Level of significance, 0.001

et al. 2006). While fine sediment accumulates in both channel macrophyte patches and along the margins, the sediment properties differ due to differences in sediment inputs. Fine sediment accumulates in the margins primarily by the deposition of suspended sediment, so is composed primarily of clays and silts; however the sediment is coarser-grained within the macrophyte patches in the channel centers because the fine sediment originates from both the deposition of suspended sediment and the physical retention of bedload (Heppell et al. 2009). In this study, median particle sizes were greater in the fine sediment deposits in the channel centre than margins in both streams (see Fig. 8c–f). This difference was greater in the Bere Stream, where the gradient in flow velocity across the channel was greater due to the presence of abundant marginal vegetation, and erosion thresholds were consistently higher on average in the channels than in the margins (see Fig. 3).

The positive correlation between median particle size and erosion threshold found in this study supports earlier research on particle entrainment for non-cohesive sediment (for reviews, see Dade et al. 1992; Grabowski et al. 2011). Although clay contents were in excess of the minimum threshold needed for cohesion in sand-mud mixtures for most of the sediment samples, the high silt/clay ratios and low bulk densities, particularly of the finer-grained marginal sediment, yielded sediment that was non-cohesive (van Ledden et al. 2004). The sediment framework was principally silt- or sand-dominated, in which cohesive forces were negligible and gravity was the major resisting force. If water contents in the finer-grained sediments were lower (i.e., higher bulk densities), forces of cohesion and adhesion within the sediment would have become more dominant and erosion thresholds would

have likely increased with a decrease in average particle size, thereby producing the familiar negative unimodal entrainment curves of Hjulström and Postma (Dade et al. 1992).

Median effective particle size was identified as the primary predictor variable for erosion threshold in both streams (see Eqs. 4 and 5). Effective particle size is the diameter of natural sediment aggregates (i.e., flocs), and is contrasted with absolute particle size, which is the diameter of the constituent mineral grains. Virtually all fine sediment is aggregated in aquatic environments due to the effects of cohesion between clay minerals and adhesion by organic matter (Droppo et al. 1997; Droppo 2001). Sediment aggregates are microcosms of microbial life, and support communities of diatoms, bacteria and fungi, which alter the physical, chemical, and mechanical properties of the aggregates. Consequently, the properties and behavior of a sediment aggregate differ markedly from a single mineral grain of the same size. For example, aggregates typically have lower densities and lower settling velocities than mineral grains of the same diameter (Droppo et al. 1997). Accordingly, recent research on fine sediment transport in rivers has emphasized the need to measure effective particle sizes (Walling and Amos 1999; Droppo 2001; Cotton et al. 2006; Heppell et al. 2009). The results of the field study strengthen this claim, by providing the first empirical evidence of the importance of effective particle size on the erosion threshold of fine riverbed sediments.

The significant temporal variations in erosion threshold are suggestive of an annual cycle. Erosion thresholds were greatest in September and November (autumn in the Northern Hemisphere), decreased over the subsequent sampling periods (winter and early spring) reaching a minimum in May, and then increased to July (summer) (see Fig. 3). Superimposed on this annual cycle are high erosion threshold values in March 2009

What caused these temporal variations in erosion thresholds? Chalk streams experience temporal cycles in many environmental variables, including discharge, water chemistry, temperature, and biological production, any of which may impact sediment properties and erosion thresholds. For example, the peak in erosion thresholds in autumn coincided with the peak coverage of aquatic macrophytes in chalk streams (Flynn et al. 2002; Heppell et al. 2009). It also corresponded with a period of low baseflows and a reduced frequency and intensity of high water events, due to the depletion of aquifers and reduced rainfall during the drier summer months. These changes in discharge and baseflow are responsible for the temporal variations observed in sediment cation contents (see Fig. 7). Cation concentrations, particularly calcium, would be highest when baseflow from the chalk aquifer comprised the majority of the flow in the river

(e.g., late summer/early autumn). As runoff increased in the rainy winter months, cation levels would decrease (Berrie 1992). This temporal signal is clear in the baseflow-dominated Bere Stream, but not in the flashier River Frome, which receives more input from runoff (see Fig. 7). Dissolved cations increase the cohesion of clay particles and stabilize the EPS frameworks produced by the sediment's biological community (for a review, see Grabowski et al. 2011). Consequently, erosion thresholds have been shown to be positively correlated with cation content, often expressed as total salinity, in several studies (Kandiah 1974, as cited in Parchure and Mehta 1985; Winterwerp and van Kesteren 2004; Spears et al. 2008). Therefore, the temporal variations in cation contents may have contributed to the temporal trends in erosion thresholds.

The sediment's biological properties displayed similar temporal trends as erosion threshold, particularly in the Bere Stream, which suggests they may also be contributing to the temporal variation in erosion threshold (see Fig. 8). Research conducted in estuarine mudflats has identified significant temporal variation in erosion thresholds caused by biological communities, in which benthic diatoms and cyanobacteria stabilize surficial sediment during the summer months due to the production of EPS (e.g., Amos et al. 2004). Significant correlations between erosion thresholds and EPS content have been identified for fine riverine sediment in several studies as well (e.g., Gerbersdorf et al. 2005, 2007), one of which presents evidence to suggest that EPS is better able to stabilize sediment in the spring rather than winter (Gerbersdorf et al. 2005).

Benthic diatoms are abundant in chalk streams, particularly in early spring when large blooms occur on and in the sediment (Berrie 1992). Diatoms have been shown to have a significant stabilization effect on the sediment through the production of EPS (Paterson 1989; Droppo et al. 2007; Lundkvist et al. 2007) and may strongly influence erosion thresholds in the chalk streams. While the measures used to quantify EPS or photoautotrophic microbial community abundance were not identified as significant predictor variables for erosion threshold for each stream (see Eqs. 4 and 5), the green surficial layers present on sediment surfaces and the high erosion thresholds observed in March 2009 do suggest a possible causal linkage (see Figs. 1b, 4, and 5). The lack of statistical significance is perhaps not unsurprising given the complexity of EPS, both in its molecular composition (e.g., non-colloidal carbohydrates, proteins, and DNA) and structure (e.g., fibrous and capsular) (Decho 2000; Flemming and Wingender 2001, 2010), and the targeted laboratory techniques employed in this study. Therefore, temporal changes in the quantity or quality of EPS in the sediment could be responsible for some of the temporal

variations in erosion thresholds observed in this study, and we would recommend that future studies endeavor to quantify a wider range of EPS fractions.

5 Conclusions

This study has identified significant spatial and temporal variations in erosion thresholds for fine riverbed sediment in two lowland rivers that were caused by changes in the physical, chemical and biological properties of the sediment. The variable nature of erosion thresholds has important implications for the management and modeling of fine sediment dynamics in lowland rivers. Estimates of river flow or individual measurements of erosion threshold are insufficient to assess the stability of riverbed deposits, or predict scour events, and must be combined with information on the sediment erodibility over the relevant spatial and temporal scales. This is particularly important when ecological, hydrological or toxicological impacts are associated with fine sediment erosion and transport, such as benthic habitat loss and sediment-bound contaminant mobilization. To better understand these seasonal variations in erosion thresholds, more research is needed that investigates how river flow, particularly the timing, magnitude and sequencing of flow events, influences sediment properties and erosion thresholds.

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References

- Aberle J, Nikora V, Walters R (2004) Effects of bed material properties on cohesive sediment erosion. *Mar Geol* 207:83–93
- Acornley RM, Sear DA (1999) Sediment transport and siltation of brown trout (*Salmo trutta* L.) spawning gravels in chalk streams. *Hydrol Process* 13:447–458
- Amos CL, Bergamasco A, Umgiesser G, Cappucci S, Cloutier D, DeNat L, Flindt M, Bonardi M, Cristante S (2004) The stability of tidal flats in Venice Lagoon—the results of in-situ measurements using two benthic, annular flumes. *J Mar Syst* 51:211–241
- Avnimelech Y, Ritvo G, Meijer LE, Kochba M (2001) Water content, organic carbon and dry bulk density in flooded sediments. *Aquac Eng* 25:25–33
- Bale AJ, Widdows J, Harris CB, Stephens JA (2006) Measurements of the critical erosion threshold of surface sediments along the Tamar Estuary using a mini-annular flume. *Cont Shelf Res* 26:1206–1216
- Berrie AD (1992) The chalk-stream environment. *Hydrobiologia* 248:3–9
- Bickerton M, Petts G, Armitage P, Castella E (1993) Assessing the ecological effects of groundwater abstraction on chalk streams—3 examples from eastern England. *Regul Rivers* 8:121–134
- Black KS, Tolhurst TJ, Paterson DM, Hagerthey SE (2002) Working with natural cohesive sediments. *J Hydraul Eng-ASCE* 128:2–8
- Boulton AJ, Findlay S, Marmonier P, Stanley EH, Valett HM (1998) The functional significance of the hyporheic zone in streams and rivers. *Annu Rev Ecol Evol Syst* 29:59–81
- Bowes MJ, Leach DV, House WA (2005) Seasonal nutrient dynamics in a chalk stream: the River Frome, Dorset, UK. *Sci Total Environ* 336:225–241
- Clarke SJ (2002) Vegetation growth in rivers: influences upon sediment and nutrient dynamics. *Prog Phys Geogr* 26:159–172
- Collins AL, Walling DE (2007a) Fine-grained bed sediment storage within the main channel systems of the Frome and Piddle catchments, Dorset, UK. *Hydrol Process* 21:1448–1459
- Collins AL, Walling DE (2007b) The storage and provenance of fine sediment on the channel bed of two contrasting lowland permeable catchments, UK. *River Res Appl* 23:429–450
- Cotton JA, Wharton G, Bass JAB, Heppell CM, Wotton RS (2006) The effects of seasonal changes to in-stream vegetation cover on patterns of flow and accumulation of sediment. *Geomorphology* 77:320–334
- Dade WB, Nowell ARM, Jumars PA (1992) Predicting erosion resistance of muds. *Mar Geol* 105:285–297
- Decho AW (2000) Microbial biofilms in intertidal systems: an overview. *Cont Shelf Res* 20:1257–1273
- Defew EC, Tolhurst TJ, Paterson DM (2002) Site-specific features influence sediment stability of intertidal flats. *Hydrol Earth Syst Sci* 6:971–981
- Dickhudt PJ, Friedrichs CT, Sanford LP (2011) Mud matrix solids fraction and bed erodibility in the York River estuary, USA, and other muddy environments. *Cont Shelf Res* 31(10):S3–S13
- Droppo IG (2001) Rethinking what constitutes suspended sediment. *Hydrol Process* 15:1551–1564
- Droppo IG, Leppard GG, Flannigan DT, Liss SN (1997) The freshwater floc: a functional relationship of water and organic and inorganic floc constituents affecting suspended sediment properties. *Water Air Soil Pollut* 99:43–53
- Droppo IG, Liss SN, Williams D, Nelson T, Jaskot C, Trapp B (2009) Dynamic existence of waterborne pathogens within river sediment compartments: implications for water quality regulatory affairs. *Environ Sci Technol* 43:1737–1743
- Droppo IG, Ross N, Skafel M, Liss SN (2007) Biostabilization of cohesive sediment beds in a freshwater wave-dominated environment. *Limnol Oceanogr* 52:577–589
- European Parliament (2002) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000: establishing a framework for Community action in the field of water policy. European Parliament, Luxembourg
- Flemming HC, Wingender J (2001) Relevance of microbial extracellular polymeric substances (EPSs)—Part I: structural and ecological aspects. *Water Sci Technol* 43:1–8
- Flemming HC, Wingender J (2010) The biofilm matrix. *Nat Rev Microbiol* 8:623–633
- Flynn NJ, Snook DL, Wade AJ, Jarvie HP (2002) Macrophyte and periphyton dynamics in a UK cretaceous chalk stream: the River Kennet, a tributary of the Thames. *Sci Total Environ* 282:143–157
- Friend PL, Ciavola P, Cappucci S, Santos R (2003) Bio-dependent bed parameters as a proxy tool for sediment stability in mixed habitat intertidal areas. *Cont Shelf Res* 23:1899–1917
- Friend PL, Lucas CH, Rossington SK (2005) Day-night variation of cohesive sediment stability. *Estuar Coast Shelf Sci* 64:407–418
- Gerbersdorf SU, Jancke T, Westrich B (2005) Physico-chemical and biological sediment properties determining erosion resistance of contaminated riverine sediments—temporal and vertical pattern at the Lauffen reservoir/River Neckar, Germany. *Limnologica* 35:132–144

- Gerbersdorf SU, Jancke T, Westrich B (2007) Sediment properties for assessing the erosion risk of contaminated riverine sites. *J Soils Sediment* 7:25–35
- Gerbersdorf SU, Jancke T, Westrich B, Paterson DM (2008) Microbial stabilization of riverine sediments by extracellular polymeric substances. *Geobiology* 6:57–69
- Gotelli NJ, Ellison AM (2004) A primer of ecological statistics. Sinauer, Sunderland
- Grabowski RC, Droppo IG, Wharton G (2010) Estimation of critical shear stress from cohesive strength meter-derived erosion thresholds. *Limnol Oceanogr-Methods* 8:678–685
- Grabowski RC, Droppo IG, Wharton G (2011) Erodibility of cohesive sediment: the importance of sediment properties. *Earth Sci Rev* 105:101–120
- Gurnell AM, van Oosterhout MP, de Vlieter B, Goodson JM (2006) Reach-scale interactions between aquatic plants and physical habitat: River Frome, Dorset. *River Res Appl* 22:667–680
- Hancock PJ (2002) Human impacts on the stream-groundwater exchange zone. *Environ Manag* 29:763–781
- Hanson GJ, Simon A (2001) Erodibility of cohesive streambeds in the loess area of the midwestern USA. *Hydrol Process* 15:23–38
- Heppell CM, Wharton G, Cotton JAC, Bass JAB, Roberts SE (2009) Sediment storage in the shallow hyporheic of lowland vegetated river reaches. *Hydrol Process* 23:2239–2251
- Kandiah A (1974) Fundamental aspects of surface erosion of cohesive soils. Ph.D. thesis, University of California, Davis, USA
- Loring DH (1991) Normalisation of heavy-metal data from estuarine and coastal sediments. *ICES J Mar Sci* 48:101–115
- Lundkvist M, Gangelhof U, Lunding J, Flindt MR (2007) Production and fate of extracellular polymeric substances produced by benthic diatoms and bacteria: a laboratory study. *Estuar Coast Shelf Sci* 75:337–346
- Luoma SN, Rainbow PS (2008) Metal contamination in aquatic environments: science and lateral management. Cambridge University Press, Cambridge
- McNeil J, Lick W (2004) Erosion rates and bulk properties of sediments from the Kalamazoo River. *J Great Lakes Res* 30:407–418
- Mehta AJ, Hayter EJ, Parker WR, Krone RB, Teeter AM (1989) Cohesive sediment transport. I. Process description. *J Hydraul Eng-ASCE* 115:1076–1093
- Naden P, Rameshwaran P, Mountford O, Robertson C (2006) The influence of macrophyte growth, typical of eutrophic conditions, on river flow velocities and turbulence production. *Hydrol Process* 20:3915–3938
- Owens PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, Horowitz AJ, Kondolf GM, Marden M, Page MJ, Peacock DH, Petticrew EL, Salomons W, Trustrum NA (2005) Fine-grained sediment in river systems: environmental significance and management issues. *River Res Appl* 21:693–717
- Packman AI, Salehin M (2003) Relative roles of stream flow and sedimentary conditions in controlling hyporheic exchange. *Hydrobiologia* 494:291–297
- Parchure TM, Mehta AJ (1985) Erosion of soft cohesive sediment deposits. *J Hydraul Eng-ASCE* 111:1308–1326
- Partheniades E (2007) Engineering properties and hydraulic behavior of cohesive sediments. CRC, Boca Raton
- Paterson DM (1989) Short-term changes in the erodibility of intertidal cohesive sediments related to the migratory behavior of epipellic diatoms. *Limnol Oceanogr* 34:223–234
- Paterson DM, Black KS (2000) Temporal variability in the critical erosion threshold of saltmarsh and upper intertidal sediments. In: Sherwood BR, Gardiner BG, Harris T (eds) British saltmarshes. Linnaean Society of London, Cardigan, UK, pp 51–63
- Pretty JL, Hildrew AG, Trimmer M (2006) Nutrient dynamics in relation to surface-subsurface hydrological exchange in a groundwater fed chalk stream. *J Hydrol* 330:84–100
- R Development Core Team (2009) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
- Ravisangar V, Sturm TW, Amirtharajah A (2005) Influence of sediment structure on erosional strength and density of kaolinite sediment beds. *J Hydraul Eng-ASCE* 131:356–365
- Sanford LP (2008) Modeling a dynamically varying mixed sediment bed with erosion, deposition, bioturbation, consolidation, and armoring. *Comput Geosci-UK* 34:1263–1283
- Spears BM, Saunders JE, Davidson I, Paterson DM (2008) Microalgal sediment biostabilisation along a salinity gradient in the Eden Estuary, Scotland: unravelling a paradox. *Mar Freshw Res* 59:313–321
- Tipping E, Rieuwerts J, Pan G, Ashmore MR, Lofts S, Hill MTR, Farago ME, Thornton I (2003) The solid-solution partitioning of heavy metals (Cu, Zn, Cd, Pb) in upland soils of England and Wales. *Environ Pollut* 125:213–225
- Tolhurst TJ, Defew EC, de Brouwer JFC, Wolfstein K, Stal LJ, Paterson DM (2006a) Small-scale temporal and spatial variability in the erosion threshold and properties of cohesive intertidal sediments. *Cont Shelf Res* 26:351–362
- Tolhurst TJ, Friend PL, Watts C, Wakefield R, Black KS, Paterson DM (2006b) The effects of rain on the erosion threshold of intertidal cohesive sediments. *Aquat Ecol* 40:533–541
- Tolhurst TJ, Jesus B, Brotas V, Paterson DM (2003) Diatom migration and sediment armoring—an example from the Tagus Estuary, Portugal. *Hydrobiologia* 503:183–193
- Underwood GJC, Paterson DM, Parkes RJ (1995) The measurement of microbial carbohydrate exopolymers from intertidal sediments. *Limnol Oceanogr* 40:1243–1253
- USEPA (1997) In vitro determination of chlorophylls *a*, *b*, *c*₁, *c*₂ and pheopigments in marine and freshwater algae by visible spectrophotometry. National Exposure Research Laboratory, Office of Research and Development, US EPA, Cincinnati
- van Ledden M, van Kesteren WGM, Winterwerp JC (2004) A conceptual framework for the erosion behaviour of sand-mud mixtures. *Cont Shelf Res* 24:1–11. doi:10.1016/j.csr.2003.09.002
- Vardy S, Saunders JE, Tolhurst TJ, Davies PA, Paterson DM (2007) Calibration of the high-pressure cohesive strength meter (CSM). *Cont Shelf Res* 27:1190–1199
- Walling DE, Amos CM (1999) Source, storage and mobilisation of fine sediment in a chalk stream system. *Hydrol Process* 13:323–340
- Wharton G, Cotton JA, Wotton RS, Bass JAB, Heppell CM, Trimmer M, Sanders IA, Warren LL (2006) Macrophytes and suspension-feeding invertebrates modify flows and fine sediments in the Frome and Piddle catchments, Dorset (UK). *J Hydrol* 330:171–184
- Widdows J, Brinsley MD, Pope ND, Staff FJ, Bolam SG, Somerfield PJ (2006) Changes in biota and sediment erodability following the placement of fine dredged material on upper intertidal shores of estuaries. *Mar Ecol Prog Ser* 319:27–41
- Widdows J, Friend PL, Bale AJ, Brinsley MD, Pope ND, Thompson CEL (2007) Inter-comparison between five devices for determining erodability of intertidal sediments. *Cont Shelf Res* 27:1174–1189
- Winterwerp JC, Van Kesteren WGM (2004) Introduction to the physics of cohesive sediment in the marine environment. Elsevier, Amsterdam
- Wood PJ, Armitage PD (1997) Biological effects of fine sediment in the lotic environment. *Environ Manag* 21:203–217
- Yallop ML, de Winder B, Paterson DM, Stal LJ (1994) Comparative structure, primary production and biogenic stabilization of cohesive and non-cohesive marine sediments inhabited by microphytobenthos. *Estuar Coast Shelf Sci* 39:565–582
- Zuur AF, Ieno EN, Smith GM (2007) Analysing ecological data. Springer, New York