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Suspended and bed load sediment transport dynamics in two lowland UK streams—storm integrated monitoring

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Abstract A great deal of work recently has focussed on suspended and bed load sediment transport, driven primarily by interest in contaminant transfer. However, uncertainties regarding the role of storm events, macrophyte beds and interactions between the two phases of sediment still exist. This paper compares two study sites within the same catchment whose geology varies significantly. The differences in hydrology, suspended sediment (SS) transport and bed load transport that this causes are examined. In addition, a method to predict the mobilization of different size fractions of sediment during given flows is investigated using critical entrainment thresholds.

Key words bed load sediment; Enborne; entrainment thresholds; Lambourn; suspended sediment; storm samples

INTRODUCTION

There is little information on the role of channel storage and remobilization in determining sediment transport dynamics in lowland streams (Walling, 1996). In particular the response of SS and bed load to macrophyte cutting and storm events has not been well quantified. Technologies to monitor these parameters are available, but have seldom been applied in unison to one study to consider events and processes on a seasonal scale. For instance, it is clear that low-resolution sampling programmes have grossly underestimated the SS load transported downstream (e.g. Hooda *et al.*, 1997). In addition, few studies have investigated the seasonal interrelationships between suspended and bed load sediment transport in river systems. Clearly there is a need for a holistic approach to monitoring sediment dynamics using cheap, freely available technologies. This paper presents data from a larger two-year monitoring programme investigating phosphorus transport and transformation dynamics.

STUDY SITES

A monitoring programme was conducted at two contrasting tributaries of the River Kennet, in southeast England.

The River Lambourn catchment lies on Chalk with deposits of Clay and Flints capping much of the Chalk interfluves (Geological Survey of England and Wales, 1943). The blue line drainage density of 0.12 km km^{-2} reflects the absence of

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impermeable strata in the basin and the dominance of the groundwater flow pathway. A shallow, rapid flowing channel with low seasonal variation in discharge (2-year range 0.725–2.77 $m^3 s^{-1}$) and extensive macrophyte beds results from these conditions. The dominant land use type across the catchment is arable and mixed farming (Institute of Terrestrial Ecology, 1990). A 400-m reach two-thirds down the river at Boxford village was selected as a study site on the Lambourn. The river here has an average depth of 0.8 m and slope of 0.05°. The bed material comprises gravel and coarse sub-angular flint.

The River Enborne catchment is underlain by Chalk but is covered by low permeability Tertiary Sands, Silts and Clays (Geological Survey of England and Wales, 1943). The blue line drainage density is more than twice that of the Lambourn (0.27 $km\ km^{-2}$). During baseflow conditions, the river's flow is sluggish within a deep channel. However, during high intensity rainfall events, generation of overland flow pathways led to peaky, variable flow (2-year range 0.116–25.3 $m^3 s^{-1}$). Arable/mixed farming land constitutes only 40% of the Enborne catchment and is most prominent on hills and valley slopes. This is interspersed with large areas of mown/grazed turf and meadow (Institute of Terrestrial Ecology, 1990). A 500-m reach close to the mouth of the river adjacent to the village of Brimpton was selected as a study site on the Enborne. Average water depth during baseflow here was larger than at the Lambourn (1.05 m) but slope was shallower (0.03°). Substrate in the river is derived mainly from clays and sands with limited regions of unstable gravel bed deposits.

METHODS

Discharge at the Lambourn was determined using a regression between instantaneous velocity-area data measured on site (as covered in British Standards Institute, 1997) and hourly mean flow at the nearest Environment Agency gauging station at Shaw. The River Enborne site was immediately upstream of an Environment Agency gauging station, which was instrumented with an asymmetrical compound crump weir.

SS concentrations were determined using two automatic watersamplers on each river reach (upstream and downstream stations) set on a 24 h collection cycle. At the onset of storm events, an additional sampler at each river was triggered to collect samples every 60 min. These two samplers were controlled by the closure of an external contact float switch set at approximately 20% above the present water level. Filtration was performed on water samples through pre-rinsed, pre-weighed cellulose nitrate membrane filter papers (pore size 0.45 microns).

Bed load material transported along the streambed of the river was sampled using two 25 × 25 cm pit type sediment traps on each river reach (upstream and downstream stations). These four traps were placed in excavated depressions in the bed. A wire mesh (diameter 5 mm) on top of the box allowed transported material to drop inside. The boxes were emptied weekly. Samples were stored in their wet form in the dark at <4°C prior to being analysed. Bed load sediment was then wet sieved into four separate grain size fractions (>0.250, 0.250–0.063, 0.063–0.038 and <0.038 mm) using Endecott stainless steel laboratory test sieves as detailed in British Standards Institute, 1990. Discrete samples were then dried at 80°C for at least 24 h and weighed until no further change in weight.

RESULTS AND DISCUSSION

Suspended sediment transport

SS concentrations in the Enborne were high (means 29 and 39 mg l^{-1}) and very variable (Fig. 1(a)). During baseflow, suspension of bed sediment and bank erosion were postulated as the main sources of sediment. Concentrations increased during high flow periods in the winter. For example, from 22–23 December 1999, flow increased from approximately 4 to >13 $m^3 s^{-1}$. During the same period, SS concentrations rose to 619 mg l^{-1}. A clockwise, cyclical loop in SS response to storm events indicated that concentrations were higher on the rising than on the falling stage of the hydrograph. This was probably due to the activation of overland flow and drainage ditch pathways that delivered considerable quantities of sediment to the channel during the storm events (Table 1). Strong, linear relationships between SS and flow were observed at the two Enborne sampling stations (r^2 0.63 and 0.78). Varied response times to increases in flow, displaying multiple peaks in concentration, indicated the variety of sediment sources to the channel. The period between December 1998 and January 1999 exemplified the effect of sediment exhaustion in the River Enborne channel (Fig. 1(b)). On 26 December 1998 the second largest storm occurred, transporting all the readily available sediments and leaving little time for additional sediments to accumulate before extended storms on the 3, 15, and 19 of January 1999. Although the 26 had lower flow, the rainfall and subsequent runoff had a high potential for sediment transport because of the wet, non-planted soils present in the Enborne catchment. In addition, the lower partial area contributing to sediment supply contributed to the lack of response on 3 January. Storm events on 26 December and 15 January resulted in overflow into the adjacent fields.

In the Lambourn, SS concentrations were lower (means 8 and 9 mg l^{-1}) and year round variations were less marked (Fig. 1(c)). The only sources of sediment to the channel were suspension of bed sediment and bank erosion. This explains why timing of peaks in flow and SS concentrations occur concomitantly. A clockwise, cyclical SS response to storm events was observed as on the Enborne but the loops were much tighter. Although increasing SS concentrations were generally associated with high flows, the relationship between the two parameters was much weaker than on the Enborne. This complex relationship was partly due to abundant macrophyte stands at the site trapping sediment particles previously in suspension by retarding the water velocity. For instance, maximum SS concentrations values of 34 and 35 mg l^{-1} on 27 and 30 January 1999, respectively, occurred during a high flow period. However, notably high SS concentrations also occurred on the Lambourn during low flows (Fig. 1(d)). Periodic flushing of fine material during macrophyte clearance and livestock disturbance of bed sediment at the time of sampling caused this.

Bed load sediment transport

Bed load transport weights were far lower in the Lambourn (weekly means 12.7 and 19.7 g) than the Enborne (weekly means 87.2 and 102 g) (Fig. 2). This was a function of hydrological behaviour, sediment supply, and in the Lambourn, macrophyte

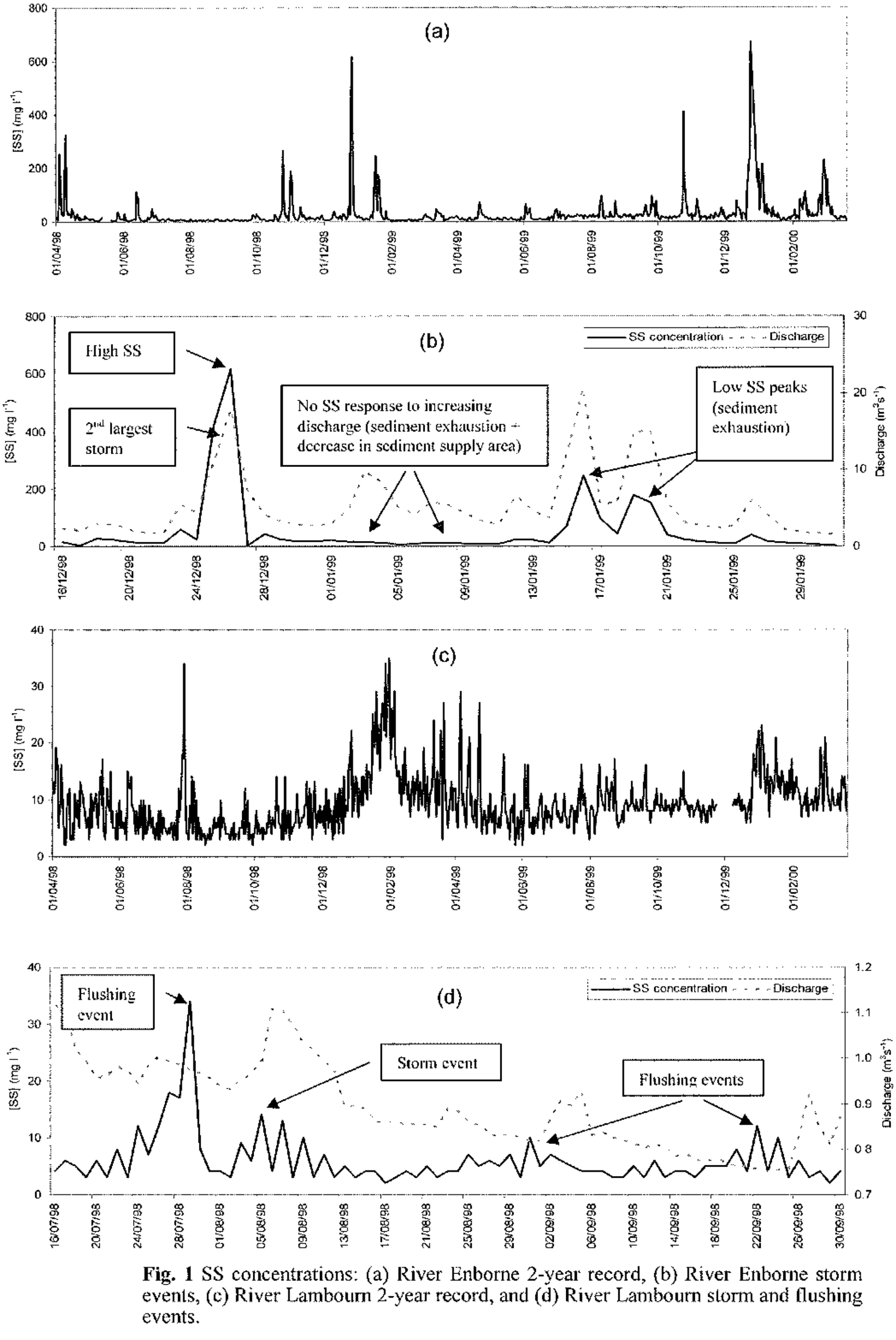

Fig. 1 SS concentrations: (a) River Enborne 2-year record, (b) River Enborne storm events, (c) River Lambourn 2-year record, and (d) River Lambourn storm and flushing events.

Table 1 Manually collected SS sample concentrations (in mg l^{-1}) during two storm events.

Sample location	Storm event 1	Storm event 2
Drainage ditch	287	423
Overland flow 1	322	355
Overland flow 2	357	376

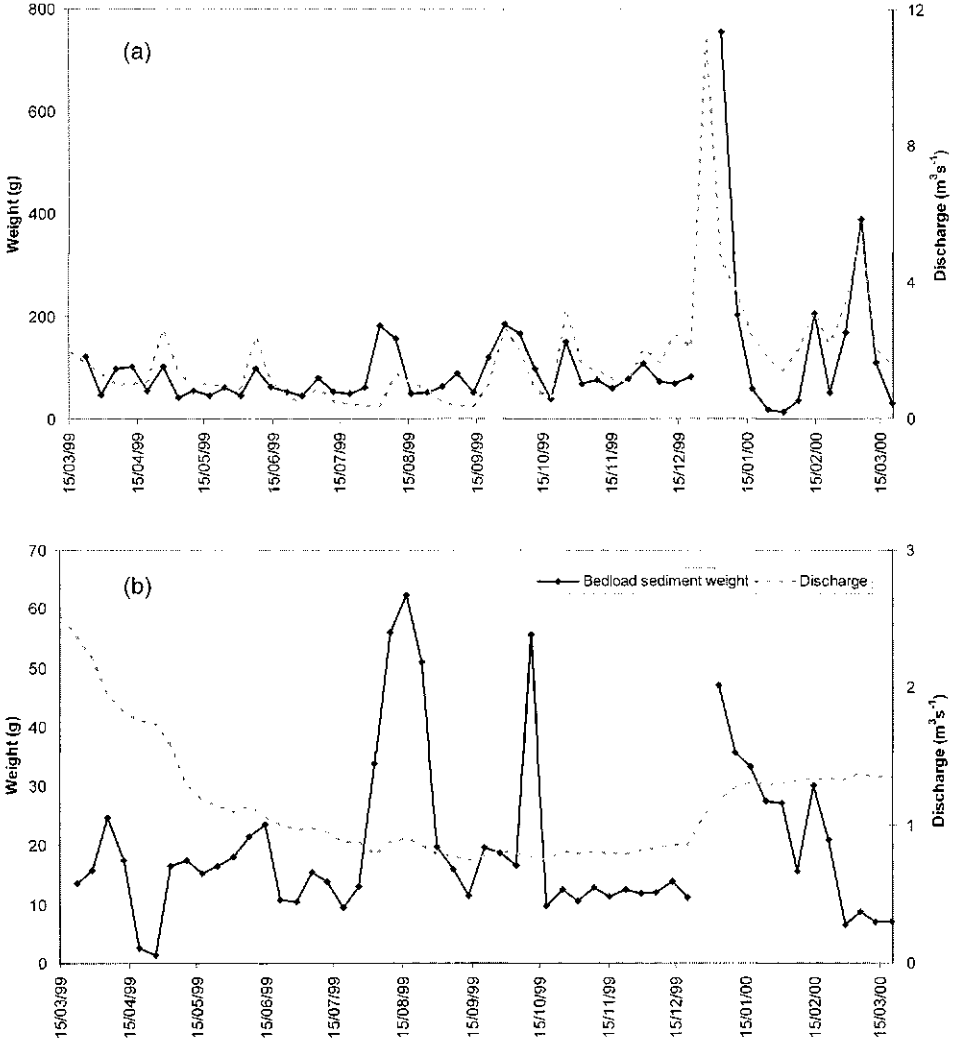

Fig. 2 Total bed load and flow: (a) River Enborne upstream station, (b) River Lambourn upstream station.

trapping and bed armouring. River Enborne bed load had a stronger relationship to flow (e.g. r^2 0.84 for 5.00–0.250 mm size fraction) than in the Lambourn. There were no pulses of high bed load transport during low flows on the Enborne (as were recorded during August and October in periods of low flow on the Lambourn). This

Table 2 Estimating shear velocity (μ_*).

Flow conditions	Lambourn μ_* (ms^{-1})	Enborne μ_* ($m\ s^{-1}$)
Low	0.0596	0.0027
High	0.0646	0.0065

reflected decreased sediment trapping because of the lower macrophyte growth in the Enborne channel compared to the Lambourn. However, stored sediments that were deposited in dead zones during the recession of storm events were re-suspended during later rises in flow. A weak relationship between weight transported and discharge was observed at the Lambourn stations. Generally, high bed load was associated with periods of higher flow (e.g. 29.99 g on the 14 February 2000 at the upstream station with a flow of 1.337 $m^3\ s^{-1}$). Increasing discharge within the river was associated with higher mean velocities and higher shear velocities near the bed surface (Table 2). Therefore, with increasing discharge, the threshold of particle entrainment of progressively larger grains was exceeded. As the shear velocity became sufficiently high to break the coarse armour layer of the Lambourn bed, all size fractions on the bed surface were in motion. Finer particles were displaced to the surface of the bed creating a smooth surface on top of which the coarse particles easily rolled. This illustrates the fact that different particles are moved in a non-uniform size mixture during low flows. These differences in bed load transport rates between the Lambourn and Enborne catchments were consistent with the trends in SS.

Entrainment thresholds

The competence of flows to mobilise bed sediment of different calibres was investigated. In the Enborne, bed load was dominated by fine sand-sized particles (0.250–0.063 mm). Preferential transport of finer material (<0.038 mm) occurred during storm events. In the Lambourn however, a more even distribution of particle sizes were transported with fine material transported in baseflow conditions. These contrasts were a function of different critical shear velocities for the two rivers (Table 2).

Prediction of flows that would not exceed the entrainment threshold for a given size particle were estimated from the regression of linear lines of best fit (Fig. 3). Fine sand, silts and clays were transported irrespective of flow conditions in the Lambourn. However, movement of granule gravel and coarse sand was restricted at low flows (<0.3 and 0.15 $m^3\ s^{-1}$, respectively) indicating the higher entrainment threshold required. A decrease in silt and clay-size material in the bed load during high flows (>2.2 and 2.0 $m^3\ s^{-1}$, respectively) suggested that these particles were resuspended into the water column.

In the Enborne, lower shear velocities explained the absence of coarse material in traps during baseflow conditions (<1.2 $m^3\ s^{-1}$). In addition, unlike the Lambourn, coarse particles were absent from the top layer of the bed sediment. Only the largest magnitude storm flows uncovered the finer top layer of bed sediment to leave coarser layers more vulnerable to transport. However, larger rates of change in shear velocities and bed load transport to increasing flows implied that particles were more responsive to changes in flow than in the Lambourn. Reasons for this were three-fold:

(a) Absence of macrophytes/bed armouring which protect fine bed material from transport by retarding flow and sheltering in the Enborne.

(b) Supply of additional particles into the channel via overland flow pathways in the Enborne.

(c) Steeper and larger magnitude rising limbs on the hydrograph in the Enborne.

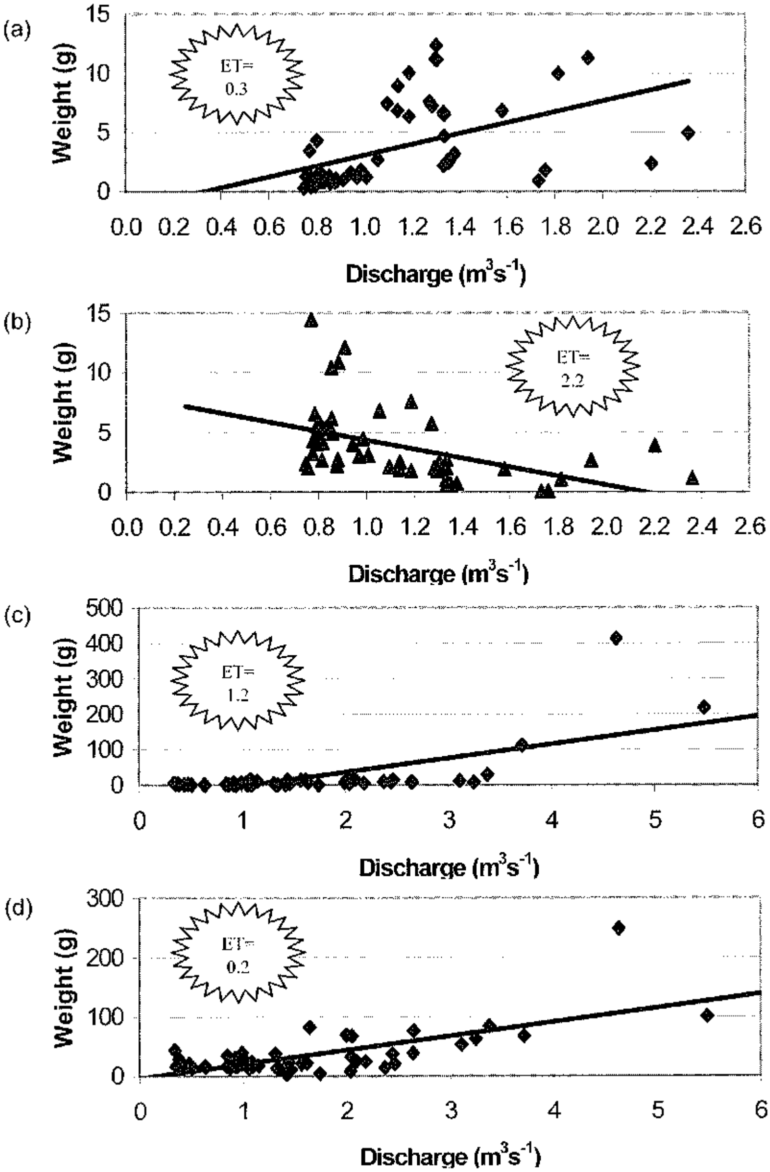

Fig. 3 Entrainment thresholds (ET) for selected size fractions (a) 5.000–0.250 mm and (b) 0.063–0.038 mm bed load fraction *vs* flow at Lambourn upstream station and (c) 5.000–0.250 mm and (d) 0.250–0.063 mm bed load fraction *vs* flow at Enborne upstream station.

CONCLUSIONS

Suspended and bed load sediment transport varied on both a temporal and spatial scale. Factors affecting sediment dynamics included catchment geology, flow delivery pathways, flow magnitude, physical retention devices (macrophyte growth, bed armouring) and readily available sediment within the catchment/river channel. Low frequency, high magnitude storm events exerted a large influence on sediment transport dynamics which any sampling programme should take into account. It was shown that although bed load transport was characteristically intermittent, flow entrainment thresholds provided a useful guide to the transport of different size particles at any given flow.

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