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Downstream changes in suspended sediment fluxes in the River Severn, UK

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Abstract Movement of waves of fine sediment through catchment systems is important for what it can reveal about catchment dynamics. Previous studies have focused on "managed" systems; few have reported on natural flows from individual events. We report preliminary findings from an integrated study of downstream changes in suspended sediment transport during individual storm events in the upper part of the Severn. Downstream change in sediment transport is examined at four sites through detailed records of turbidity and discharge during three consecutive flood events in September 1994. Preliminary results indicate that while suspended sediment concentrations generally increase in the downstream direction for both storms, suspended sediment yield first decreases in the upper basin and then increases towards the lower basin. This trend has important implications for water transport schemes and for modeling movement of pollutants.

INTRODUCTION

Traditionally, physical measurement of suspended sediment in rivers has been used to study the magnitude of catchment sediment yields. This includes establishing magnitude and frequency characteristics of geomorphological processes (Webb & Walling, 1982), and studying relations among erosion, sediment yield, and storage (Dietrich & Dunne, 1978). More recently, the importance of sediment chemistry and particle size has been highlighted in studies of sediment-associated transport of nutrients and contaminants (Walling & Kane, 1982; Horowitz *et al.*, 1990). The use of turbidity monitors provides crucial detail on temporal variation of fluxes. Deployment of turbidity monitors in catchment networks also facilitates observation of waves of fine sediment as they move through river systems.

Little detailed research has been carried out on suspended sediment propagation through river systems during natural flood events. Downstream change in gross sediment output over long time scales has been examined (e.g. Walling, 1983; Richey *et al.*, 1986; Church & Slaymaker, 1989), but few studies have been reported at the event time scale. Previous work has also suggested that the sediment delivery ratio decreases downstream, as depositional opportunities increase with drainage basin area (Walling, 1983; Knighton, 1987). This view has been challenged, however, by Church & Slaymaker

(1989), who concluded that sediment yield increased with distance downstream for rivers in British Columbia. This was ascribed to contributions from bank erosion and channel migration. To help disentangle these competing hypotheses, this study was established to monitor downstream changes in sediment concentration and sediment yield within, and between individual, natural flow events. Such studies are vital to the inference of sediment discharge and delivery processes. This controversy is surrounded by wider methodological problems. Much work has focused on efficiency of sampling methods (Simanton *et al.*, 1993), the most accurate and precise methods of calculating sediment yields (Dickinson, 1981; Crawford, 1991), and interpretation of the data (Slaymaker, 1977; Walling, 1978). Further discussion of methods and justification of interpretation of data is therefore worthwhile.

This paper reports preliminary findings from an integrated study of downstream change in suspended sediment transport from individual storm events within the River Severn, one of the UK's major river systems. These events are compared to those from reservoir release experiments and results are used to test long-standing concepts regarding variations in sediment transport and yield in the downstream direction.

METHODOLOGY AND STUDY AREA

This paper is based on the upper 35 km of the River Severn in mid-Wales, UK (Fig. 1). Sites are divided equally between the upper, experimental part of the Severn catchment (8.7 km^2), which has been instrumented by the Institute of Hydrology (IH) since 1968, and the River Severn immediately downstream of this as far as Caersws (catchment area 355 km^2). Within the experimental catchment rock types are chiefly Ordovician and Silurian shales and mudstones, with superficial deposits of stony boulder clay (M. D. Newson, 1976). Soils are typical of upland UK, ranging from peat on hill tops, podsols and gleys on valley slopes with the occasional development of brown earths, and peat bogs in valley bottoms (Rudeforth, 1970). Vegetation is predominantly woodland, of which 67.5% is commercial forest (Sitka and Norway spruce). The remaining 32.5% is moorland and heathland (M. D. Newson, 1976). The climate is humid temperate, dominated by heavy, steady rainfalls caused by fronts and accentuated by orographic influences. Mean annual precipitation near the basin head is 2300 mm (A. J. Newson, 1976). Downstream from the experimental catchment the geology is mainly Silurian slaty mudstone and siltstone, on which fine loamy or silty soils develop. Monitoring sites are on river alluvium with permeable silty soils overlying a gravelly subsoil. Vegetation is predominantly grass, used for grazing. The climate remains dominated by heavy, steady, frontal rainfall. In upper reaches, channels have small-scale alluvial and bedrock reaches. The channel then becomes confined in a bedrock gorge that is stable for 2 km above Llanidloes (Fig. 1). There the channel is alluvial with a narrow flood plain, but with large meanders and frequent channel change (Lewin, 1987; Thorne & Lewin, 1979). Banks are composite with sandy-silt upper units and a lower coarse section of sand, gravel, and cobbles.

Instrumentation for this study (Fig. 1) includes a tipping-bucket rain gauge (at Tanllwyth), Institute of Hydrology flumes (upstream of sites 1 & 2), pressure transducers (Shape Instruments SH3500) at sites 3 and 4, and Partech IR40C turbidity sensors (at all sites). Calibration of turbidity meters was carried out using river sediment from

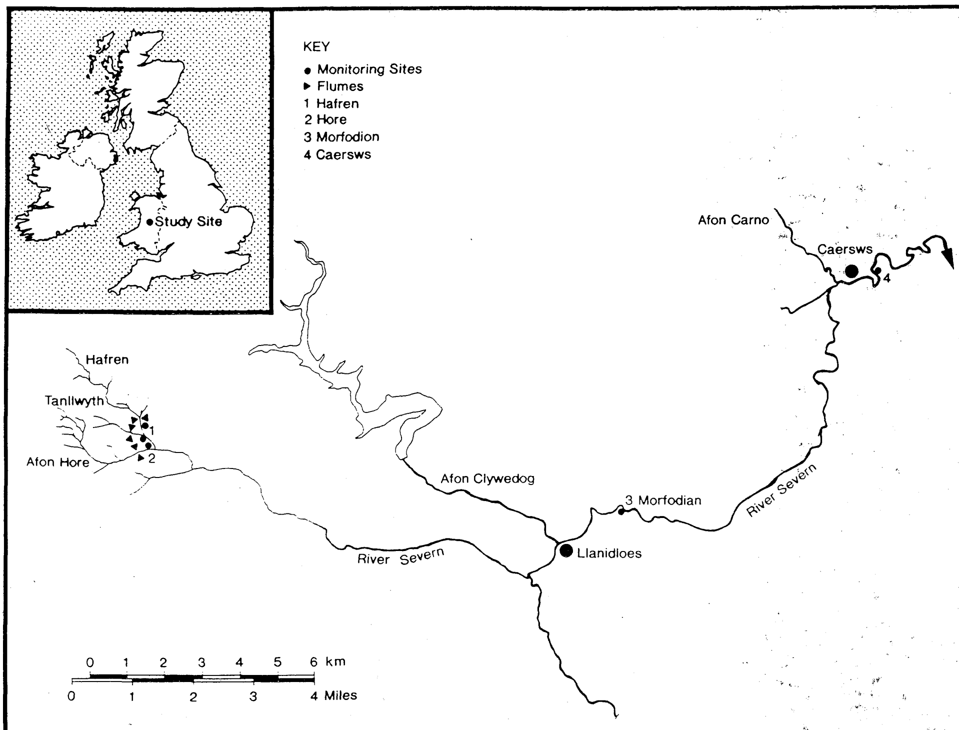

Fig. 1 Map of study area showing location of sites on the River Severn.

fine deposits upstream of each site; samples were dried and sieved, and the sub-105 μm fraction was used in dilution calibrations. This procedure resulted in calibration curves with R^2 values of 99.9%, with mean standard errors of 3.94 mg l^{-1}. By using river sediment, inaccuracies arising from differences between the material used for calibration and the actual suspended sediment were limited; i.e., differences in color and particle size that affect turbidity (e.g. Gippel, 1989; Foster *et al.*, 1992; Lawler, 1995). Sensor heads were located in the near-bank zone of the channel using metal booms. Single point sampling of turbidity may raise questions of representativeness, but because straight sections of an upland channel were selected, strong mixing reduces these problems (e.g. Gippel, 1989). Calculations of suspended sediment load were determined by:

$$L_s = Q_i * C_i \tag{1}$$

where L_s is suspended sediment load (kg s^{-1}), Q_i is discharge at time interval i (m^3 s^{-1}), and C_i is suspended sediment concentration at time interval i (mg l^{-1}). Sediment yield was determined by dividing the load by the basin area at each site. Fifteen minute interval flow and turbidity data were collected and used in these calculations.

RESULTS

Sediment results from three consecutive flood events of 1994 are presented: event A (11-

14 September), event B (12-19 September), and event C (beginning 13 September). Working downstream, the four monitoring sites are known as site 1 (Hafren), site 2 (Hore), site 3 (Morfodion), and site 4 (Caersws) (Fig. 1).

This was the first week of heavy rain after a long dry spell that lasted throughout the summer. The first rainstorm of 17.2 mm (measured at Tanllwyth) produced a single discharge peak that moved downstream over the next 36 h. Peak discharges increased downstream (Fig. 2). The integrated speed of the flood wave between sites 1 and 4 was 1.31 km h^{-1}, or 0.36 m s^{-1} (Table 1). For this event suspended sediment did not increase at either site 1 or 2. At both downstream sites (3 & 4) suspended sediment concentration increased on the rising limb, attaining peak concentration 5.25 and 6.25 h before peak discharge, respectively (Fig. 2). Site 4 had a much higher concentration and also had a secondary peak 8 h later. The integrated speed of the sediment wave between sites 1 and 4 was 0.78 km h^{-1} (Table 1). With both suspended sediment concentration and discharge increasing downstream, the sediment load increased in the downstream direction (Fig. 3). Sediment yield first strongly decreased from site 1 to 3, then recovered a little by site 4 (Fig. 3). The weight of sediment removed during the event increased downstream and reached 1297 kg at site 4 (Table 1).

The second event was a double-peaked event lasting from 12 to 19 September (Fig. 2). This was produced by 25.3 mm of rain on 11 September followed by 14.1 mm on 12 September. Peak discharge again increased in the downstream direction. The characteristic discharge trace is mirrored at all sites (Fig. 2), and both peaks (events B and C) moved at 0.55 km h^{-1} (Table 1). There was no increase in suspended sediment concentration at site 2, but site 1 shows a double-peaked event. The suspended sediment trace at site 3 does not have a secondary peak, whereas site 4 does. The sediment wave moved at 0.58 km h^{-1}. Sediment load again increased downstream (Fig. 3), whereas sediment yield decreased from site 1 to site 3 and then increased to site 4 (Fig. 3). Weight of sediment removed during the flood was 3957 kg at site 4.

In all events the relation between suspended sediment concentration and discharge exhibits hysteresis, with concentrations on the rising limb of the hydrograph exceeding those for a similar discharge during recession (Fig. 4). For the double-peaked event, there is a secondary clockwise loop that relates to the second discharge peak (Fig. 4). This shows that exhaustion effects occur over each event, but exhaustion of sediment also occurs between events (Table 1). Event C removed much less sediment than did event A, although event C had a greater discharge than did event A.

DISCUSSION

Comparisons drawn between the two events show that flood wave velocity varies with magnitude of storm and resulting discharge. Perhaps surprisingly, for these two events, the velocity was greater for the first, smaller discharge event (Table 1). This may suggest that the channel conveyed water at much greater efficiency at lower flow, and further research is addressing this. Differences occurred from site 1 to site 3 because the velocity of the flood wave was constant between sites 3 and 4. For these events the sediment wave moved slower than did the flood wave, except for the largest flood, for which the velocity of the sediment wave was greater than that of the flood wave (Table 1).

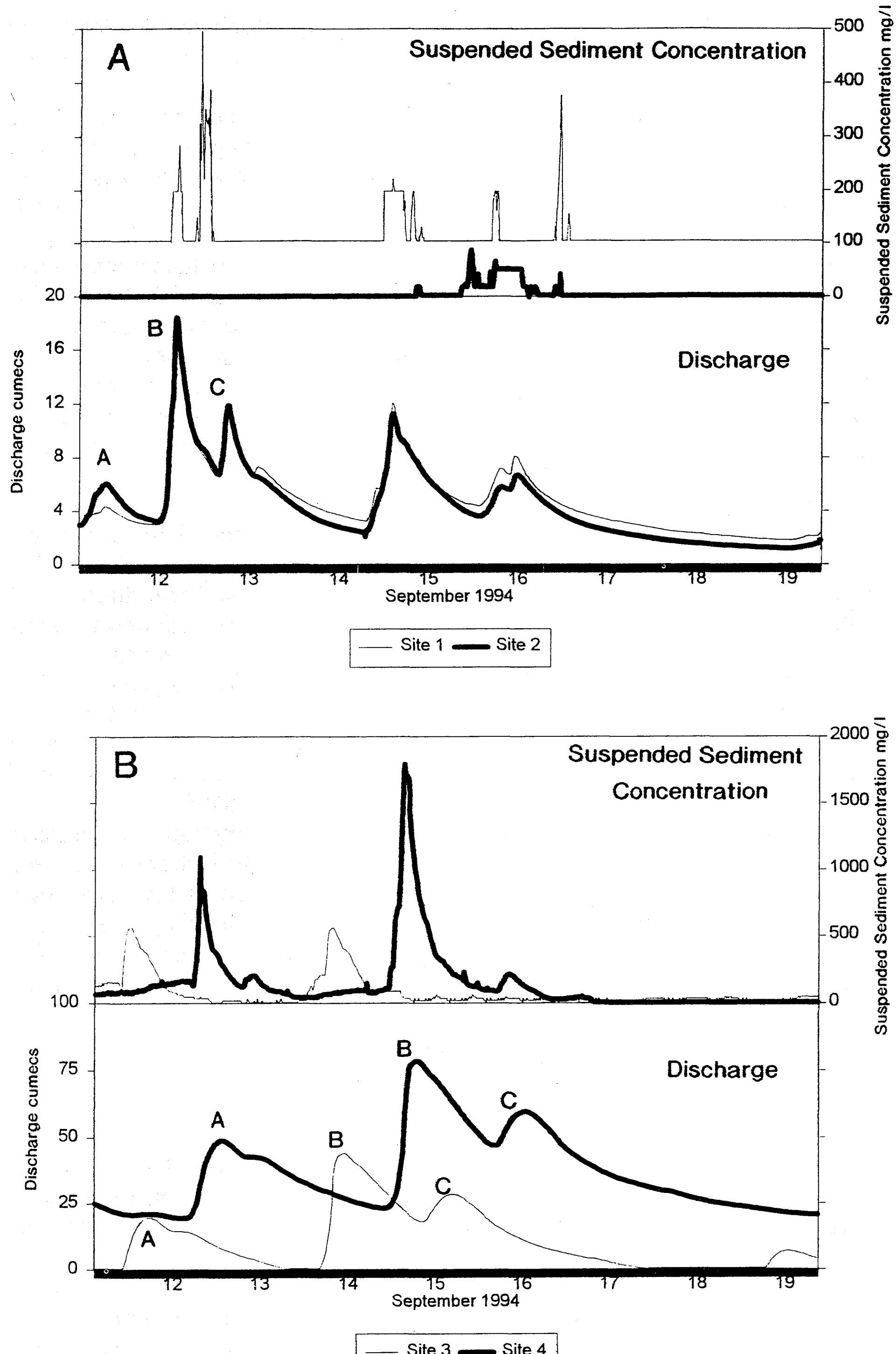

Fig. 2 Discharge and suspended sediment traces for (A) upstream sites and (B) downstream sites; each site as waves propagate downstream.

Table 1 Characteristics of flood and sediment wave behavior.

Event	$d1$	$d2$	t_f1	t_f2	U_f1	U_f2	U_f	t_s1	t_s2	U_s1	U_s2	U_s	q_{max}	SSC_{max}	tot. sed.
A (11 September 1994)	14.95	14.85	8	20	1.87	0.74	1.31	na	19	na	0.78	0.78	48.8	1095	1297
B (12 September 1994)	14.95	14.85	42.5	20	0.35	0.74	0.55	38.75	19.5	0.39	0.76	0.58	78.5	1794	3475
C (12 September 1994)	14.95	14.85	42.5	20	0.35	0.74	0.55	62	19	0.24	0.78	0.51	59.6	217	487

where:

1 represents Tanllwyth to Morfodion;
2 represents Morfodion to Caersws;
d is the distance between sites in km;
t_f is the time the flood wave takes to move between sites in h;
U_f is the velocity of the flood wave in km h^{-1};
t_s is the time the sediment wave takes to move between sites in h;
U_s is the velocity of the sediment wave in km h^{-1};
q_{max} is the maximum value of discharge in m^3 s^{-1} recorded at site 4 (Caersws);
SSC_{max} is the maximum value of suspended sediment concentration in mg l^{-1} recorded at site 4; and
tot. sed. is the weight of sediment exported during the floods in kg recorded at site 4.

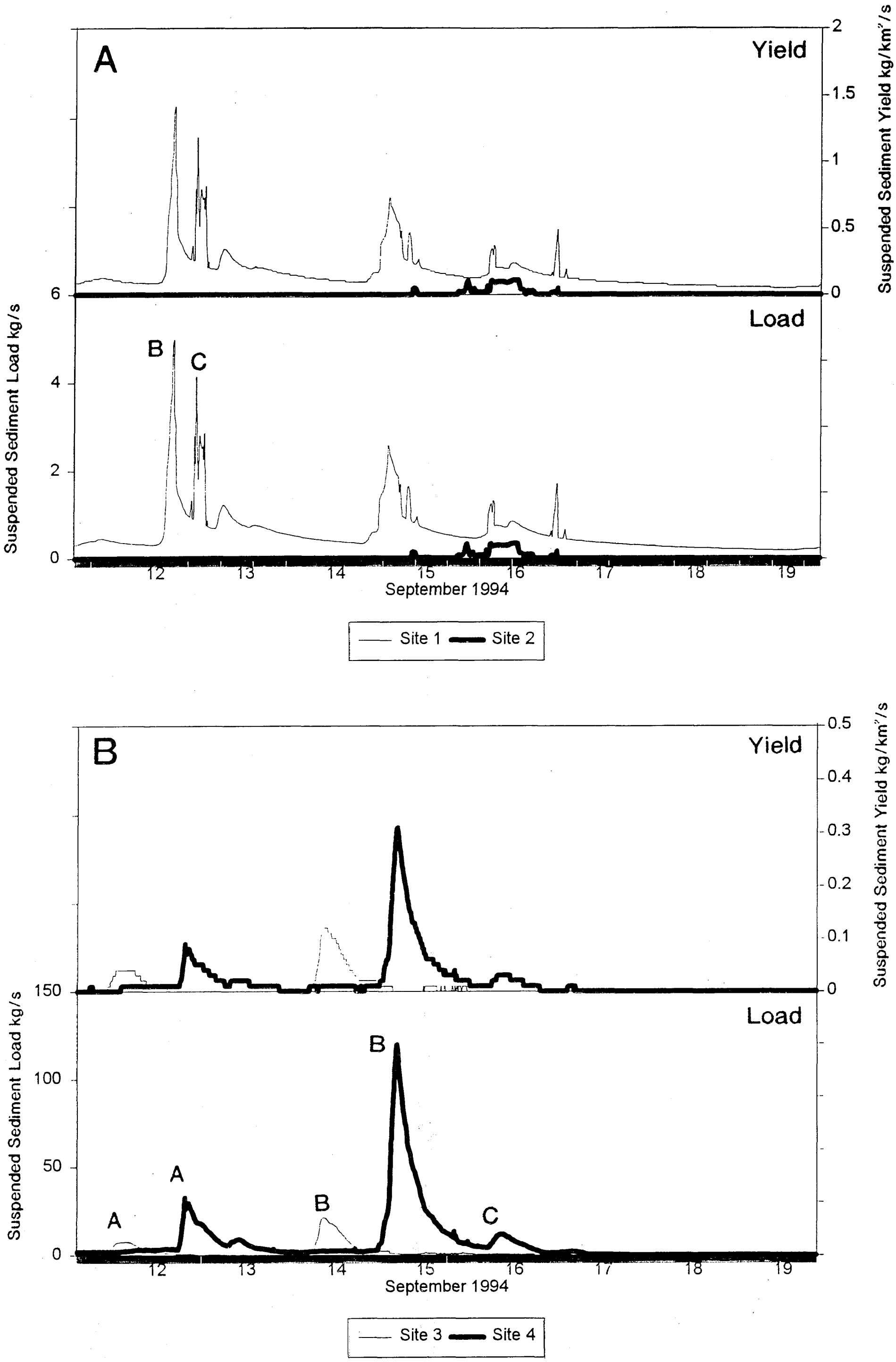

Fig. 3 Suspended sediment load and sediment yield traces for (A) upstream sites and (B) downstream sites.

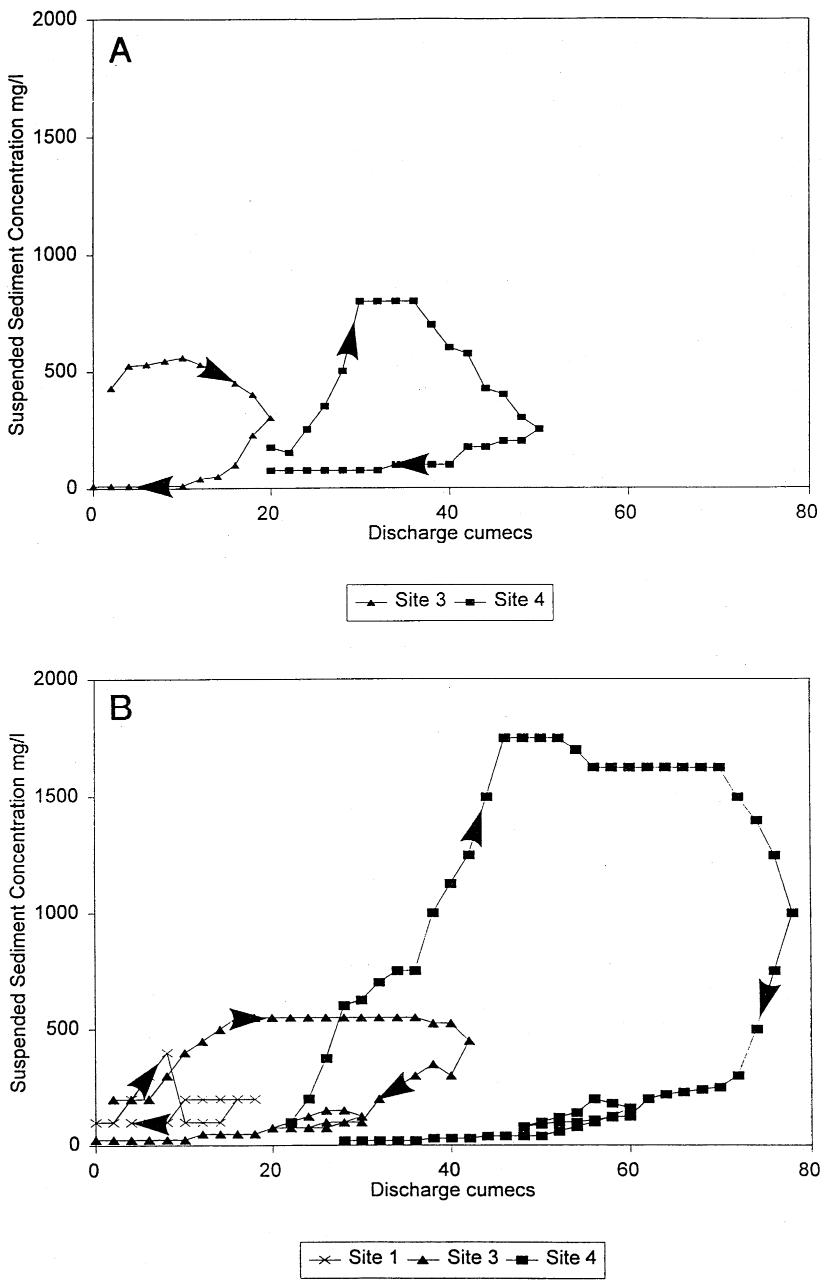

Fig. 4 Hysteresis graphs for storm events A and B.

Load increased downstream and was probably due to increasing sediment sources, either catchment or channel derived. Catchment sources increase with drainage basin area, but the degree of connectivity between source areas and channel should weaken downstream. This is probably due to long grass and flat areas adjacent to the channel, so that considerable sediment-laden runoff is probably filtered or infiltrates before it can transport material to the channel. The main source of sediment is likely to be channel derived. The initial decrease in sediment yield may have been due to declining importance of catchment sources between sites 1 and 3 (Hafren and Morfodion), which was not compensated by supply from channel banks. Between sites 3 and 4 (Morfodion and Caersws) increased yield may have been by additions from banks: note that this is known as a laterally active section (Lewin, 1987; Thorne & Lewin, 1979). The inference of processes changing downstream is complicated by scale effects as other variables change, such as channel shape, gradient, and boundary materials (Knighton, 1987). It is likely that a distinction exists between the upper and lower reaches with respect to processes occurring. The nature of the sediment and discharge waves therefore varies between sites 1 and 3 and sites 3 and 4, which is probably due to differences related to channel gradient.

From studying patterns of discharge and sediment traces, we hope eventually to infer processes of storage and transport in the River Severn. Different processes result in different characteristic traces. For site 3, a single sediment pulse occurred for these two events, whereas at site 4 a double-peaked trace was produced each time (Fig. 2). The Caersws trace was likely caused by an initial sediment wave related to rise in stage, and another wave occurred with attainment of peak stage.

Results are consistent with the findings of Gilvear & Petts (1985), Petts *et al.* (1985), and Leeks & Newson (1989), who demonstrated that peak suspended sediment concentration increases with distance. Results also agree with Petts *et al.* (1985), that a double-peaked sediment trace is produced, although this is apparent for only one site. Comparison of results from natural events and reservoir releases may be used to identify sediment delivery processes. If sediment traces mirror those produced by reservoir releases, in-channel sources of material are likely to be dominant, because during a release there is negligible sediment contribution from the catchment. Comparison of gradients on the rising and falling limbs of the sedograph may provide a useful index for assessment. Results do not confirm findings elsewhere, that the flood wave moves faster than does the sediment wave (Heidel, 1966; Leeks & Newson, 1989).

Differences between human-induced and natural events are possible due to variation in sediment supplied to the channel. Reservoir releases result in large contributions from channel margins, whereas sediment waves associated with logging (as frequently happens in the Upper Severn) release sediment to the channel more quickly with the onset of rain. Both types of human-induced events are likely, therefore, to provide sediment with different characteristics (e.g.particle size, color, chemistry) to "naturally" supplied sediment. Interestingly, our results demonstrate that, within individual catchments, sediment yield may both decrease and increase in a downstream direction. They therefore support elements of both hypotheses (downstream decreases and increases) argued by Walling (1983) and Church & Slaymaker (1989), respectively.

CONCLUSIONS

Although results are preliminary, suspended sediment concentration and load for these two events increase with basin scale. Sediment yield, however, first decreases, then increases. Downstream change in the shape of the suspended sediment trace is interpreted as change in the amount of sediment moving into and out of storage; further work is needed to clarify rates and processes involved. Certain reaches of the channel may thus be predominantly storage areas or areas of remobilization over a series of events, although this will probably vary through the year and with basin size.

Different size fractions of the sediment load may have a different relation to flood wave clarity and movement into and out of storage. This is an area for future investigation. Other areas for research include how sediment waves behave over greater distances than considered in this study; which factors affect the velocity of the sediment wave, such as discharge, sediment characteristics, channel roughness, gradient and channel geometry; the impact of seasonal changes in sediment sources; and how sources interconnect to produce characteristic sediment delivery traces throughout the basin. The pattern of sediment yield also needs to be studied over different storm events and for larger basin areas.

Finally, results have important implications for river management, e.g. water transfer schemes and pollutant transport. Increases of sediment yield with basin area may affect the most acceptable point of water extraction and necessary filtration for potable supply. The nature of sediment discharge change in a downstream direction, and the pattern of the sediment trace, has important implications for transport and storage of contaminants and nutrients. If characteristic sediment traces occur for different events, modeling of pollutant transport may be strengthened.

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