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Evaluating fine sediment mobilization and storage in a gravel-bed river using controlled reservoir releases

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Abstract:

Two controlled flow events were generated by releasing water from a reservoir into the Olewiger Bach, located near Trier, Germany. This controlled release of near bank-full flows allowed an investigation of the fine sediment (<63 μm) mobilized from channel storage. Both a winter (November) and a summer (June) release event were generated, each having very different antecedent flow conditions. The characteristics of the release hydrographs and the associated sediment transport indicated a reverse hysteresis with more mass, but smaller grain sizes, moving on the falling limb. Fine sediment stored to a depth of 10 cm in the gravels decreased following the release events, indicating the dynamic nature and importance of channel-stored sediments as source materials during high flow events. Sediment traps, filled with clean natural gravel, were buried in riffles before the release of the reservoir water and the total mass of fine sediment collected by the traps was measured following the events. Twice the mass of fine sediment was retained by the gravel traps compared with the natural gravels, which may be due to their altered porosity. Although the amount of fine sediment collected by the traps was not significantly related to measures of gravel structure, it was found to be significantly correlated to measures of local flow velocity and Froude number. A portion of the traps were fitted with lids to restrict surface exchange of water and sediment. These collected the highest amounts of event-mobilized sediments, indicating that inter-gravel lateral flows, not just surface infiltration of sediments, are important in replenishing and redistributing the channel-stored fines. These findings regarding the magnitude and direction of fine sediment movement in gravel beds are significant in both a geomorphic and a biological context.

KEY WORDS fine sediment; sediment mobilization; channel bed storage; infiltration rates; controlled release events; artificial floods; sediment traps; sediment transport; gravel-bed rivers

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INTRODUCTION

Fine sediment transfer and/or storage in aquatic systems is environmentally significant, because fine sediment is both a vector for the transport of contaminants (Jobson and Carey, 1989) and in its own right a pollutant, particularly in the context of habitat quality (Newcombe and MacDonald, 1991). Fine-grained sediment (fines) is known to be a major potential sink for hydrophobic pollutants in the aquatic environment (Means *et al.*, 1980; Voice and Weber, 1983), and the occurrence of contaminants in freshwater sediment has been correlated with the abundance of particles smaller than 63 μm (Mudroch and Azcue, 1995). Furthermore, it has been assumed that the exchange sites on the fines and the associated organic matter are responsible for the amount and the behaviour of the sorbed substances (Karickhoff and Brown, 1978). Because fine sediment acts as a biogeochemical sink and, due to desorption, a potential source for toxins, it can have a considerable influence on water quality. Increases in suspended solids and associated nutrients and contaminants can lead to increased turbidity and eutrophication, as well as to eco-toxicological risks.

The role of fine sediment as an agent of habitat degradation has been documented in numerous field and laboratory experiments. It has been demonstrated that high levels of fine sediment in gravel-bed rivers have a deleterious effect on the survival of the incubating embryos of trout and salmon and macroinvertebrates (Turnpenny and Williams, 1980; Olsson and Persson, 1988; Soulsby *et al.*, 2001). Although the definition of the size of the fine sediment contributing to habitat degradation cited in the fisheries literature varies, it always includes the portion smaller than 63 μm. Storage of fine sediment in river channels has important implications for the delivery and fate of sediment-associated contaminants. Increased accumulation of fines in gravel beds not only modifies the benthic habitat, but also increases the retention time of sediment-associated contaminants in these biologically active areas of river systems.

In a geomorphic context, fine sediment storage has important implications for drainage basin sediment budgets and sediment yield modelling, through its influence on sediment conveyance losses within fluvial systems

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(e.g. Meade, 1982; Walling *et al*., 1998). Mobilized sediment can be stored at intermediate locations within a basin, such as on hillslopes, floodplains and in the channel, with the amount stored frequently being of similar magnitude, or higher in large basins, to the suspended sediment export from the catchment (Trimble, 1983; Walling, 1983; Phillips, 1991; Owens *et al*., 1999; Walling *et al*., 1999).

Controlled water releases have been used, with varying degrees of success, as 'flushing flows' to improve fish habitats in rivers downstream of reservoirs that have experienced artificially lowered flows and modified gravel habitats. Such controlled release events have been used for this purpose for a long time and include, for example, a 1952 release from the Granby Dam on the Colorado River (Eustis and Hillen, 1954) and a 1995 release from the Ruby Dam in southwestern Montana (Dalby *et al*., 1999). Several studies have used these events as an opportunity to evaluate the mobility (transfer and storage) of fines in streams below reservoirs (e.g. Beschta *et al*., 1981; Gilvear and Petts, 1983; Sear, 1993). Sear (1993) evaluated the factors influencing the infiltration rate of sediments <16 mm in eight salmonid spawning beds downstream of a hydropower generation site (during both natural and controlled release events), finding significant differences between sites influenced only by regulated flows (i.e. downstream of the reservoir but upstream of tributaries) versus those downstream sites affected by both unregulated tributaries and regulated flows. This indicates the importance of fine sediment source and availability in the process of gravel infiltration. The results from laboratory flume studies generally agree on the importance of suspended sediment concentration in controlling infiltration rates (Einstein, 1968; Beschta and Jackson, 1979; Carling, 1984), but they differ on the influence of gross flow hydraulic parameters, such as velocity, shear stress and Froude number. Beschta and Jackson (1979) found that Froude number was significantly correlated with the intrusion of sands into a gravel bed, whereas Einstein (1968) and Carling (1984) found that mean flow parameters did not correlate with sand accumulation in their flume studies. Although the extrapolation of these results to field conditions must be treated with caution (Beschta and Jackson, 1979), Sear (1993) observed that infiltration rates were influenced by the transport mechanism (i.e. suspended or bedload), the local hydraulics, the dimensions of the interstices between the framework gravels, and the reach morphology. Everest *et al*. (1987) summarized the three primary mechanisms associated with particle collection by the streambed as gravitational settling, interception and sieving. Clearly, one would expect flow velocity, suspended sediment concentration and the porosity of the streambed to regulate these processes.

It is important to note that all of these studies of the rate of infiltration of fine sediment into gravels have focused on sand-sized particles, even though the field studies included silts and clays. In the context of fish habitat, the sands are an important concern, as they fill the interstitial gravel space, thereby changing flow patterns, and they can also form a cap on the surface of the sediment, thus restricting infiltration of fines and flow from the surface.

The objective of the work reported in this paper was to determine the amount of fine sediment (<63 µm) mobilized and deposited in riverine gravels during a controlled release event and to determine whether the fine sediment enters the gravels primarily from the surface or from lateral interstitial flows. In this study, the emphasis has been placed on evaluating the movement of the silt and clay fractions; the sand has not been investigated. The rationale for looking at the <63 µm fraction is that these particles are potentially carrying contaminants and organic material through the system and that they can behave physically like sand-sized particles. In natural waters, small mineral grains are commonly observed to be bound with particulate organics into composite particles termed flocs or aggregates. As these larger composite particles exhibit increased settling rates and decreased densities, their mobility towards and within the gravels is modified from their original behaviour as individual mineral particles (Droppo *et al*., 1998). In some riverine environments these composite particles have been reported to exhibit settling velocities similar to those of fine sands (Petticrew and Droppo, 2000).

While composite particles can be more transitory and fragile than discrete sand particles, the fact that they can move into the gravels results in the storage of both the associated contaminants and the organic matter. This is problematic for organisms inhabiting the gravels, since the biological and chemical oxygen demand on the interstitial water can be increased (Storey *et al*., 1999). The presence of fines can, therefore, cause chemical, biological and physical changes to the gravel habitat.

As the focus of this work was to determine the quantity and direction of fine sediment infiltrating into the gravels in high flow conditions, a controlled release event that simulated a flood was generated. The use of a controlled reservoir release to generate a flood wave allowed the resuspension of sediment in the channel system, without the introduction of sediment transported from the catchment. This approach specifically permits investigation of the movement of fine sediment stored within the channel. The artificially generated flood wave simulated bank-full flow conditions similar to those of a storm event and provided an opportunity to measure sediment mobilization and storage before, after and during the flood wave.

THE STUDY AREA

The work was undertaken in the northern part of the Olewiger Bach basin (35 km^2), located in the Northern Hunsrück mountains near the city of Trier in southwest Germany (Figure 1). Devonian shales with quartz and diabase veins dominate the underlying geology. The land use is a mixture of arable land on the plateaus, forests on the north- and east-facing slopes of the valley, and

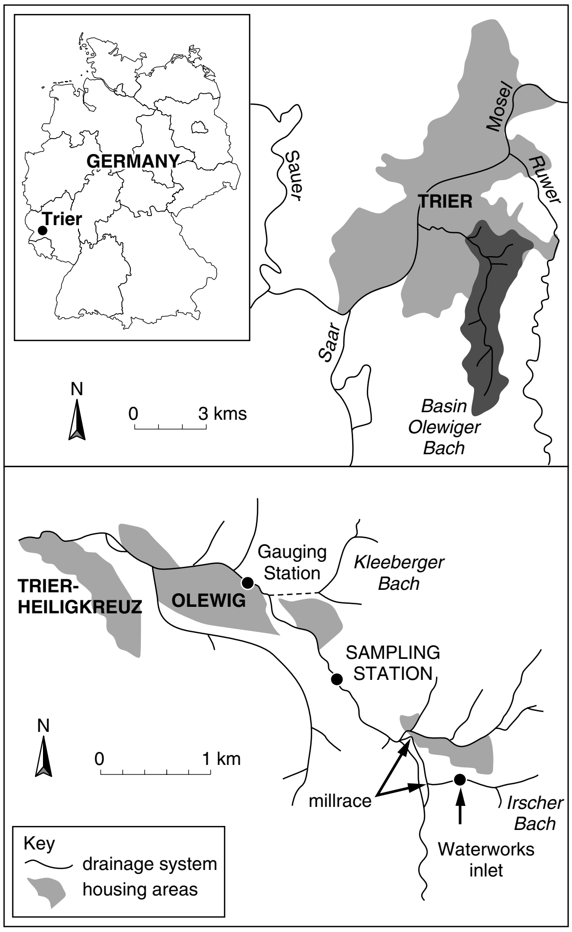

Figure 1. Maps of the field site locations in the Olewiger Bach basin in the region of Trier, Germany. Note the location of the waterworks inlet and the sampling location, which is separated by the 1·8 km of channel the release flows traversed

vineyards on the south-facing slopes. The valley bottom is occupied by pasture.

The Trier municipal waterworks can regulate the discharge of the Olewiger Bach through releases from their drinking-water reservoir that is located in an adjacent basin of the Ruwer River. A pipeline from the drinking-water reservoir can be opened at a waterworks inlet to release water into the Irscher Bach, which is an upstream tributary of the Olewiger Bach (Figure 1). The reservoir water can be released at a known rate to produce a flood wave in the downstream reaches of the study basin. These controlled releases permit the installation of equipment for monitoring conditions before, during and after the simulated flood waves. The release water is characterized by low conductivity values ($<100\ \mu S\ cm^{-1}$) and very low suspended sediment concentrations ($<2\ mg\ l^{-1}$) that aid in tracking the flood wave at points downstream. The path of the flood wave from the waterworks inlet to the downstream gauging station can be separated into four sections of varying slopes and widths. The 2230 m reach upstream of the gauged site (Figure 1) which includes the sample riffles, has a slope of 1·7% and an average width of 2·7 m. Cross-sectional profiles of the Olewiger and Irscher Bach are rectangular with vertical river banks in relatively stable argillaceous material. The gravel-bed Olewiger Bach exhibits a well defined pool-and-riffle pattern, with the riffle gravels having a geometric mean diameter d_g of 13·85 mm. More detailed information about streambed morphology and sediment characteristics is provided by Krein and Schorer (2000) and De Sutter *et al.* (2000).

METHODS

Two controlled release flows were generated in the Olewiger Bach, one representing winter conditions (30 November 1999) and the other summer conditions (8 June 2000). The two release flows were of similar magnitude (Figure 2) and exhibited channel discharges and velocities sufficient to entrain sands and fine sediments. A 120 m reach of the mainstem Olewiger Bach, located approximately 1·8 km downstream of the waterworks inlet (Figure 1), was sampled before, during and after the controlled releases.

The antecedent stream flow conditions for both events are shown in Figure 2. November was a relatively dry month with nearly 20 days of baseflow preceding the controlled storm, whereas the June event was preceded by several large thunderstorms that exhibited high concentrations of suspended sediment and discharge. The surface conditions of the gravels varied between events:

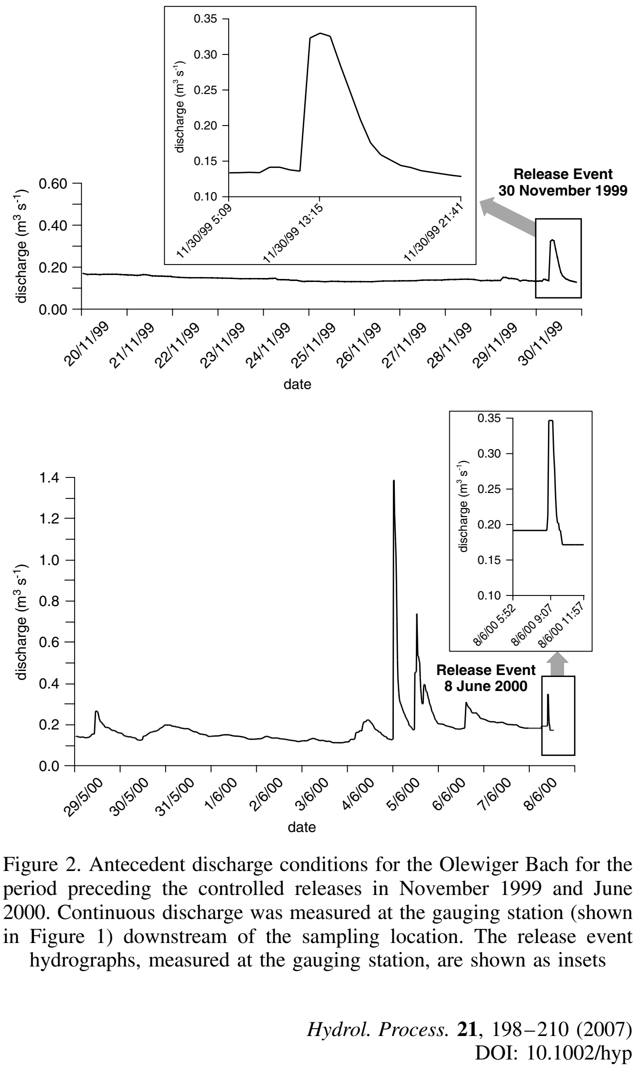

Figure 2. Antecedent discharge conditions for the Olewiger Bach for the period preceding the controlled releases in November 1999 and June 2000. Continuous discharge was measured at the gauging station (shown in Figure 1) downstream of the sampling location. The release event hydrographs, measured at the gauging station, are shown as insets

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the November flows promoted riffle armouring, whereas the antecedent thunderstorms in early June mixed the gravel bed, leaving it loose and unarmoured.

November 1999 release event

Release discharge and suspended sediment. At 10:00 on 30 November the release flows began for the first controlled event. Cross-sectional velocity profiles and suspended sediment concentrations were sampled upstream of riffle 3 before, during and after the passage of the released reservoir water or flood wave (Figure 3). Velocity profiles were measured with an Ott meter, and stage and flow velocity were measured continuously using a Unidata ultrasonic doppler Starflow meter (model 65 268) positioned approximately 8 m downstream on riffle 3. Water temperature and conductivity were also recorded continuously at this location. Grab samples of suspended sediment were collected just below the water surface in the thalweg, upstream of riffle 3, using a wide-mouth Nalgene bottle. We chose to collect surface samples, as we were interested in the fine suspended sediment transport and not the sands saltating nearer to the channel bed. Samples were taken several times before and after

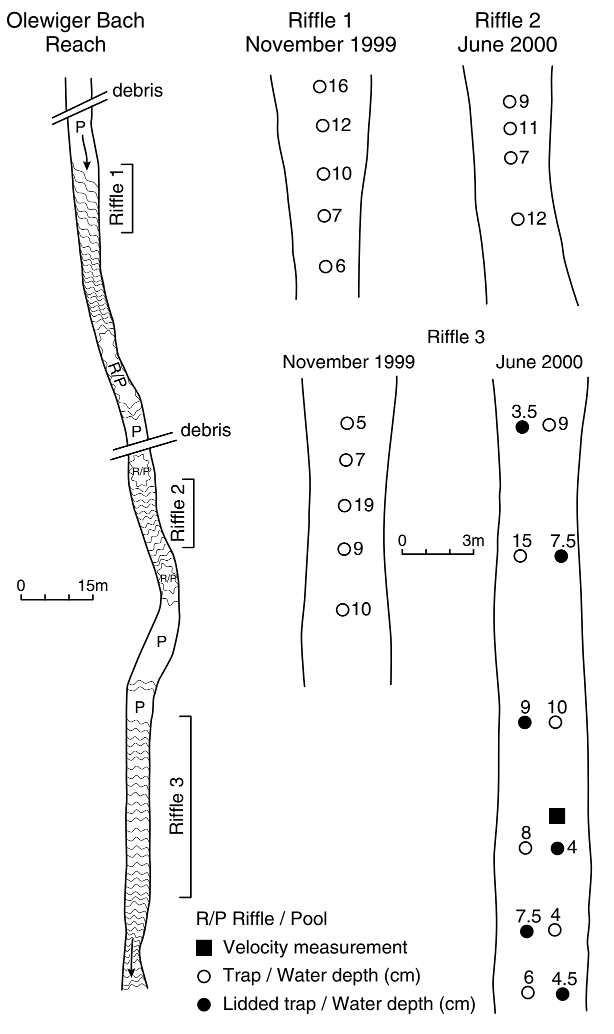

Figure 3. Schematic maps of the geomorphic features of the study reach and the sample layout for the individual riffles

the flood wave passed the station and at more frequent intervals of approximately 3–5 min during the rising and falling limbs.

Channel-stored fine sediment mass. In November 1999, two riffles within the study section were selected for gravel-bed sampling (Figure 3). Pre- and post-release sampling of the riffle gravels was undertaken to determine the amount of fine sediment stored in and on the channel bed. This was done by using a modified method of Lambert and Walling (1986), which involved pushing a 23 cm diameter cylinder into the gravels to form a seal. Following this, the water above the gravels was stirred to resuspend the sediment stored on the gravel bed surface. When stirring ceased, a 10 s settling period was allowed before the top 3 cm of water was sampled using a wide-mouth Nalgene bottle. This time delay allowed the majority of the sand-sized sediment to settle out of the water, such that only material less than approximately 100 μm was sampled. The calculated sediment concentration of the sample, in combination with the total volume of water in the tube above the gravels, permitted the total mass of fine sediment stored on the channel bed to be estimated. Following the resuspension of the surface sediment the gravels were agitated to a depth of 10 cm using a steel ruler. The fines stored to this depth in the gravels were maintained in suspension by stirring and another suspended sediment sample was collected following a 10 s wait to allow the larger sand-sized fraction to settle. These two measurements of the channel-stored fine sediment mass associated with the riffle gravels were undertaken at three locations on each of the riffles both before and after the simulated flood wave.

Gravel-trapped fine sediment mass. Sediment traps were installed in the riffle gravels following the pre-measurements of channel-stored fine sediment described above. In November, each riffle had five gravel traps installed (Figure 3). The traps were placed near the centre of the stream at intervals of approximately 1·5 m. These sediment traps consisted of a collapsible watertight bag that was placed at the bottom of a 25 cm hole dug into the gravels. A cylindrical wire cage constructed from 2 cm mesh was placed in the hole inside the folded-down bag. The cage measured 20 cm in height and 22 cm in diameter and held approximately 10 kg of gravel. With these dimensions, the traps represent approximately double the volume of gravels sampled using the resuspension cylinder. The mesh cage was filled with streambed gravels that had been wet sieved with stream water such that only material larger than 2 mm was retained. The hole surrounding the mesh cylinder was carefully backfilled with washed gravels and the sediment traps were left overnight prior to the release event.

The sediment traps were retrieved after the release event when the stage had returned to baseflow levels. Straps, attached to the upper lip of the folded bag at the base of the hole, had been positioned vertically along the sides of the mesh cylinder during burial so that

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they were accessible at the gravel–water interface and allowed the waterproof bag to be easily pulled up over the gravel-filled mesh cage. This ensured a minimal loss of fine sediment upon retrieval of the sediment trap from the riverbed. For the November event, nine of the ten traps were removed without any problems and each was placed into a bucket. The water and suspended sediment contained within the trap were transferred through a 2 mm sieve into a second calibrated bucket immediately, while in the field. The water was sampled for sediment particle size and the trap gravels were then thoroughly washed through a 2 mm sieve into the bucket, to release any fine sediment stored within the gravel. The water in the bucket was then sampled to determine the fine sediment concentration.

Particle size analysis. Subsamples of the channel-stored, suspended and gravel-trapped sediment were collected and analysed for absolute particle size (APS) of the inorganic fraction at the Bedford Institute of Oceanography. The sediment size spectra were obtained using a Coulter Counter Multisizer that can provide concentrations of particles in size classes from 0·5 to 1000 μm. The sample preparation methods, including organic matter removal by low temperature ashing, are detailed in Milligan and Kranck (1991). The channel-stored and gravel-trapped sediment samples had been artificially truncated at approximately 100 μm through the timing of the subsampling, but the suspended sediment samples collected from the water column represented the wash load, which was not truncated. Therefore, the Coulter counter was set up to size particles between 0·6 and 400 μm if they occurred in the samples.

Gravels contained in three of the nine sediment traps were returned to the laboratory for sizing using a nest of sieves that included 2, 4, 6·3, 8, 16, and 20 mm sizes. Grain size distributions were used to determine the geometric mean diameter d_g, a sorting index S_o and the Fredle index f_i. These parameters provide surrogate methods of characterizing porosity and are calculated thus:

$$d_g = d_1^{W1} d_2^{W2} \ldots d_n^{Wn}$$

$$S_o = (D_{75}/D_{25})^{0.5}$$

$$f_i = d_g/S_o$$

where d is the midpoint diameter of particles retained by a given sieve (1 to n), W is the decimal fraction by weight of particles retained by a given sieve (1 to n) and D_{75} and D_{25} respectively represent the diameters of the 75th and 25th percentiles of the sample (Lotspeich and Everest, 1981).

June 2000 release event

Similar sampling procedures as those described above were used for the controlled release on 8 June 2000, but in this case riffles 2 and 3 were sampled (Figure 3). This change was made because the water depths and the surface structure of the riffles appeared more comparable than riffles 1 and 3 at the time. Riffle 2 was located 30 m upstream of riffle 3, which was the same downstream site as used in November. Pre- and post-release channel storage of fine sediment mass at the surface and at 10 cm depth was determined in the gravels of both riffles with the same procedures used for the November samples. The upstream site had four traps buried in the thalweg that was approximately the middle of the 3 m wide stream. The downstream riffle had 12 traps installed, with pairs being placed approximately 1 m apart near the middle of the 4 m wide channel. In this downstream riffle, one of each pair of traps had a lid covering the surface of the trap that was kept in place for the complete period. These lids prevented sediment or water from entering or leaving the trap at the gravel-water interface, thereby allowing sediment retention associated with lateral flows to be determined. Lidded and unlidded traps alternated from the right to the left side of the trap pairs (Figure 3). All 16 sediment traps were retrieved successfully. APS analysis was undertaken on selected samples of channel-stored sediment and suspended sediment from the June release. Gravel sizing of all samples was undertaken in June for determination of size indices. Water depth and velocity over each of the 16 traps was recorded using an Ott current meter under baseflow conditions, which allowed the calculation of the Froude number. These parameters were not measured at each of the trap sites during the release event as we did not want to disrupt sediment transport processes by wading in the stream. We used these pre-release measures as a relative comparison of site condition differences.

As mentioned previously, the antecedent conditions for the 8 June release flow event included three natural storm events in the three preceding days, two of which exceeded the peak discharge of the controlled flows (Figure 2). Suspended sediment concentrations in the stream had returned to relatively low levels preceding the release event (11 mg l^{-1}), but a modification to the sediment trap deployment involved burying a plastic sheet vertically on the upstream side of the trap cage when it was deployed, to ensure that overnight movement of turbid water, or another evening thunderstorm, would not bias the trap results. This plastic sheet was easily removed 15 min prior to the start of the controlled release.

RESULTS

Release discharge and suspended sediment

The two flood waves generated with the controlled reservoir releases exhibited similar maximum discharges, but different periods of duration, with the November release returning to baseflow conditions in 3·5 h and the June release taking only 1·3 h, as shown in Figure 2. Discharges measured at the sample station, located approximately halfway between the waterworks inlet and the continuous gauging station, exhibited slightly higher maximum discharge values of 0·42 $m^3 s^{-1}$ and

0·35 m^3 s^{-1} for November and June respectively. Suspended sediment concentrations were higher in the June release, with maximum values reaching 753 mg l^{-1}, whereas a maximum concentration of 546 mg l^{-1} was recorded in November. The suspended sediment concentration data for the releases in both seasons exhibited reverse hysteresis, with lower concentrations on the rising limb than on the falling limb (Figure 4). Although not shown here, the same behaviour was also noted at the downstream continuous gauging station (Figure 1).

The APS analysis of the stream's inorganic suspended sediment from the November event indicated that baseflows preceding the release carried a maximum particle size of 64 μm ($n = 3$) when suspended sediment concentrations were 8–9 mg l^{-1} (Figure 5a). On the rising limb, five samples that were collected as the discharge and suspended sediment concentrations increased from 0·10 to 0·36 m^3 s^{-1} and 18 to 492 mg l^{-1} had maximum sizes of 75–97 μm. On the falling limb, the reverse hysteresis was apparent when discharges equivalent to those on the rising limb carried higher concentrations of suspended sediment (100–546 mg l^{-1}). The seven APS samples from the falling limb indicated that the maximum particle size transported in suspension had decreased to 24–37 μm. Figure 5 presents the APS spectra for baseflow and three discharge regimes. At approximately equivalent discharge

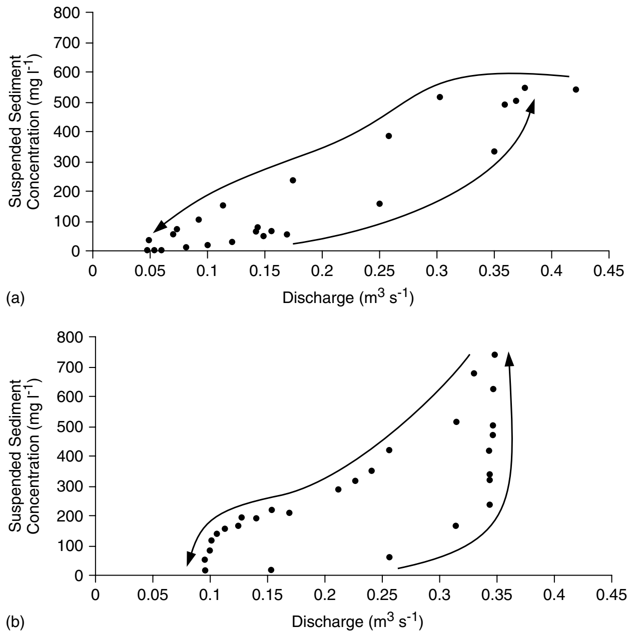

Figure 4. Suspended sediment concentrations at measured discharges for the two release events in (a) November 1999 and (b) June 2000. Both sets of measurements were collected at the sampling station, 1·8 km downstream of the waterworks inlet (Figure 1). The temporal order of sampling, as shown by the arrow, indicates lower concentrations on the rising limb, or a reverse hysteresis for both events

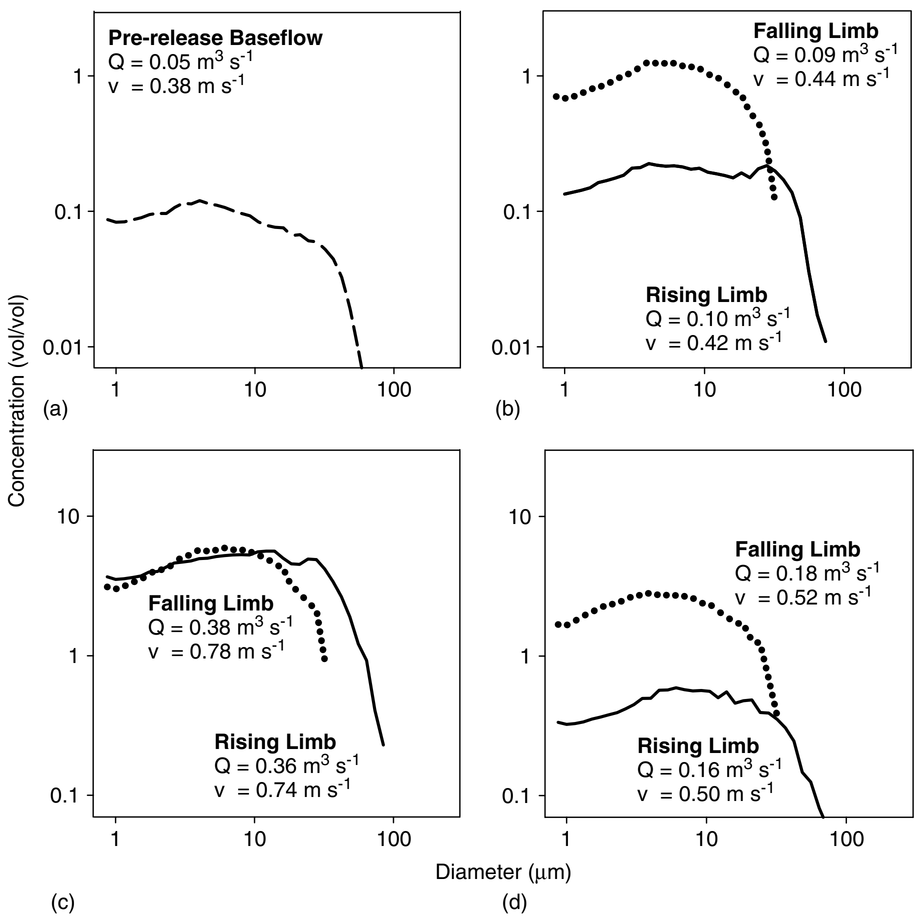

Figure 5. APS spectra for the inorganic sediment fraction of suspended sediments at different times in the release event of November 1999. Concentration on the y-axis is presented as sediment volume (cm^3) per water volume (ml). The reverse hysteresis of higher sediment concentrations on the falling limb at equivalent rising-limb discharge and velocity is exemplified in (b) and (d)

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and velocities, the falling limb shows greater sediment concentrations and smaller maximum particle sizes carried in suspension. The fine sands (between 63 and 100 μm) collected in these samples were being moved in the surface water column on the rising limb, but at equal discharges and velocities they were not present on the falling limb.

During the June release event, seven samples were collected for APS spectra. The controlled release hydrograph has distinct rising and falling limbs in addition to a period of about 20 min of steady peak discharge (Figure 2). One baseflow, one rising limb, three peak discharge and two falling limb samples were collected for APS analysis. At this time of year as well, the maximum particle size suspended in pre-release baseflow was 64 μm. Maximum suspended sediment APS was again largest on the rising limb and in the peak flows (75 μm) and reduced to 55 μm in the falling limb. The June release event exhibited the same trend as the November event in terms of APS grain sizes, but the differences in maximum particle size for the rising and falling limbs were not as extreme.

Channel-stored fine sediment mass

The mass of fines stored on the surface of the natural gravels before and following the release flows is shown in Figure 6. In November, the mass of fines settling onto the surface of the gravels ranged between 2 and 5 mg cm^{-2} and were not significantly different ($p < 0{\cdot}05$) before and following the release event. The sediment stored to a depth of 10 cm shows more variation spatially and temporally. Pre-release conditions indicated 23–33 mg cm^{-2} of stored fine sediment, whereas post-release values were significantly lower ($p < 0{\cdot}05$) at 9–13 mg cm^{-2}. The June surface sediment storage was of similar magnitude to the November pre-release conditions, 2–6 mg cm^{-2}, but less sediment was stored on the surface gravels post-release. In both riffles, fine sediment stored at depths of 10 cm also decreased following the June release, but greater sample variability meant that pre- and post values were not statistically different. A comparison of the results of the pre- and post-release storage of fines in natural gravels indicated that the November release acted to flush fine sediment from within the gravels, whereas higher sample variability masked the significance of this effect in June.

Figure 7 presents APS spectra for naturally stored fine sediment pre- and post-November release. For both the surface and the gravel-stored (10 cm) samples the pre-release exhibits larger maximum grain sizes. Specifically, the 60–100 μm class is present at both depths pre-release but is absent in both surface and 10 cm storage post-release. The natural gravels appear to have been flushed of larger grain sizes (60–100 μm).

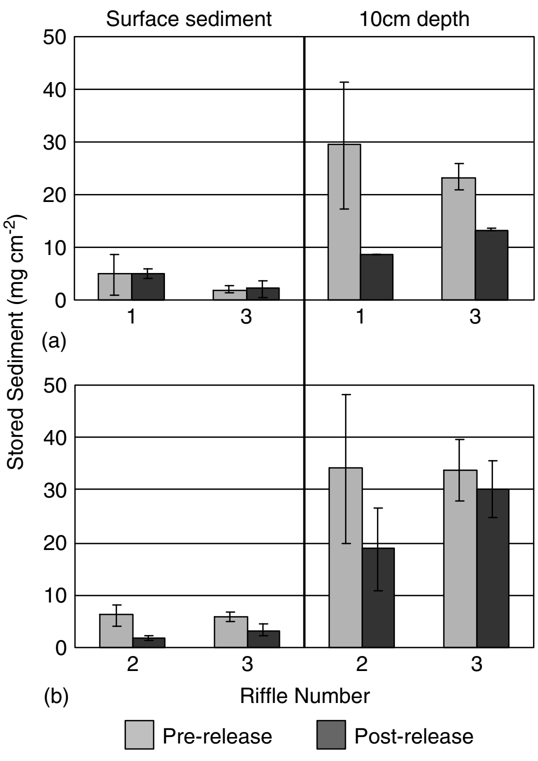

Figure 6. A comparison of fine sediment stored in the natural gravels in upstream and downstream riffle sites preceding and following the (a) November 1999 and (b) June 2000 release events. The surface-stored sediments and the sediment stored to a depth of 10 cm are presented for each event on the left and right sides of the figures respectively. The error bars represent one standard error

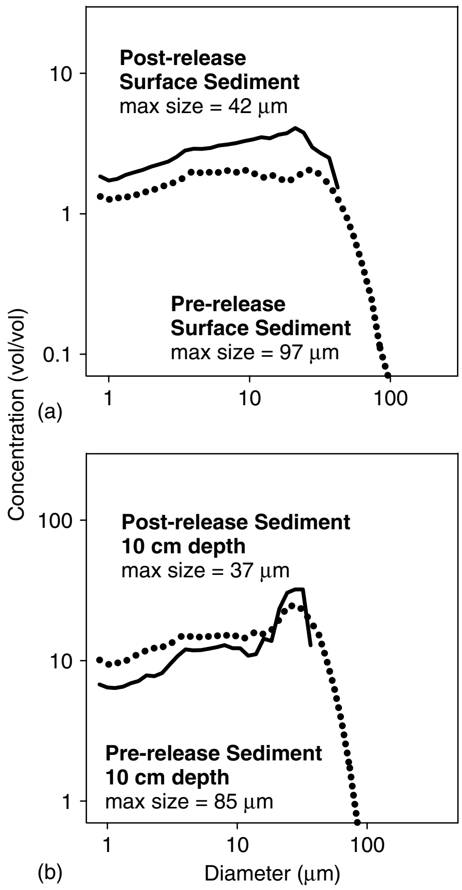

Figure 7. APS spectra for pre- and post-November release event fine sediments collected from (a) surface storage and (b) to 10 cm depth in natural riffle gravels

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Gravel-trapped fine sediment mass

For the nine sediment trap samples recovered after the November release, the amount of fine material collected in the traps ranged between 40 and 120 mg cm^{-2} (Figure 8a). In the June release event, the 16 traps collected between 55 and 145 mg cm^{-2} of fine sediment (Figure 8b). As indicated above, the June sampling protocol was modified to clarify the directional source of the infiltrated sediment. Figure 8b shows the amount of sediment stored in traps in the upstream and downstream riffles, but also identifies the traps that were lidded during the controlled release. When comparing the six sets of traps, the lidded traps of each pair provided the highest values for trapped fine sediment, with only one exception (trap 15 > trap16).

The mass of sediment collected in the 20 cm deep traps can be compared with post-release, natural gravel storage, as it represents approximately twice the volume of the natural gravels sampled to a depth of 10 cm. Figure 6 indicates that June post-release fine sediment storage, to a depth of 10 cm, in natural gravels ranged between 18 and 30 mg cm^{-2}, whereas in November it was approximately half that (9–13 mg cm^{-2}). For both controlled releases, all but one of the sediment traps (June, trap 11) contained at least double the mass of the maximum amount of fine sediment found in the post-release natural gravels, indicating that these open mesh traps are very effective in collecting fine sediment.

The APS of the gravel-trapped fine sediments was only measured for the November release. Figure 9 indicates that the size composition of the post-release trapped sediments was very similar in size composition to the falling limb suspended sediments.

Gravel particle size characteristics

Parameters characterizing the channel gravel structure in the 16 traps in June were not very useful in explaining the variance in the amount of gravel-trapped fine sediment. Although the proportion of pore space and Fredle index exhibited positive relationships, they explained only 1% and 21% respectively of the variance in the mass of fine sediment trapped. Water depth, velocity and Froude number measured above the traps before the release during baseflow (Table I) were all significantly related to the mass of trapped fine sediment, explaining 43%, 70% and 81% of the variance

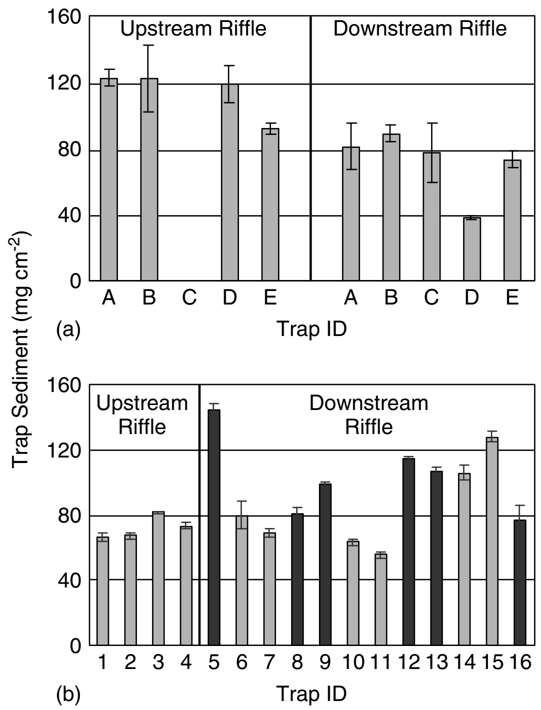

Figure 8. (a) Mass of fine sediment caught by traps in two riffles in the November 1999 controlled release event. (b) Fine sediment mass trapped at 16 sites during the June 2000 release event, which was preceded by several large thunderstorms. Note that six of the 16 traps were installed with surface lids. Lidded traps are shown as black bars. The error bars represent one standard error

Table I. June 2000 baseflow conditions, gravel trap response and gravel composition

Flow conditions				Gravel trap conditions		Gravel characteristics				
Trap no.	Water depth (cm)	Velocity (m s^{-1})	Froude no.	Trap sediment (mg cm^{-2})	Gravel–water interface	d_g	D_{25}	D_{75}	Sorting index	Fredle index
1	9·0	0·277	0·09	66·47	Open	11·56	3·30	17·25	2·29	5·06
2	11·0	0·337	0·11	67·14	Open	12·69	4·00	17·80	2·11	6·02
3	7·0	0·533	0·41	81·67	Open	14·71	6·30	18·25	1·70	8·64
4	12·0	0·300	0·08	73·39	Open	13·06	4·00	17·80	2·11	6·19
5	3·5	0·617	1·11	144·70	Lidded	15·71	6·60	18·50	1·67	9·38
6	9·0	0·440	0·22	79·52	Open	15·17	6·30	18·40	1·71	8·88
7	15·0	0·317	0·07	69·27	Open	14·48	6·20	18·25	1·72	8·44
8	7·5	0·390	0·21	80·67	Lidded	14·79	6·20	18·25	1·72	8·62
9	9·0	0·497	0·28	98·47	Lidded	12·78	4·50	17·50	1·97	6·48
10	10·0	0·373	0·14	63·14	Open	13·54	4·90	18·00	1·92	7·07
11	8·0	0·457	0·27	55·82	Open	13·30	4·50	17·90	1·99	6·67
12	4·0	0·567	0·82	113·90	Lidded	13·40	5·50	17·90	1·80	7·43
13	7·5	0·620	0·52	106·21	Lidded	14·20	6·30	17·00	1·64	8·64
14	4·0	0·590	0·89	105·56	Open	12·46	3·75	17·75	2·18	5·73
15	6·0	0·670	0·76	127·50	Open	15·78	6·60	18·25	1·66	9·49
16	4·5	0·403	0·37	77·20	Lidded	13·98	6·20	17·00	1·66	8·44

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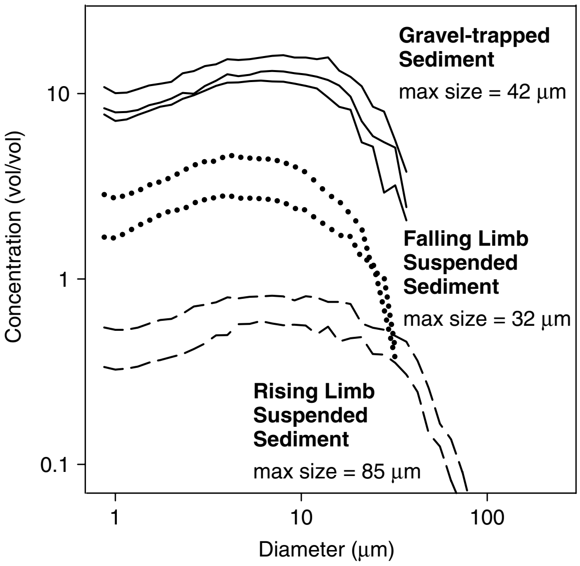

Figure 9. Comparison of APS spectra from the 1999 gravel traps and the 1999 rising and falling limbs of the hydrograph

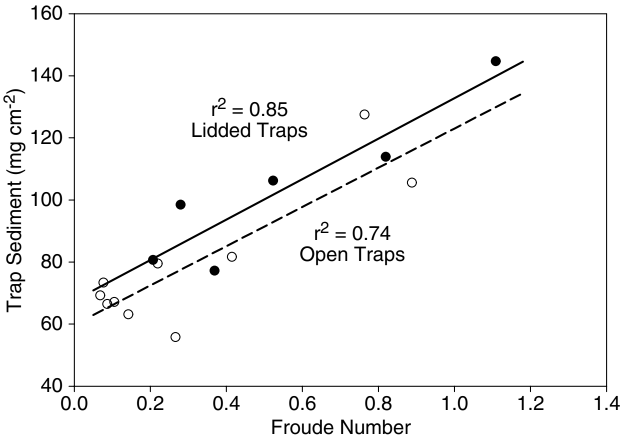

Figure 10. Relationships between the Froude number, as determined from June pre-release water depths and velocities, and sediment collected in traps following the release event. Data for lidded traps are represented by filled circles and a solid line; open traps are shown as open circles and a dashed line

respectively. Figure 10 shows the regression relationship between Froude number and sediment collected for both open and lidded traps. The slopes of the two lines are not significantly different, but the intercept of the lidded traps is elevated approximately 8 mg cm^{-2} above that of the regression line for unlidded traps.

DISCUSSION

Release flows and suspended sediment

The use of reservoir releases to generate flood waves in natural river systems is an excellent means of controlling the supply of sediments by limiting it to bank and channel bed sources. In the Olwiger Bach, the channel banks are relatively stable and no evidence of bank slumping was observed before or after the release events; therefore, we assumed that the majority of the sediment we measured moving in the release events was previously channel-stored.

Given the restricted sources of sediment supply, the high concentrations of suspended sediment evidenced in both the winter and summer release events allows us to distinguish the dynamic nature and importance of channel bed storage as a source of fine sediments. The observations of reverse hysteresis in this system indicate that sediment mobilization, which in this case includes only in-channel sources, is delayed relative to the available energy. The release wave has the ability to entrain the fine sediment on both the rising and falling limbs, but it does not carry its highest concentrations on the rising limb. The source of sediment on the rising limb would be the fines stored on the surface of the river bed, a small amount from the channel banks and material that is mobilized from the interstitial spaces in the gravel. Temperature and conductivity measurements of both flood waves indicate that the arrival of the reservoir water at the sampling site 1·8 km downstream of the waterworks inlet was delayed relative to the change in stage. This means that the rising limb is composed of water being pushed ahead of the flood wave, whereas the reservoir water arrives at the monitoring site only a few minutes ahead of the peak suspended sediment concentration and comprises the water of the falling limb. Therefore, the increase in suspended sediment concentrations over the period of the rising limb, before the arrival of reservoir water, reflects the delivery of material from progressively further up-channel as the wave preceding the reservoir release water moves past the sampling station. With the arrival of the reservoir water, which initially was almost devoid of suspended sediment, higher concentrations of fine sediment are carried past the study site. These higher concentrations on the falling limb can be explained in two ways. At the upper portion of the stream channel, an approximately 400 m section of channel, termed the millrace, comprises a gravel bed covered with a surface layer of fine sediments. The increased entrainment velocities of the release water would resuspend this fine sediment and transport it downstream. A second explanation is that the falling limb of the release event could carry more fines than the rising limb by having an increased source area for fines. Although the total surface area of channel scoured by the reservoir water is the same as for the rising limb wave that precedes it, the volume of gravels flushed by this water could be increased over time. This implies that the sediment on the falling limb has fine sediment contributions from deeper within the gravel bed.

Gilvear and Petts (1985) noted the same reverse hysteresis in a release flow that they monitored, although they found no differences in fine sediment particle size structure over the event. In our case, grain size analysis of the inorganic fraction of suspended sediment collected during the rising and falling limbs of the November event indicate that the rising limb is comprised of particles up to 97 μm in size and the falling-limb samples were depleted in fine sands and larger silts and exhibited maximum

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sizes in the range 25–37 μm. Equivalent discharges (and, therefore, velocities) on the rising and falling limbs show a consistent depletion of larger sized fine particles on the falling limb, indicating a source rather than a competency limitation (Figure 5). It is important to appreciate that the APS analysis represents inorganic, dispersed fine (<100 μm) sediments and, therefore, does not inform us of the natural or effective size of the sediments that would be moving as aggregates or flocs in the stream.

Channel-stored fine sediment mass

Given that only small amounts of fine sediment are stored on the surface gravels along the majority of the stream channel (Figure 6) and that suspended sediment concentrations reach very high levels in these simulated release flows, it is apparent that the inter-gravel sediment is available for removal and is redistributed in release events. The loss in mass of the deeper (10 cm) naturally stored fine sediments following the release events (Figure 6) confirms the dynamic nature of the channel-stored sediment and indicates that it is mobilized during flow events. The antecedent discharge conditions for both release events (Figure 2) indicate that November was a relatively dry month with nearly 20 days of baseflow preceding the controlled storm, whereas the June event was preceded by several large thunderstorms that exhibited high concentrations of suspended sediment and discharge. The surface conditions of the gravels were quite different, in that the November low flows were not of sufficient magnitude to move the gravels, thereby promoting armouring, whereas the antecedent thunderstorms in early June left the surface gravels unarmoured. In addition, the earlier storms provided an increased supply of channel-stored sediment from sources that included both channel sediment and sediment eroded from the surrounding catchment. These storms can explain the higher amounts of gravel-stored (10 cm) sediment indicated in the June pre-release sampling (Figure 6). This is corroborated by the fact that discharge regimes with maximum values of 0·42 $m^3 s^{-1}$ and 0·35 $m^3 s^{-1}$ were inversely related to maximum suspended sediment concentrations of 500 mg l^{-1} and 750 mg l^{-1} in November and June respectively. The November low flow antecedent conditions are likely responsible for a relative supply deficiency in the channel-stored sediments.

The reduced amounts of natural channel-stored sediment found post-release (Figure 6) indicate that, over the course of the release event, the flows are acting to flush fines from the gravels. This is corroborated by the higher concentrations and smaller maximum grain sizes observed on the falling limb of the release hydrograph (Figure 5). It would appear that a surface sand cap noted in many flume (Beschta and Jackson, 1979; Carling, 1984; Lisle, 1989) and field experiments (Sear, 1993, Soulsby *et al*., 2001) was removed from the channel bed on the rising limb, thus allowing the fine sediment stored deeper in the gravel to be flushed out of, or through, the gravels. Note that fine sands were observed in all of the November rising-limb samples but in none of the falling-limb APS analyses (Figure 5). This would mean the sand cap was destroyed and transported in the high flows of the rising limb. The APS spectra in Figure 7a and b show evidence of this sand cap on the pre-release surface sediments. Although the fine sand also appears in the pre-release 10 cm stored fines, this may be an artefact of the sampling technique as the surface sediments must be resuspended along with the deeper gravels to obtain the 10 cm sample. Note in Figure 7b that the modal size of the gravel-stored (10 cm) samples is approximately 27 μm and this fine sediment is nearly an order of magnitude more abundant (see *y*-axis, concentration) than the sediment on the surface of the gravels (Figure 7a). This supply of channel-stored fine sediment could be mobilized by inter-gravel flows releasing it to the surface waters when the sand cap is removed.

The June APS spectra for the release hydrograph do not show the same strong difference in maximum particle size for the rising and falling limbs, but the spectral mode sizes do decrease consistently on the falling limb, indicating a change in the source material structure and not the competence of the flows. Greater quantities of finer sediments are being transported on the falling limb of this release event as well, although the surface sand cap was not in evidence before the event. The absence of the sand cap is probably due to the frequent, large antecedent storms that broke up the armoured gravel bed surface and allowed the deeper infiltration of sands. The delay of maximum concentrations of fine sediment delivery when no sand cap was in place may indicate that there is a delay in flushing fines from deeper gravel depths or that the dominant source of the fines on the falling limb comes from the millrace reach (Figure 1). The APS spectra for samples of the millrace surficial sediment indicate a maximum grain size of 73 μm with an average mode size of 24 μm. This is similar in mode size to the deeper gravel-stored fine sediment and, therefore, it is likely that the higher concentrations noted on the falling limb are a combination of the two sources of fine sediments. Investigations as to the timing of sediment release from deeper in the gravels could also be undertaken in the future.

Gravel-trapped fine sediments

The flow of water through the gravels moves material both out of and into the gravels, sometimes acting as a flushing flow and in other conditions causing the gravels to act as a sink for fines. The results from the gravel traps indicate that fine sediments are mobilized and redistributed in the gravel bed during high flow events as sediment is moved into and out of the gravels from both the surface and laterally through the gravels (Figure 8). The traps with surface lids had larger amounts of trapped fines, implying that lateral flows through the gravels are depositing more sediment than in open traps, where the flow can enter and exit at the gravel-bed surface.

The size of the sediment collected in the traps reflects a potential mixture of two sources, i.e. millrace and

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gravel-stored fines, as the APS spectra are very similar in size composition to the falling-limb suspended sediments (Figure 9) but exhibit slightly larger modes. The efficiency of the gravel traps in collecting fine sediments exceeded that of the natural gravels by a factor of two. This is a function of the traps being prepared with washed, recently packed gravels that would have a higher porosity than natural gravels, which have settled and packed over time and whose interstitial spaces already contain fine sediments.

Solid-walled containers have been used in several experiments aimed at measuring fine material infiltration into bed sediments, (Slaney *et al.*, 1977; Beschta and Jackson, 1979; Carling, 1984; Frostick *et al.*, 1984). These will only collect the sediment that enters a volume of bed material through surface interstices. Material that is introduced laterally by inter-gravel flow, which can have high instantaneous acceleration due to turbulence near the bed, is excluded. Einstein (1968), Slaney *et al.* (1977) and Beschta and Jackson (1979) state that gravity fall is the dominant mode of ingress of fines into the gravel bed. However, Carling (1984), working in a flume, reported that solid-walled containers reduced the trapping efficiency to 62%, presumably due to the elimination of inter-gravel flow distributing sediment throughout the samples. The results of this investigation highlight the role of inter-gravel flow in redistributing fine sediment in natural river gravels.

Water flow conditions, including Froude number and water velocity, measured at the 16 gravel trap sites preceding the June release event were found to be good predictors of inter-gravel fine sediment trapping (Figure 10). The Froude numbers reflect the interaction between flow depth and velocity. As water depth decreases and velocity increases the Froude number increases. The flow of water over bedforms has been measured in the field, especially in the context of characterizing flow over salmon redds (e.g. Everest *et al.*, 1987). The reduced water depth over the crest of the redd generates accelerated flows at this location, whereas decelerated flows with potential for deposition occur in the lee of the redd. Observations of in-bed convection currents, in porous bed material, generated by small obstructions (Thibodeaux and Boyle, 1987) indicate that the flow of water flow through dune bedforms, which are similar in shape to redds, can be effluent at the crest of the dune and influent in the trough, where the water pressure is higher. Given that these processes occur when water flows easily through the gravels, as would have been likely in June with a poorly armoured bed, the sites that have high Froude numbers (shallowing of water and increased flow velocity) would be receiving water from flowlines within the gravels and potentially sieving the fines from the pore water. As there were not large variations in either the gravel sorting or Fredle indices of the 16 samples, the sieving ability of the gravels was expected to be similar. If this is the case, but differences in inter-gravel flow are generated by small elevation differences along the riffle, then we would expect to see a correlation with both velocity and Froude number. Further corroboration of this explanation is provided by the increase in trapped fines associated with lidded traps, as shown in Figure 10. For similar flow conditions, lidded traps collected nearly 8 mg cm^{-2} more fine sediment than unlidded traps. This indicates that the lids are preventing material from leaving the traps at the gravel–water interface. According to Thibodeaux and Boyle (1987), effluent flow should be maximized at the bedform crest, where streamflows are fast and shallow, exhibiting high Froude numbers, so more inter-gravel sediments would pass though these sites. Conversely, in the deeper, slower water, reduced inter-gravel accumulation of fines would be offset by increased surface accumulation associated with interception and gravitational settling in slower flows.

It would be of interest to test the relationships shown in Figure 10 using velocity and depth data collected at several times during the release event, as they would reflect better the dynamic conditions redistributing the sediment within the gravel bed. As indicated earlier, we did not do this as we did not want to disturb the gravels during the release event. Although the 12 traps in riffle 3 were set up in pairs, the initial flow and depth conditions were not equal, as indicated in Figure 3, and, therefore, cannot be compared as sets. Five of the six pairs had lidded traps in the shallower water, such that the inter-gravel flows would have been dominant. But the patterns shown in Figure 10 indicate that for similar flow conditions the lidded traps tended to collect more sediment than the open traps, as the lids prevented any effluent surface flows from removing inter-gravel sediments from the traps. This confirms the importance of the inter-gravel flows in redistributing channel-stored sediment in natural gravel-bed rivers.

CONCLUSIONS

The use of managed release flows from upstream reservoirs to natural stream channels allows a degree of control over the source of sediment moving in high flow events. In both the winter and summer, controlled release flows mobilized abundant fine sediments within the channel bed, verifying the importance of channel surface and gravel storage as a sediment source in gravel-bed rivers. Fine-grained sediment mobilization was found to be delayed relative to the available energy, as indicated by the reverse hysteresis. This, combined with evidence of reduced post-release storage within natural gravels, indicated that fines stored deeper in the gravel beds were being released to the surface waters and redistributed. The postulated destruction of a sand cap in the November event during the rising limb would have facilitated the release of the fines stored at depth in the gravels. The variation between the two events reflects the importance of the antecedent flow conditions in regulating the conditions for sediment transport, since the lack of armouring due to antecedent storms was thought to enhance the transfers of fine sediment from within the gravel bed in the June event.

The dynamic nature of the channel-stored fines and their significance as a sediment source during storm events is corroborated by the changing mass of sediment observed in both the natural gravels post-release and the collection of fines by the gravel traps. Although the sieving characteristics of the gravels (sorting index, Fredle index) were not found to be significant in explaining the variation in trapping efficiency in the June release event, the flow parameters were noted to be important. Contrary to other field studies, the Froude number was found to be a useful predictor of the amount of fine sediment trapped. This, combined with the observed increase in fine sediment trapped at lidded sites, confirmed the significant role of inter-gravel flows in transporting fine sediment.

The amount of channel-stored fines can influence habitat quality for benthic organisms, being beneficial when it serves as a food vector but deleterious in large amounts as it can reduce the transfers of oxygen. The quality of the stored sediment is also a factor regulating habitat conditions, as it may include adsorbed contaminants that can be released in the gravel matrix. As both the magnitude of stored sediment and its quality are important in maintaining aquatic processes, these findings on the dynamic nature of channel-stored fine sediment, along with evidence regarding the significance of lateral transfers with the gravel-bed matrix, are important in both a geomorphic and a biological context.

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