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

E. L. Petticrew,[1]* A. Krein[2] and D. E. Walling[3]

[1] School of Geography, University of Plymouth, Plymouth, Devon, UK
[2] Department of Environment and Agro-Biotechnologies, Public Research Centre Gabriel Lippmann, Belvaux, Grand Duchy of Luxembourg
[3] Department of Geography, University of Exeter, Exeter, Devon, UK

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 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. Copyright © 2006 John Wiley & Sons, Ltd.

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
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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

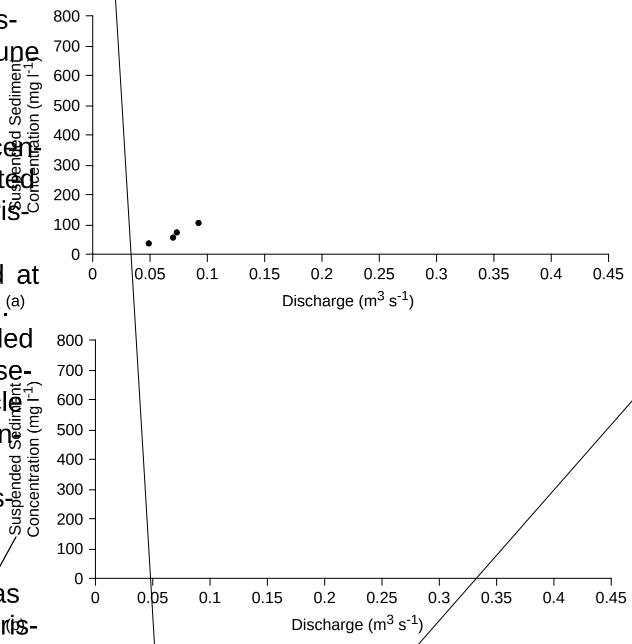
the November flows promoted riffle armouring, whereas the antecedent thunderstorms in early June mixed the gravel bed, leaving it loose and unarmoured.

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 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

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 64μm ($n = 3$) 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 75–97μm. 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 24–37μm. Figure 5 presents the APS spectra for baseflow and three discharge regimes. At approximately equivalent discharge

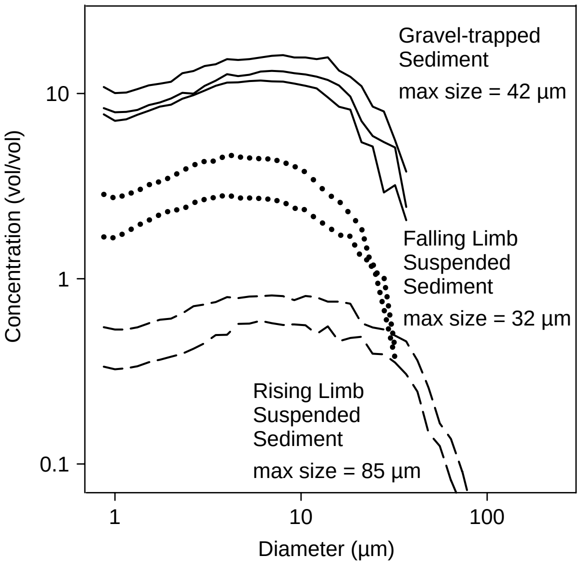


and velocities, the falling limb shows greater sediment concentrations and smaller maximum particle sizes car-

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 half2i(post-relea6)-421.9o sixh4 Tc eoublTD 0meT(twice)5(that)2 TD m().)516raps,dimen0.meT(twmhe)-6a8


Gravel-trapped
Sediment
max size = 42 µm
Falling Limb
Suspended
Sediment
max size = 32 µm
Rising Limb
Suspended
Sediment
max size = 85 µm
Concentration (vol/vol)
10
1
0.1
1
10
100
Diameter (µm)

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

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

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