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Unravelling flood history using matrices in fluvial gravel deposits

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Abstract Experiments carried out in a laboratory flume have shown that the infiltration of sands into gravels is largely controlled by flood magnitude and frequency. Three sets of experiments were used to simulate low flows, small floods and large floods and these showed that at low and moderate flows almost all sand stays close to the surface; however, during large flood events the surface framework particles are entrained, the bed dilates and material falls through the pore spaces and accumulates at the base of the bed. In addition, bed load transport is enhanced when gravels are mixed with sand and heavy and light minerals become separated. These results suggest that the distribution of matrices in gravels carries with it a signal linked to flood history which might be unravelled given careful research.

Key words bed load; flood history; gravel bed; river deposits; sediment mixtures

INTRODUCTION

Understanding the impact of flood magnitude and frequency on bed material character is central both to the interpretation of preserved alluvial sequences and to predicting the impact of climate change on our river systems. The latter is particularly significant since predictions for many parts of the world, where weather systems track across a warming sea surface, are for increasing frequency of major storms as climate change progresses. Such changes are already evident in the UK (Hadley Centre, 2003) and will become increasingly unpredictable as climate change progresses. This will impact on river hydrology which in turn will trigger alterations in patterns of sediment transport, river bed characteristics and ecology. Finding ways of both predicting and adapting to these changes is therefore a priority.

Studies of the impacts of climate change on river systems are generally informed by data extracted from preserved river deposits from different climatic periods. However, these carry with them the disadvantage that the record is invariably incomplete and exposures are two-dimensional representations of three-dimensional structures even where preservation is good (Jones *et al.*, 2001). However, when preservation is poor little can be inferred except perhaps a measure of mean/maximum flow velocity derived from grain size. Detailed studies tend to rely on the examination of either flood plain or basin sediments (e.g. Walling & Bradley, 1989; Reid & Frostick, 1993).

This study reports a series of laboratory experiments whose results suggest that there might be recognizable distinctions between river bed deposits after floods of different magnitude and frequency in rivers where the sediment size available for transport ranges from coarse gravel to fine sand. If this is the case, then there are opportunities both to improve and refine our interpretations of alluvial deposits and use these insights to infer future impacts of progressive climate change on river bed character and ecology.

EXPERIMENTAL PROGRAMME AND PROCEDURES

Experiments were carried out in a standard, Armfield S6, glass-sided, tilting flume (12 m × 0.3 m × 0.45 m). The channel was 0.3 m wide and the working section was in the central 3 m of the channel unaffected by inlet and outlet flows. The sediments comprised a gravel framework with a mean grain size of 8 mm and in some of the experiments three different mixtures of sands were added, all with mean grain sizes of between 0.07 and 0.09 mm but with two different densities (quartz 2.65 t m^{-3}, olivine 4.2 t m^{-3}). In most sand-gravel mixture experiments quartz sand was used, but in selected runs olivine sands were used either on their own or mixed 1:1 with crushed quartz sand.

The experimental conditions were designed to simulate three hydraulic scenarios (Table 1): low flows where the bed does not undergo major disturbance; moderate flows where the framework was disturbed to a limited extent, causing "fluttering", but not displacement; and high flows in which the whole bed surface was both disturbed and displaced.

At the beginning of each experiment a framework of coarse gravel particles, some coloured white with black dots, was introduced into the flume. Sands were introduced upstream of the experimental reach and allowed to migrate across the surface framework pores. Traps were introduced into the bed of the flume beneath gravels to catch any sand penetrating to the base of the bed. The white particles were filmed using digital video cameras directed through the side wall of the flume. Parts of the bed were frozen and extracted and the sediments examined to assess the impact of side wall effects. These proved to be minimal and movements recorded through the side wall of the flume can be considered to be reasonably representative of the bed as a whole.

In addition, several new and existing image analysis techniques were used to process the digital video image data collected during the experiments. The first was reported in Middleton *et al.* (2000) and tracks the movement of marked particles through progressive video frames. The output from this program was used in a new application to identify the gross temporal patterns of significant particle movement. This produces a graphical display of the bed movement at any time in the sequence, which was invaluable for identifying the timing of significant sediment entrainment "events" and in calculating bed load transport.

A technique for detecting significant areas of matrix movement using between-frame differences in pixel values has already been demonstrated under the same

Table 1 Experimental conditions designed to simulate three hydraulic scenarios.

Experiment	Mean velocity (at 0.6 depth) (m s^{-1})	Average water depth (m)	Froude range
Low flows	<0.4	0.12	0.3–0.4
Moderate flows	0.46	0.12	0.4–0.5
High flows	>0.6	0.12	0.7–0.9

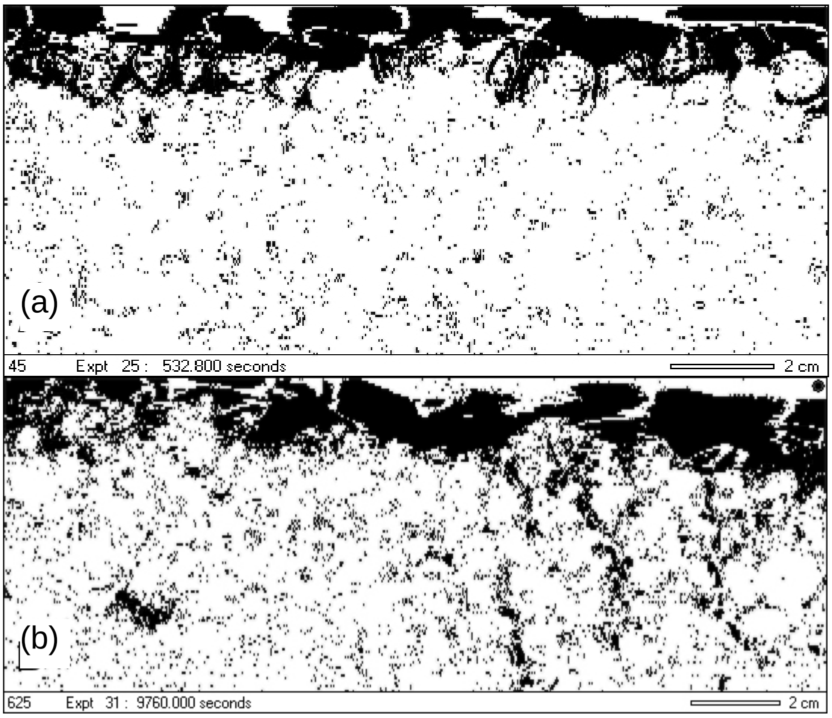

Fig. 1 Differenced images for (a) gravel only, (b) with sand, during bed entrainment events. Flow direction left to right.

conditions as those used in these experiments (Brasington *et al.*, 2000). This generates a sequence of images highlighting the areas of change with black fringes and allows the locations of major areas of movement to be picked out and analysed for any period of time in the experiment (see Fig. 1). Bed load transport rates were calculated with considerable accuracy by identifying the individual particles which had moved out of the experimental reach in a unit time (one second). These were then converted to a sediment mass per unit width by summing individual particle masses and multiplying the result to convert to a unit metre width equivalent from the 0.3 m flume width. This standardization allowed inter-comparison of results from different experiments.

RESULTS

These experiments have revealed differences in the behaviour of fine matrix material introduced into gravels during the passage of small, medium and large flood events. They have also shown interesting differences in both entrainment patterns and the behaviour of heavy and light minerals which might prove useful in river management and mineral exploration.

Bed behaviour prior to framework entrainment

During the first and second series of experiments, designed to simulate low and moderate flows only, the matrix materials were entrained and the gravel framework remained static. For the duration of all of these experiments the funnels inserted in the base of the flume beneath the gravel bed remained uniformly empty. Many parts of the surface pores were completely blocked, significantly reducing surface roughness and permeability. Observations through the side wall of the flume suggested that little fine material penetrated below two grain-diameters depth; although during the second series of experiments individual grains fluttered, lifted slightly and returned to their original position, only small amounts of interstitial sand were disturbed and none of it penetrated to the base of the bed.

Large quantities of the sand were picked up and transported downstream in a selective way. The lighter and larger sand grains were entrained preferentially leaving behind a deposit enriched with the finer quartz and, in appropriate experiments, olivine particles in a manner similar to the winnowing effect described by Reid & Frostick (1985b).

Behaviour of the bed during framework entrainment

During the higher flow experiments, framework particles were entrained as the surface of the bed was mobilized. Analyses of the images captured using the digital video camera have shown that sections of the bed dilate just prior to framework entrainment (Allan & Frostick, 1999). However, in the gravel-only experiments this dilation is isolated to the near surface layers, not penetrating beyond 2 grain-diameters (Fig. 1(a)). In contrast, dilation in the sand-gravel mixtures extended well into the bed, sometimes reaching the base of the flume (Fig. 1(b)). The loci for dilation shifted over periods of between 5 and 20 seconds.

Movement of the sand fraction of the bed also intensified and the near-surface pores became enriched with slightly finer quartz particles and, in experiments involving olivine sands, the heavy minerals. On average there were 10% more olivine particles in the final surface pore fill than at the beginning of the experiment. Pore dilation caused sand particles to move down in the bed along well defined pathways (Fig. 1(b)) and sand began to accumulate in the sub-bed traps for the first time. Extrapolation from data drawn from excavating both the bed and the funnels at the end of the experiments suggests that on average 56% of the material left in the bed at the onset of entrainment finally penetrated to the base. This material then began to fill the pore spaces in the gravels from the base of the bed upwards, the amount and character of the filling depending on the supply of sediment from the rapidly eroding surface.

The pathways exploited by the matrix particles as they travelled into the bed were similar in frequency and distribution across all of the experiments. Once in the bed, movement was no longer under the control of the external fluid stream and differences in particle density became more important in controlling the onward trajectory of the matrix sediment (Fig. 2) with olivine grains assuming a steeper trajectory than quartz (70–85° compared with 55–70° to the horizontal). Mixed density sands gave a much more confused pattern of trajectories, ranging widely from less than 35° to more than 110° to the horizontal, but with two modes at 75° and 55°, not dissimilar to those for separate quarts and olivine sands.

The temporal and spatial patterns of bed load transport in the gravel and mixed sand-gravel experiments were different (Fig. 3). In the absence of finer material,

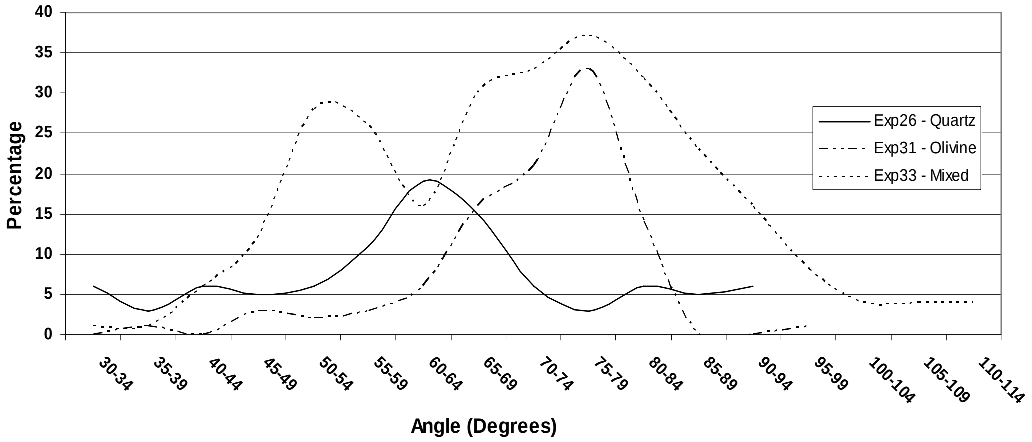

Fig. 2 Trajectories of major matrix movement pathways into the bed expressed in degrees to the horizontal with zero being horizontal orientation in the direction of flow. Note the differences between the quartz and olivine matrices and the "mixed" trajectories of the quartz-olivine mixtures.

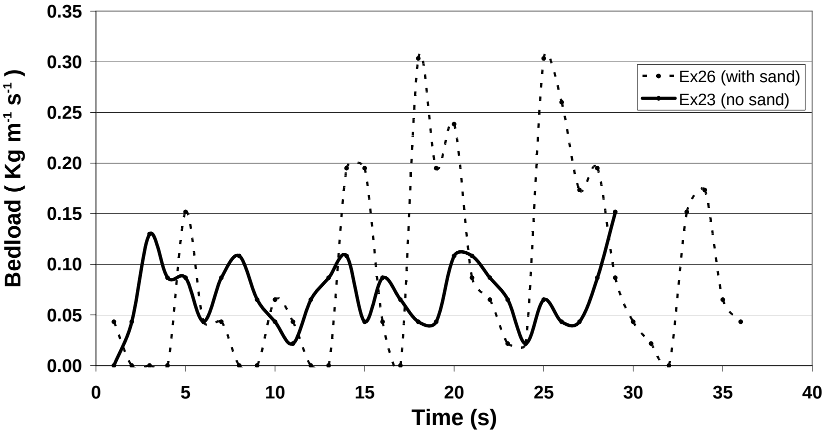

Fig. 3 Bed load transport calculated for gravels and sand gravel mixtures for selected, representative experiments. Note the larger rates and increased variability in the presence of sand.

gravels entrained more or less continually, with individual or small groups of two or three particles moving out of a number of sites within the bed at any one time. Bed load transport varied around an overall mean value of 0.075 kg m^{-1} s^{-1}, with a relatively low standard deviation from the mean of 0.034. In the presence of sand, bed load transport was not only much more intense, averaging 0.09 kg m^{-1} s^{-1}, but also much more variable (standard deviation 0.083). Entrainment in mixtures was always very localized with specific areas of the bed "destabilized" causing pebbles to move in large groups of eight or more.

DISCUSSION

The results of these experiments have begun to illuminate the processes controlling sediment transport in a gravel bed river and their link with the character of preserved deposits. The behaviour of the gravel bed of a river during flood events is poorly understood since flooding rivers are heavily charged with sediment, restricting visibility and precluding direct observations. As a result we rely on indirect measures of sediment transport through bed load samplers which have restricted temporal and spatial coverage (Habersack & Laronne, 2002; Reid *et al.*, 1980). There are also questions about how bed load transport should be calculated, whether measures taken using different equipment can be compared, and what this means for the actual behaviour of the river bed (Reid & Frostick, 1994).

Flume experiments offer the advantages of close observation of processes and the direct calculation of bed load transport from observed movements of particles. Some interesting sets of experiments were reported by Wilcock *et al.* (2001), who observed that gravel transport rates are different in gravel and sand-gravel mixtures. The results presented here support this observation and also offer insight into some of the mechanisms involved. The localized erosion of the bed in sand-gravel mixtures is linked directly to subsurface dilation, whereas gravel-only beds experienced near surface dilation which was less patchy. One possible explanation for this might be that matrix-free areas of the bed have high permeability and enhanced fluid movement which contrasts with the lower permeability of matrix-filled areas. This might lead to concentration of flows through the cleaner parts of the bed which, if intense enough, could result in the incipient bed fluidization in a manner similar to that suggested by Diplas (2005). This idea is supported by the fact that the first particles to move out of the bed during an entrainment event have an initial vertical movement (Brasington *et al.*, 2000).

The movement of sand within a gravel bed depends on the size and shape of particles entering the bed surface, the size and shape of inter-framework pores and water flow through the bed (Frostick *et al.*, 1984). Theoretically, suspended particles less than $0.4D_{50}$ in size should be able to move freely in sub-surface pores with larger material retained at the surface blocking pore throats and preventing subsequent infiltration. However, the experiments reported here show very clearly that fine materials delivered to a gravel bed will often remain very close to the surface even if they should theoretically be able to move into subsurface pore spaces. This suggests that river beds experiencing long periods of low flows and small floods will have their surfaces packed with fine sediment. Such accumulations will impact on river bed ecology and make the framework gravel resist entrainment when a flood does finally occur (Reid & Frostick, 1984, 1985a).

Once entrainment is under way, pore spaces dilate and fine sediment settles deeper into the bed. Dilation is patchy and active areas of the bed can have pore spaces up to 15% wider than those in inactive ones, with rims more than 4 mm wide around the base of framework clasts. It is not clear what controls the precise movement pathways through the bed, but the importance of gravity is attested to by the differences in patterns of subsurface matrix movement between heavy and light mineral sands (Fig. 2). Without measurements of fluid movement through the bed we cannot quantify its contribution to subsurface matrix movements.

The surface layers of a gravel river bed which has undergone a large flood event will normally be relatively clean of matrix fines close to the surface but be packed in the subsurface. If sufficient matrix material is available the bed can become completely

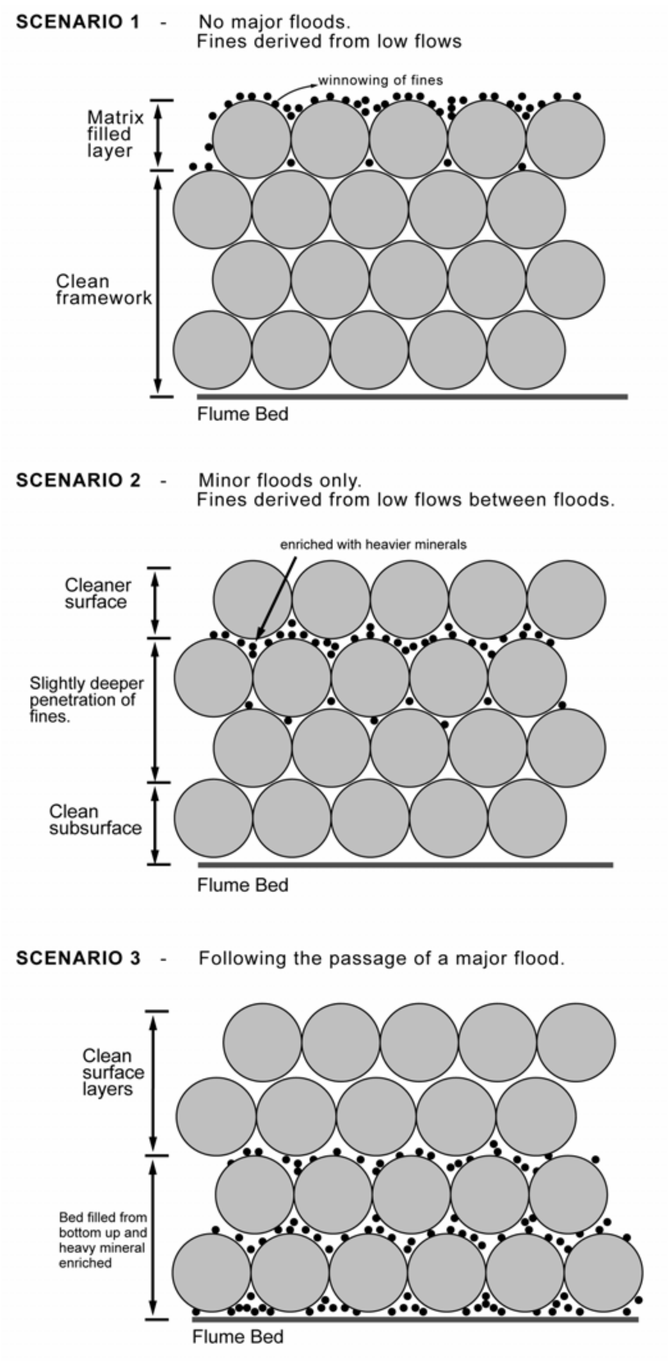

Fig. 4 Schematic diagram showing hypothetical patterns of matrix deposition given different flood scenarios: 1. after long periods of low flow; 2. after a small flood event; 3. after a major flood event.

packed with fine material filling almost all pore spaces from the bottom up, so impacting on river ecology. The material that penetrates into the bed will reflect the processes which have gone on in the surface during the preliminary stages of the flood. The winnowing of slightly larger and lighter particles can enrich the fines with heavy minerals which may be sufficiently concentrated to form a placer deposit. Even if this is not the case, the composition of a post-flood matrix infill will have higher than expected levels of heavy minerals and may well have a more restricted grain-size range, reflecting the impact of pre-flood winnowing processes.

CONCLUSIONS

The series of flume experiments reported here have yielded results which have given new insight into the processes governing both bed load transport and matrix redistribution in a gravel bed river. They have given insight into the processes that cause increases in the mobility of gravels when mixed with sand. The dilation of sand-gravel beds is a new observation which may be significant in enhancing entrainment. The measures of bed load transport obtained from these experiments may not be comparable with field observations, but show that sand increases bed load transport by an average of 20%.

These results carry with them implications for river character at the reach scale. Variations in fine matrix distribution should lead to spatial differences in entrainment. For example, bars in sand gravel rivers often show a discreet distribution of sand and gravel components in upland stream beds and across the bar surfaces. Areas of the bar with mixed grain sizes should erode preferentially, changing the bar morphology in a systematic way. The authors could not find any previously published work which reported such changes and so this remains a working hypothesis. There are also implications for sediment flux to basins, since more rapid erosion should lead to reduced accumulation of coarse sediment within channels and more rapid passage of sediment waves towards the receiving basins (Frostick & Jones, 2002).

A series of idealized scenarios for matrix distribution in river gravels reflects different flood histories (Fig. 4). Long periods of low flow and the passage of only small floods result in the surface of the gravel being packed with fine matrix material but retaining a high level of porosity and permeability in the subsurface layers (Scenario 1). Winnowing processes occur during small floods which change the composition of the fines, leaving behind smaller and heavier particles (Scenario 2). The passage of large floods removes all surface fines which are either eroded or move down into the bed through dilated pore spaces filling pore spaces at depth in the bed. The extent of the fill will depend on the supply of fine sediment from above (Scenario 3).

These scenarios suggest that changes in storminess linked with climate change will impact directly on river bed character. A shift towards more flashy flood regimes will be accompanied by greater overland flow and a larger supply of fine sediment to the river system. When this combines with the impact of large floods on matrix movement, the result could be river beds completely packed with matrix fines, with negligible permeability and with very restricted faunal diversity.

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