EXPERIMENTS ON THE EFFECT OF HYDROGRAPH CHARACTERISTICS ON VERTICAL GRAIN SORTING IN GRAVEL BED RIVERS

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Abstract

Desert ephemeral gravel-bed streams typically have bed surfaces that are relatively unarmored compared to the substrate below, while gravel-bed streams in humid and snowmelt areas typically have well-armored surfaces. The degree of armoring can be characterized in terms of an armor ratio defined as the ratio of the surface median size to the substrate median size. A set of field data shows desert ephemeral gravel-bed streams with armor ratios range from 0.5 to 2.4, and with an average value of 1.2. The armor ratio of snowmelt-fed gravel-bed streams in the same set ranges from 2 and 7, with an average value of 3.4. The reason for this difference is sought in terms of differing hydrological characteristics and sediment supply regimes. Thirteen experiments were conducted to study the formation of armoring under a range of hydrological conditions. The experiments have two limiting cases; a relatively flat hydrograph that represents conditions produced by continuous snowmelt and a sharply peaked hydrograph that represents conditions associated with flash floods. All constant-hydrograph experiments developed a well-armored structured surface, while short asymmetrical hydrographs did not result in substantial vertical sorting. All symmetrical hydrographs show some degree of sorting, and the sorting tended to become more pronounced with longer duration. Sediment supply appears to be a first-order control on bed surface armoring, while the shape of the hydrograph plays a secondary role.

(225 words)

1. Introduction

Gravel-bed rivers typically display a coarse surface layer known as the armor layer. The armor layer is defined as stratum with a thickness of 1~2 very coarse grains, at least part of which are exposed on the bed surface [e.g., *Gessler*, 1990]. For example, this "very coarse grain" size is often defined in terms of the size D_{90s} or D_{84s} such that 90% or 84%, respectively, of the surface material is finer. The armor layer is often considered to be time-dependent, as is the distribution of the critical shear stress on which its formation partially depends. The state of the bed surface layer may shift from static to mobile during a flow event; this does not imply that the whole bed is simultaneously active, or that the armor layer is totally destroyed. Based on field data and empirical observation, Parker and Klingeman [1982] inferred that some form of armor layer remains intact during typical sediment transporting events. Andrews and Erman [1986] have provided field evidence in support of this. Experimental results show that armor layers vary little with increasing sediment transport rates [Wilcock et al. [2001]. Recently, Wilcock and de Temple [2005] back-calculated the grain size distribution of the bed surface of Oak Creek, Oregon and inferred that the armor layer remained intact and essentially invariant during relatively high flows.

Traditionally it has been believed that the development of the armor layer takes place at flows strong enough to move the smaller sizes but too weak to move the larger ones. Selective transport and horizontal winnowing of fines and bed degradation continue until there is sufficient cover of coarse material to prevent further sediment transport [e.g., *Harrison*, 1950; *Gessler*, 1970; *Little and Mayer*, 1972; *Proffitt and Sutherland*, 1983; *Chin et al*., 1994]. An alternative mechanism for armoring was suggested by

Parker and Klingeman [1982] and Parker et al. [1982]. The surface was found to be coarser than the substrate even under conditions sufficient to mobilize all sizes. The resulting armor can be called mobile armor, as opposed to the static one associated with vanishing motion [e.g., *Parker et al*., 1982]. Parker and Kligeman [1982] noted, like many others, that the bed surface becomes coarser as it makes the transition from mobile to static armor. Mobile armor can be explained in terms of the concept of equal mobility of all sediment supply sizes of a graded stream [*Parker and Toro-Escobar*, 2002]. Equal mobility of all sizes in the sediment supply is sustained by a surface grain size distribution which shelters small particles in the lee and interstices of coarse particles, and increases the exposure of large ones, causing the development of the coarsened surface [*Parker et al*., 1982; *Parker and Klingeman*, 1982; *Andrews and Erman*, 1986; *Andrews and Parker*, 1987]. The process continues until all size fractions are transported in proportion to their presence in the supply.

Most of the research done to date in flumes provides a basis for understanding the development of surface armoring in channels characterized by long periods of flow at constant or nearly constant flow discharge. Such work may thus not be applicable to ephemeral streams that carry water only during flash floods. It may also lack applicability in the case of humid streams with episodic sediment supply from slopes or upstream tributaries. This study focuses on the formation of armor layers over a range of hydrologic conditions that includes two limiting cases; relatively flat hydrographs that simulate conditions produced by continuous snowmelt and sharply peaked hydrographs that simulate conditions associated with flashfloods. The specific objective of the study is to examine the effect of hydrograph shape on the armoring processes, and in particular, the effect of flashiness of the flood on armoring development. To achieve this goal a range of hydrographs, varying from steady flow to flash flood conditions was studied.

It has been observed that gravel-bed streams in humid environments typically have a well armor layer while streams in arid environments often show little evidence of surface coarsening. What might be the reason for this? Other factors being equal (e.g., sediment supply and lithology), here the reason is sought in terms of differing hydrological regime. The following is hypothesized: hydrologic regimes characterized by relatively flat, long hydrographs can be associated with conditions that promote the development of armoring, whereas regimes characterized by short, peaky floods tend to subdued or destroy this armor. The latter flows cause strong vertical interchange of sediment throughout the active layer and continuous exposure and entrainment of fine sediment from the subsurface.

2. Field evidence

Our field effort was focused on arid environments for the following reason: whereas documentation showing the extent of armoring in perennial streams is readily available, corresponding documentation for the case of ephemeral streams appears to be lacking. We begin by reporting on armoring within ephemeral streams and then compare this to armoring in humid streams.

2.1. Data Collection in ephemeral streams

The fieldwork encompassed 22 ephemeral streams in the Dead Sea region, Arava Depression, and the Negev Highland, Israel (Table 1). The streams examined carry flow only during flashfloods and cover a wide range of bed grain size distribution and channel morphology. Data on sediment supply and transport are available for a small number of the examined streams (e.g., Eshtemoa, Hebron, Og, Yael, Yatir). These observations indicate relatively high sediment supply and transport rates [*Schick et al.*, 1987; *Hassan*, 1990b; *Laronne and Reid*, 1993; *Schick and Lekach*, 1993; *Laronne et al*., 1994; *Reid and Laronne*, 1995; *Powell et al*., 2001]. Visual inspection of the channel and watershed of the rest of the streams indicates that most of these streams have a substantial supply of sediment. Flow events are characterized by a steep, highly turbulent bore of water moving down the channel, tearing at the bed material and throwing coarse grains into suspension [*Schick*, 1971; *Hassan*, 1990a; *Laronne et al*., 1994**]**. Such bores are capable of directly mobilizing sediment below the surface layer (e.g. *Fraccarollo and Capart*, 2002). Events are short; the time lapse from bore to flood peak averages about 16 minutes [*Schick*, 1971, 1988; *Hassan*, 1990] and the whole event is typically over within a few hours. Although such river systems are morphodynamically dormant most of the time, in a morphologic sense they may be more active than their humid counterparts [*Schick et al*., 1987; *Laronne et al.*, 1994**]**. In a few cases (e.g., Nahal Og), however, flows are generated in the adjacent, more humid mountains, and so the hydrologic regime is less dominated by flashfloods.

The surface was sampled by spray-painting it, and then the marked stones were removed with the adjacent finer material. Since the subsurface samples are volumetric, surface samples were converted to volumetric samples using the procedure of Kellerhals and Bray [1971]. At each study site, one sample each of the surface and immediate subsurface material was measured. In order to accurately characterize the size distribution of the bed material, Church et al. [1987] recommended that the largest clast weight should not exceed a 1% of the total sample weight. The sampling efficiency of the subsurface ranged between 0.1 and 2%; most of the samples did not exceed the 1% sampling efficiency as indicated by Church et al. [1987]. In comparison, the sampling efficiency of the surface material ranged between 1 and 5%. To assess the spatial variability of bed surface armoring, extensive sampling was carried out in one bar in Nahal Zin (n=21 samples), and two bars and main channel in Nahal Og (n=15) (for more details see *Hassan* [1990b, 2005]). The examined reaches were selected near a gauge station so that the hydrological regime could be assessed (Table 1).

2.2. Armoring in ephemeral streams

For comparison, and in order to examine the impact of flow regime on the development of armoring, we compiled published data on armoring for streams in humid areas and snowmelt dominated regimes in addition to arid streams. The data were, however, collected using a range of methods. The main problems associated with sampling are the definition of the armor layer, the sampling method, and the sample size. A wide range of methods and sample sizes has been used by researchers. This fact imposes limitations on the comparison between the examined streams. Another problem is related to the location and the number of samples required to describe the state of bed surface. Most of our results and most of those reported in the literature are based on one sample only, which raises questions concerning adequate representation. Therefore, some of the inconsistency and variability in the reported studies may be attributed to differences in sampling procedure.

The degree of armoring, or armor ratio is here defined as the ratio of surface median size to subsurface median size, or D_{50s}/D_{50sub}, where D_{50s} denotes the median grain size of the surface material and D_{50sub} denotes the median grain size of the subsurface material. An essentially unarmored stream is one for which the armor ratio is near unity; armoring is well-developed at armor ratios of 2 or higher. Figure 1a shows a plot of armor ratio D_{50s}/D_{50sub} as a function of D_{50sub} for all 22 of the ephemeral streams in Table 1. The degree of armoring is seen to be rather weak, with armor ratios ranging from 0.5 to 2.4, and with an average armor ratio of 0.94. Underlying the variation of the armor ratio are the three typical sorting patterns presented in Figure 2. In the first type the size distributions of the surface and the subsurface layers are about the same, indicating no vertical sediment sorting. In the second type the surface is finer than the subsurface, implying a coarser subsurface layer. In the third type some degree of armoring was observed. In the cases of the Nahal Og and the Nahal Zin, for which multiple samples were taken, the mean value of D_{50s} and the standard deviation of values of D_{50s} about the mean are presented in Figure 1a. The replicate samples in both creeks yielded a wide range of results reflecting local conditions of sediment grain size distribution, local flow conditions, and sediment supply. In Nahal Zin, for example, the armor ratio ranged between 0.4 and 2.9, demonstrating the difficulty of assigning a single armoring value for each stream. For four streams, the armor ratio was ~ 2, a value similar to that obtained for streams in humid areas [e.g., *Parker and Klingeman*, 1982; *Church et al.*, 1987]. Of these cases, two drain relatively humid mountainous areas (Nahal Hebron and Nahal Og (Table 1)). During regional frontal weather systems, flows in these streams can last for several hours, which may be long enough to develop some degree of armoring. The other two streams are located in the northern Arava; the reason for the development of armoring is not clear, but might be related to sediment supply. Finally, most of the study cases show relatively large fractions of sand (as opposed to gravel) in the surface and substrate of the bed, a condition that is not typical of perennial gravel-bed streams. Truncating samples at 2 mm yielded three streams with armor ratio larger than 1.5 and only for one site the ratio was larger than 2. For all but one case for which $D_{50s}/D_{50sub} > 1.5$, the basins in question drain relatively humid mountainous areas. Based on the above analysis, we conclude that the bed surface of arid streams tend to show poorly-developed armoring, and in some cases no vertical stratification whatsoever.

2.3. Comparison of armoring in ephemeral and humid streams

Data characterizing armoring in humid areas and snowmelt-dominated areas were collected from the literature (see Figure 1b caption) in order to allow comparison with the ephemeral streams of Table 1. The comparison is not as straightforward as might appear due to two factors. The first of these is due to the use of somewhat differing definitions of the armor layer, as well as somewhat differing techniques used to sample and characterize the surface and subsurface grain size distributions. The second of these relates to the number of samples used to characterize the bed. Most of our results, as well as most of those reported in the literature, are based on a single sample site where a single surface sample and a single subsurface sample were taken, and are not based on averages of data sets. A comparison of armoring in ephemeral streams versus non-ephemeral streams is undertaken below in full cognizance of these limiting factors.

In Figure 1b we present armor ratios for streams in humid areas, snowmelt dominated streams, and arid streams. As noted in the context of Figure 1a, most of the ephemeral streams plot around the line representing an armor ratio of 1, with a mean value of 0.94. The armor ratios of streams in the humid areas plot between 1 and 3 with a mean value of 1.64. Among streams in humid areas, Carnation Creek, Tom McDonald

Creek, and Redwood Creek plot close to armoring ratio 1. These creeks are characterized by relatively high sediment supply rates to the main channel from adjacent banks, slopes and upstream tributaries [*Tassone*, 1987; *Lisle and Madej*, 1992; *Hassan and Woodsmith*, 2004; *Hassan et al*., in review]. Figure 1b shows that most of the snowmelt-dominated streams plot near or above an armor ratio 2, with some as high as 6. Although there is high variability in the armor ratio within the same flow regime, a clear stratification between the two extremes, i.e. flash floods and snowmelt regimes, is evident. Within the same flow regime, the variation in armor ratio can be attributed at least in part to the sediment supply. Streams with an armor ratio of 1 appear to be in regions with a relatively high sediment supply rate, while those with an armor ratio well above 1 reflect a relatively low sediment supply. This conclusion confirms an earlier result due to Dietrich et al. [1989]. Whereas, for the same sediment supply rate, streams located near an armor ratio of 1 are likely to subject to flashfloods, while those well above it are likely to experience gradual long hydrographs likes those of snowmelt (Figure 1b). The results presented in Figure 1 are consistent, which lead us to conclude that humid/snowmelt streams are likely to develop a higher degree of armoring than desert streams.

3. Experimental Arrangements

The experimental arrangements were guided by conditions observed in both humid and arid environments. To investigate the identified hypothesis and study objectives we conducted a flume experiments over a range of hydrograph shapes. A set of experiments using triangular input hydrographs with variety of width and were conducted. Then a series of constant flow experiments run up to 96 hours were conducted in order to characterise static armoring and for to allow comparison with the experiments utilizing varied flow.

Flume experiments were carried out at the Hydraulic Laboratory in the Geography Department of the Hebrew University of Jerusalem. The experiments were conducted in a tilting flume with a length of 9 m, a width of 0.60 m and a depth of 0.50 m. The bed was fixed and immobile for the first 1.0 m downstream of the flume headbox. The size of the stones used in the fixed reach of the bed was approximately equal to the D_{84} size of the bed material. For the remainder of the flume the bed initially consisted of a layer of loose material with a depth of 0.07 m above an inerodible, flat bed. Grain sizes in this bed of loose sediment ranged between 0.180 and 45 mm (Figure 3); material finer than 0.180 mm was excluded because it would move as suspended load rather than bedload. Color-coded sediment was used in all experiments, and fluorescent tracers were used in some of the experiments. The flume represents a generic rather than specific model of field conditions in that no attempt was made to reproduce geometrical details of any prototype channel. Before commencing each experiment, the sediment was slowly flooded and then drained to aid settlement. During the lower flows studied here, sizes finer than the bulk median size were observed to be mobile; during the higher flows material at least as coarse as the bulk D_{90} was mobilized.

An adjustable gate at the downstream end of the flume controlled the water depth. All of the flow measurements and photos were made in an observation reach between 4.75 and 5.25 m downstream of the headbox. Bed slope and water depth were monitored to ensure that the flow discharge remained constant throughout the duration of each step in the hydrograph. Measurements of water surface and bed slopes were conducted using a mechanical point gauge with a precision of ± 0.001 m averaged over a distance of 6 m. Water depth fluctuations due to wave effects at a point were about 5% or less. An Acoustic Doppler Velocimeter (ADV) was used to obtain velocity measurements. For any given run, temperature varied less than 2 degrees and usually remained within 1 degree.

No sediment was fed into the flume at the upstream end. Instead, the reach upstream of the observation reach, i.e. that extending to 4.75 m downstream of the headbox, served as the source of sediment for the observation reach. Water, but not sediment was recirculated by an axial pump. Material transported from the flume was trapped in a 0.18 mm mesh screen in the tailbox. At intervals throughout the experiments, the flow was lowered to a level well below that required for particle entrainment. During these brief periods the bed was photographed, bed surface samples were taken, and the sediment trap was replaced. This procedure was adopted to keep the bed fully under water and avoid surface drying and settling. Bedload samples were dried, weighed, and then sieved at ½ phi intervals.

Digital cameras were mounted over the 0.21 m^2 observation reach so that stereophotographs of the reach could be taken. The photos were used to map patterns of particle arrangement on the bed surface. Two complementary methods were used to characterize the composition of the surface material; clay and color sampling. Underwater bed surface samples were taken using a piston device coated with clay [*Fripp and Diplas*, 1993]. The clay was pressed onto the gravel surface so that the surface sediment was embedded in the clay and then was extracted and washed to suspend and remove the clay. The remaining sediment was dried and sieved at ½ phi intervals. The minimum required area of the clay samples was calculated using the method of Fripp and Diplas [1993]. The largest particle in the flume was 0.045 m and therefore the required area is 0.20 m^2. This area is equal to five samples, which were taken across the flume from the reach below the observation area. The areal samples were converted to bulk sample equivalents using the Kellerhals and Bray [1971] formula. The clay method described above was deployed downstream of the control area. The particle size of the control area was determined using the adaptation of the Wolman method for color coded sediment introduced and tested by Wilcock and McArdell [1993]. The method is deployed *in situ*; hence there is no disturbance to the bed surface.

A range of methods for the estimation of bed shear stress has been suggested in the literature (reviewed in *Whiting and Dietrich* [1990]). In this study, the shear stress was estimated using the depth-slope product rule corresponding to normal (steady, uniform) flow. This method was selected because the focus of this work is on overall (mean) parameters controlling bed evolution rather than local parameters such as a bed shear stress determined from a given vertical velocity profile.

Thirteen experiments, with varying hydrograph shapes were conducted with the same grain size distribution in the flume. The development of an armor layer was aided by the absence of upstream sediment feed (Table 2). The hydrographs used for all thirteen runs are shown in Figure 4. Four experiments simulated constant flow (G1, G2, I3, and I4) for a duration of 96 hours in order to develop static armoring and calibrate the runs with varying hydrographs. Three sets of experiments were performed with asymmetrical hydrograph shapes and with different combinations of peak flow and duration. These experiments simulated a generic flashflood hydrograph shape, for which discharge increases quickly over the rising limb, but declines at rates varying from gradual to rapid over the falling limb. The first set of experiments, i.e. J2, D2, and D4, have the same flow magnitude but differ in flow duration. The second set of experiments, C2 and C4, were set at equal flow magnitudes that were lower than those of the first set, and with different flow durations. The third set of experiments, J2 and J5, had the same flow duration but with different flow magnitudes. Note that experiment J2 is part of the first and third sets. Three experiments simulated symmetric hydrograph shapes with different combinations of peak and duration (B4, F3, J1). These types of experiments were designed to simulate situations that range between constant flows and flashfloods. In these experiments, the discharge was varied in stages until it reached peak discharge, and then lowered in a similar set of stages. Finally, the long symmetrical/asymmetrical (e.g., B4 and F3) experiments with gradual change in the discharge were designed to simulate a snowmelt regime and promote the development of armoring.

4. Observations

4.1. Sediment transport

Figure 4 shows the variation in sediment transport rate with time for different hydrograph shapes and flow magnitudes. Experiments G1, G2, I3, and I4 represent constant flow with different magnitude (Table 2). The four experiments yielded a similar pattern of exponential decline in sediment transport rate with time. During the first two hours, the sediment transport rate was relatively high, and a large amount of fine sediment was removed from the bed surface (Figure 4a-d). After approximately 16 hours the transport rate became very low, with only a small number of grains visibly moving at any time.

Experiments B4 (Figure 4e), F3 (Figure 4i), and J1 (Figure 4k) present variations in sediment transport during symmetrical hydrograph runs. The hydrographs consist of three symmetrical rising and falling stages with a peak flow. They differ in the duration of each stage. The experiments were designed to examine the impact of symmetrical hydrograph duration on bed surface armoring and sediment mobility. Experiment J1 represents a short duration symmetrical hydrograph; the duration of each stage was 0.17 hours totaling 1.17 hours (Figure 4k). During the rising limb of the hydrograph the sediment transport increased and reached a maximum value by the end of the peak flow. Sediment transport during the falling limb showed a relatively steep declining trend as the flow decreased. In spite of the symmetrical shape of the hydrograph, the sediment transport rate tended to be slightly asymmetrical; usually the transport rates during the falling limb were slightly lower than those during the rising part of the hydrograph.

The rising limb of experiment F3 was composed of three stages of duration 1, 2, and 1 hours, respectively with a one-hour peak (Figure 4i). The durations and magnitudes of the falling limb stages were similar to those of the rising limb; the total experiment duration was 9 hours. The sediment transport pattern during experiment F3 was similar to that of experiment J1. In the experiment the sediment transport rate peaked during the peak water flow and then declined rapidly during the falling limb.

Experiment B4 represents a long-duration symmetrical hydrograph, with three rising states of duration, 14, 5, and 3 hours, and three identical falling stages (Figure 4e). The peak flow lasted for 2 hours, with a total hydrograph duration of 65 hours. Taking into consideration the duration of each stage of the experiment, the sediment transport pattern was different than that obtained for experiment F3. The longer duration of the steps in experiment B4 resulted in a different pattern of sediment transport on the rising and falling limbs. That is, the sediment transport rate underwent a step increase with each step increase of discharge, followed by a monotonic decline until the next step increase. During the falling limb, however, the sediment transport showed a declining trend with slightly lower transport rates than those of the rising limb. Comparison of the three symmetrical experiments shows that the sediment transport rates observed for experiment J1 were more than one order of magnitude higher than those obtained from experiment B4. The differences in the sediment transport rates between J1 and B4 could be attributed to the initial loose surface conditions that dominated experiment J1.

The asymmetrical (flashflood) hydrograph experiments are characterized by steep rising limbs (1-2 stages) and more gradual falling limbs (3-4 stages) (Figures 4f, g, h, j, l, and m). The first set of experiments, i.e. J2, D2, and D4, have about the same flow magnitude but differ in flow duration. Experiment J2 was of short duration (0.83 hours) and consisted of two rising stages and three falling stages each of the same duration (0.17 hours) (Figure 4l). During the rising limb of the hydrograph, the sediment transport rate increased as the flow increased slightly and then declined after the peak flow. The variability in the sediment transport rate in the asymmetrical hydrograph experiments, which had longer durations but similar flow magnitudes (D2, and D4, see Figures 4g and 4h) is more pronounced in the falling limb than the rising limb of the hydrograph. The second set of experiments, i.e. C2 and C4, were set at equal flow magnitudes that were lower than those of the first set, and with different flow durations. These experiments yielded a sediment transport pattern similar to that of the first set (D2 and D4). The hydrogaph shape of experiment J5 is similar to that of J2 but the experiments differ in the peak flow magnitude; the peak flow in J2 is a little larger than that of J5. Experiment J5 yielded a sediment transport pattern similar to that of J2. The increases in the sediment transport rates during the rising limb in experiments J1 was relatively steeper than in the asymmetrical experiments J2 and J5. The decrease in the sediment transport rate, however, for all short asymmetrical and symmetrical experiments (J1, J2 and J5) were about the same. In summary, Figure 4 show that if the run time is not too long, the flume is not depleted of sediment, and so winnowing may not be the dominant phenomenon governing coarsening.

4.2. Bed surface and bedload grain size distributions

The grain size distribution of the surface material is used as indicator of armor development in both flume experiments and field studies. Changes in the grain size distribution of the surface and bedload through time and between experiments are documented in terms of bed surface samples and analyses of trapped transported material. Bed surface and bedload grain size distributions of selected experiments that demonstrate the range of results that was obtained are presented in Figure 5. Experiment G1 illustrates textural changes during constant-flow conditions. Figure 5a shows a progressive trend of coarsening of the surface material. Most of the change in the median size of the surface material occurred within the first 24 hours. Minor changes in the grain size distribution of the surface material were observed between 24 and 96 hours of the experiment. A similar trend was obtained for constant-flow experiments G2 and I4. However, in experiment I3 the flow was so low that it was close to the threshold of movement. As a result most of the sediment remained static on the surface with little development of surface structure.

Although not shown in graphical form here, after 96 hours, the grain size distribution of the surface material remained identical to that of the original mixture. The bedload grain size distribution of experiment G1 (Figure 5a) and other constant-flow experiments, exhibited a gradual coarsening of the transported material. In all constant flow experiments, the size distribution of the transported material remained much finer than the original mixture and the bed surface material.

Figures 5b and 5c present the grain size composition of the bed surface, bedload, and original mixture for two symmetrical experiments (J1 and F3). During the rising and falling limbs of the short duration experiment J1, minor changes in the bed surface material occurred and the resulting distribution was similar to that of the original mixture. The longer-duration experiment F3 resulted in a higher degree of armoring than that of experiment J1. Furthermore, some sorting occurred during peak flow of the experiment (Figure 5c). The falling limb of the symmetrical long experiment B4 (not present) yielded surface coarsening similar to that of experiment F3 (Figure 5c). The armoring ratio increased as the flow duration increased; from 1.2 in experiment J1 (the shortest) to 1.8 in experiment B4 (the longest). The implication of these results is that most of the sediment sorting occurred during the falling limb of the hydrograph. Furthermore, as the length of each step of constant increases we should expect some sediment sorting because long steps of constant flow are similar to entire runs at constant flow.

The grain size distribution of the bedload in experiment J1 exhibited a gradual coarsening during the rising limb and gradual fining during the falling limb (Figure 5b). Similar results were obtained for experiment F3 (Figure 5c). In all the symmetrical hydrograph experiments the particle size distribution of the transported material remained finer than the original mixture.

Bed surface, bedload and original mixture compositions of the asymmetrical experiments are presented in Figures 5d, e and f. The size distribution of the bed surface material during experiment J2 straddled that of the original mixture (Figure 5d). By the end of the experiment, the final bed surface texture was close to that of the mixture. Similar results were obtained for the short duration experiment J5 (not presented). In summary, both experiments (J2 and J5) did not develop an armored bed surface. The particle size distributions of the bedload during experiment J2 are presented in Figure 6d. The trends in the bedload texture during the rising and falling limbs of an asymmetrical hydrograph for an intermediate duration are similar to those obtained for short symmetrical hydrographs (Figure 5b).

Experiments C2 and D4 represent asymmetrical hydrographs with long falling limbs. During the rising limb of experiment C2, the bed surface grain size distribution was finer than that of the original mixture, while progressive armoring was observed during the falling limb of the hydrograph (Figure 5e). Similar trends were obtained for experiments D4 (Figure 5f), D2, and C4 (not presented). In comparison to the short duration experiments (J2 and J5), the falling limb durations in experiments C2, D4, and C4 were long enough for sediment sorting and some degree of development of armor. The bedload grain size distribution of experiment J2 shows a fining trend in time (Figure 5d); a similar trend was obtained for the rest of the asymmetrical experiments.

The temporal variations of the sizes D_{50s} and D_{84s} of the surface size distribution are presented in Figure 6. The sizes D_{50sub} and D_{84sub} of the mixture are also plotted for comparison. For experiment I3, the measured results straddle the respective D_{50sub} and D_{84sub} sizes of the mixture (Figure 6c). In addition, the measurements show a fining trend in the bed surface within the first 10 hours of the experiment. A gradual increase in the D_{50sub} and D_{84sub} were obtained were obtained for experiments G1, G2 and I4 (Figures 6a, b, d).

The two long symmetrical experiments (B4 and F3) show systematic coarsening of bed surface with time (Figure 6e and 6i). The short symmetrical experiment J1 (Figure 6k) show a fining trend and then a slight coarsening of the bed surface during the falling limb. For the short asymmetrical experiments (J2 and J5), the results straddle the respective D_{50sub} and D_{84sub} sizes of the mixture (Figure 6l, m). The long asymmetrical experiments C2, C4 and D2 yielded a well armored surface (e.g. Figure 6f, g, j). Although experiments D2 and D4 have the same duration, experiment D2 shows a progressive increase in the median size of the surface material while experiment D4 shows little armoring within the first 5 hours of the run. By the end experiments, however, the median size of the surface material was about the same for both experiments (Figures 6g and 6h, also see Table 2).

4.3. Sediment mobility

The relative mobility of each size fraction was examined by computing the fractional ratio (P_i/F_i), where P_i is the fraction of each half-phi size class, i, present in the transported material and F_i is the proportion of each corresponding size fraction in the surface material (for details see *Wilcock and McArdell* [1993]). Selected representative results are shown in Figure 8**,** where the fractional ratio is plotted as a function of particle size. The fractional ratios range over 2 to 3 orders of magnitude.

Experiment G1 characterizes textural changes during constant flow conditions (Figure 7a). The fractional ratios range over 3 orders of magnitude. Figure 7a shows that sizes as large as 5.6 mm were fully mobile during the experiment. Fractions < 1 mm and > 5.6 mm were mobile in their proportion in the bed or slightly underrepresented in the transported material. Comparing the different constant flow experiments, the most significant temporal decrease in the largest size of particles in significant transport was noticed in experiment I3, from 11 mm to 2.8 mm. In addition, in experiment I3 only sizes smaller than 0.71 mm were fully mobile. The limited size mobility in experiment I3 is due to the low flow conditions under which the experiment was conducted. Our relative sediment mobility outcome is comparable to results reported for similar experiments [e.g., *Hassan and Church*, 2000].

The fractional ratios for the symmetrical experiments are presented in Figures 7b and 7c. For comparison, the fractional ratios of the rising and falling limbs, and peak flow are plotted separately. The fractional ratios are higher for finer fractions during the rising stages than the falling stages. For the rising limb of experiment J1, the size limit between partial and full mobility was about 4 mm with little changes between the different flow stages. In contrast on the falling limb the size limit between partial and full mobility dropped from 4 mm (Q=0.033) to 0.5 mm (Q=0.014). Similar trends were obtained for experiment F3. Figures 7b and 7c show that, for about the same discharge, the fractional ratios were higher during the rising limb than the falling limb. All symmetrical and asymmetrical hydrograph experiments yielded a very similar pattern (see Figure 7). This is likely due to the evacuation of large amounts of sediment during the rising limb and the lack of upstream sediment feed in the experiments.

The asymmetrical-hydrograph experiments showed a significant decrease in the largest mobile size as the flow decreased during the falling limb of the hydrograph (Figure 7d-f). During the rising limb of the hydrograph, the size limit between full and partial mobility reached 4 mm. Figure 7d, however, shows that the size limit between full and partial mobility was not that sensitive to changes in flow during the rising limb. In some of the experiments, the large fractions (> 2.8 mm) stopped moving at relatively high flow during the falling limb (Figures 7d, e). For about the same flow during the rising limb, in contrast, grains as large as 11 mm sizes were mobile. The drop in the size of the mobile sediment is likely a function of surface sorting, surface structures and lack of sediment feed.

5. Discussion and Summary

Vertical sorting of sediment in gravel bed rivers is the result of interactions between flow magnitude and duration, sediment grain size distribution, sediment supply, and initial bed surface conditions. The main controls on the bed surface compositions, therefore, are the sediment supply and flow regimes. Given the wide range of factors that are likely to influence the composition of the bed surface, it is difficult to separate the impact of flow regime from other factors, such as the sediment supply, in a field setting.

The river reaches used in the study of field data yielded a wide range of results within and between climatic zones (i.e., hydrograph type). Variability in the degree of armoring within the same climatic zone could be related to sediment supply rate and bed grain size distribution. Sediment supply plays a major role in the development of bed surface armoring. Excluding flow regime, streams with relatively low sediment supply are likely to develop a high degree of armoring, whereas streams with sufficiently high sediment supply rates are not likely to have significant vertical sediment sorting and thus can be expected to have a lower degree of armoring.

For a given sediment supply regime, the range of results obtained for arid streams indicates that streams with a long receding hydrograph limb and that experience few (3 to 5) floods per a year are likely to develop some degree of armoring. Alternatively, arid streams that experience less frequent floods and a short falling limb are less likely to develop armor. Similar results, i.e. minimal development of bed surface armoring, were obtained for humid streams where the sediment supply is relatively high (e.g. Carnation Creek, Tom McDonald; see Figure 1). The opposite is true for the case of low sediment supply in humid regions. These results lead to the conclusion that sediment supply dominates the development of bed surface armoring while hydrograph shape plays a secondary, but also important role.

Our flume experiments were conducted under the condition of vanishing sediment feed. The reach upstream of the observation reach likely served as an adequate source of sediment for the observation reach during the short experiments, so that sorting was not dominated by winnowing. In the case of the long hydrograph experiments, however, some degree of sediment winnowing should be expected. Our assumption is that significant vertical sorting of sediment is likely to occur during the falling limb of the hydrograph. The degree of sorting depends on the characteristic response time for the bed to sort the active layer in response to changing discharge (T_{sort}), on the characteristic time of the falling limb of the hydrograph (T_{hyd}), and on the characteristic response time for the bed to degrade to static armor with no sediment feed (T_{stat}). If $T_{sort} >> T_{hyd}$, there should be little time for sorting at each discharge in the falling part of the hydrograph, and the surface grain size distribution should be roughly the same at each stage in the hydrograph, reflecting the value at the peak flow. If $T_{hyd} >> T_{sort}$, there is plenty of time for sorting, and the surface grain size distribution at each flow in the hydrograph should reflect its equilibrium value, regardless of the effect of the peak flow. The movement of particles over a period of time will lead to changes in the bed (e.g. vertical sorting). In the case of short hydrographs, however all these changes are relevant only for the falling limb, since any development of the bed prior to the peak discharge will be destroyed. This is true for peak flows sufficiently strong to “reset” the bed surface grain size distribution; otherwise the bed surface grain size distribution before the peak flow will persist and is likely to affect the sediment sorting during the falling limb of the hydrograph.

Because there was no sediment feed in our experiments, our expectation is that in addition to flow characteristics sediment winnowing/starvation might affect the outcome and hence the interpretation of some of the experiments, especially those of long duration. In order to examine the possible effect of sediment starvation, we plot in Figure 8a the total (cumulative) amount of evacuated during each of several experiments against the armor ratio observed at the end of the experiment. It is seen in Figure 8a that sediment yield increases essentially linearly with armor ratio for the constant flow experiments, precisely as would be expected were winnowing to be the dominant mechanism for sorting. In the case of the runs with symmetric and asymmetric hydrographs the sediment yield is seen to be essentially independent of the armor ratio. This suggests that the armor ratio may be controlled more by hydraulic/morphodynamic factors associated with the hydrograph itself rather than winnowing from the flume. Especially in the case of the short-duration hydrographs of Table 2, the duration of the experiment was not sufficient for winnowing to play an important role in vertical sediment sorting. The data for the long-duration hydrograph experiments (with armor ratio > 2), however, plot near the constant flow trend, suggesting that the outcome in these experiments is probably the combined effect of hydrograph characteristics and sediment winnowing.

The relation presented in Figure 8a does not consider hydrograph magnitude and duration and their effect on vertical sediment sorting. A plot of the effective total stream power versus the armor ratio combines both magnitude and duration (Figure 8b). The data for the varying hydrograph experiments plot higher than those for constant flow indicating that for a given effective total stream power they developed a higher armor ratio than those of the constant flows. Again, this may reflect the ability of a hydrograph to effectively rearrange sediment in the vertical even in the absence of winnowing/starvation.

The long constant-flow experiments displayed grain size distributions of the surface material that progressively coarsened with increasing duration because of sediment winnowing and lack of sediment feed (supply). Similar observations have been reported by Tait and Willetts [1992], Church et al. [1998], and Hassan and Church [2000]. As expected, long constant flows of sufficient magnitude to mobilize the initial bed sediment resulted in the development of well-armored bed surfaces. For constant-flow experiments with discharges that were so low that the initial bed sediment was not mobilized, we rather unsurprisingly found that the bed surface grain size distribution was about the same as or only slightly coarser than the original mixture.

All of our symmetrical experiments resulted in some degree of vertical sorting and development of a bed surface that was coarser than the original mixture. For the symmetrical experiments, the armoring ratio ranged between 1.2 for the short experiment J1 and 1.8 for the long experiment B4 (Table 2). In the long experiment B4, the armoring ratio was similar to that of the constant flow experiment G2. Observations show that a substantial amount of sediment moved during the falling limb of the hydrographs (Figures 4e, i, k). This implies that, during the falling limb of these experiments, enough sediment, especially finer material, moved out of the flume to cause some degree of bed surface coarsening. It seems that the symmetrical shape of the hydrograph played a major role on the development of the bed surface, especially during the short hydrograph experiment J1.

The short asymmetrical hydrographs showed that the grain size distribution of the surface material initially became finer than the original mixture, and then the grain size distribution of the surface material returned to near the original value. For these experiments, there was a little time for sorting in the falling limb, and therefore the surface grain size distribution was roughly the same as that of the original mixture. In other words, little or no sediment sorting occurred during the falling limb of the hydrograph. Asymmetrical experiments with longer falling limbs developed some armoring. These experiments demonstrate the relative importance of flow duration for the vertical sorting of sediment and the development of armored surfaces. The armoring ratio ranged from 1 for the short experiment J2 to 2.4 for the long experiment C4 (Table 2). However, little change in the armoring ratio was noticed between C4 (44 hours) and D4 (10 hours). Judging from our results, it seems that a few hours of flow were sufficient for sorting on the falling limb.

If this is true, then why do these experimental results differ from the desert field cases that show the absence of armoring? This is likely explained by the sediment supply. Relative to the field, the flume length upstream of the observation reach was very short; in addition, there was no sediment feed at the upstream end of the flume. Hence the sediment supply was limited. Therefore, the difference in sediment supply can result in some degree of armoring in the physical model that is not represented in the natural case.

It is of some interest to note that the run with the short symmetrical hydrograph (experiment J1) resulted in weak bed armoring, whereas two runs with short asymmetrical hydrographs (experiments J2 and J5) did not result in bed armoring (Figures 5b and 5d). The difference here may be associated with the shortness of the rising limb in e.g. experiment J2 as compared to experiment J1. That is, experiment J2 may not have sustained high flows for a sufficiently long time to effectively deplete the bed of finer material, resulting in less armoring at the end of the run as compared to experiment J1.

The experiments reported here thus shed light on the role of the hydrograph in determining the degree of armoring at the end of a flood. A more detailed experimental study of the role of sediment supply on the degree of armoring at the end of a flood will require experiments in which sediment is fed in at the upstream end of the flume.

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Figure Captions

Figure 1: Median size of surface and subsurface of (a) ephemeral streams, and (b) snowmelt, humid and arid streams. Lines of equal armor ratio are shown. Bars are errors around the mean value. Figures 1a and b are based on table 1 and the following published data from humid and snowmelt streams: Allt Dubhaig (Wathen et al., 1995); Tom McDonald (Hassan and Woodsmith, 2004); Carnation Creek (Hassan et al., in press); Harris Creek (Church and Hassan, 2002); Fraser River (Church et al., 1987); Boise River, Little Slate Creek, Lochsa River, Lolo Creek, MF Red River, North Fork Clearwater River, Rapid River, Selway River, South Fork Payette River, South Fork Salmon River, and Valley Creek (Whiting and King, 2003); Jacoby Creek, Prairie and North Caspar (Lisle, 1989); Redwood Creek (Lisle and Madej, 1992); Willamette River (Klingeman and Emmett, 1982), Oak Creek (Parker and Klingeman, 1982); Segehen Creek (Andrews and Erman, 1986); Haut Glacier d'Arolla (Cudden and Hoey, 2003); Bas Glacier d'Arolla (Warbuton, 1992); Goodwin Creek (Kuhnle, 1992); Virginio Creek (Tacconi and Billi, 1987); Drau River (Habersack and Laronne, 2001); Fool Creek, East St. Louis, and Little Granite (Ryan, 2001, Ryan and Emmett, 2002); Mamquam and East Creek both in British Columbia (this study).

Figure 2: Three examples of particle size distribution of surface and subsurface bed material in three ephemeral streams.

Figure 3: Particle size distribution of flume mixture.

Figure 4: Flow and sediment transport characteristics of the flume experiments listed in Table 2. The experiments are organized based on experiment duration.

Figure 5: bed surface and transported material grain size distribution for selected experiments. Thick lines indicates samples taken during the falling limb, light lines indicates samples taken during the rising limb, number indicates the sampling time in hours, and inserted are the flow hydrograph.

Figure 6: Time evolution of D50 and D84 of the bed surface material for all experiments.

Figure 7: Fractional ratios diagrams of mobile size in selected experiments. Numbers are the flow discharge in m^3/s, numbers in prickets are the elapse time of the experiment, thick lines are the rising stages, and thin lines are the falling stages.

Figure 8: (a) Relation between armor ratio and sediment yield (total evacuated sediment). (b) Relation between armor ratio and effective total stream power as calculated above the threshold conditions.

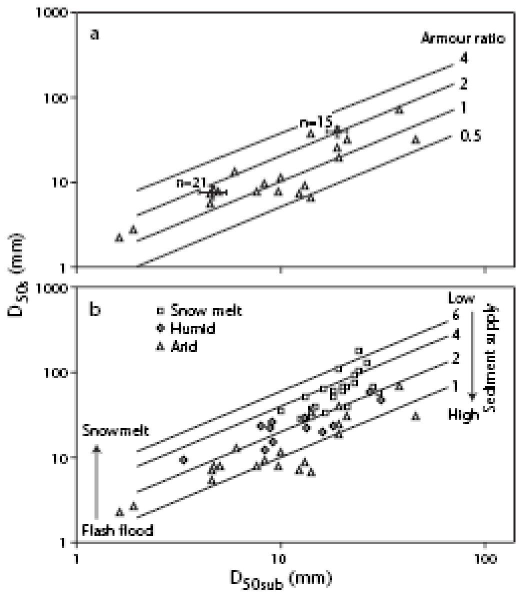
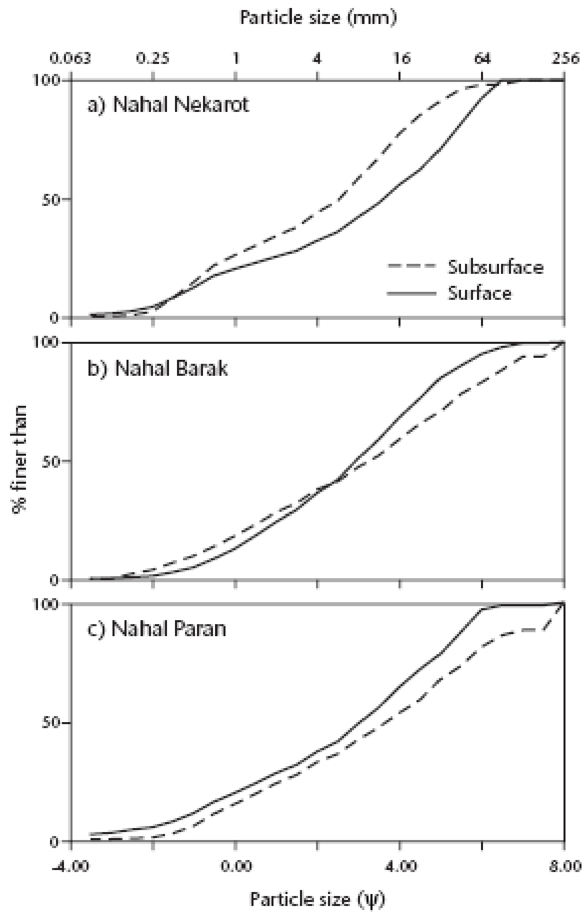


Figure 1 (Hassan et al.)



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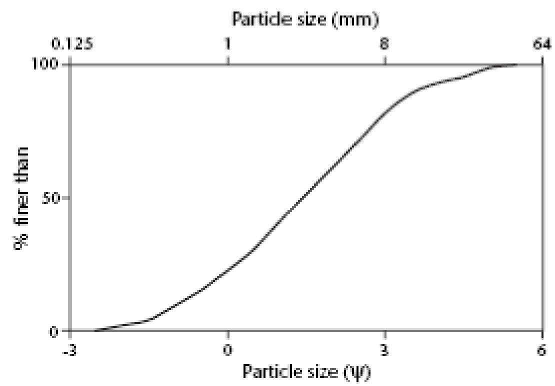

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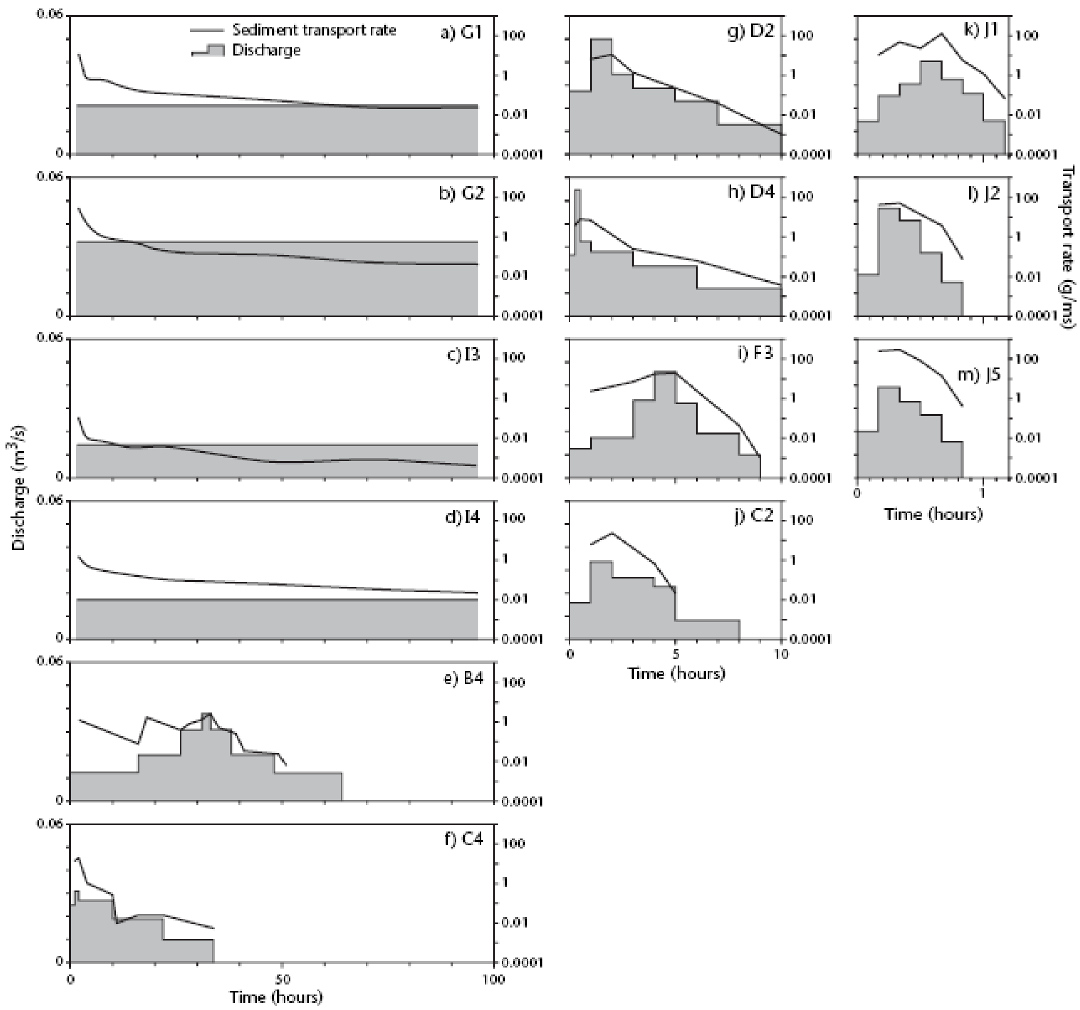

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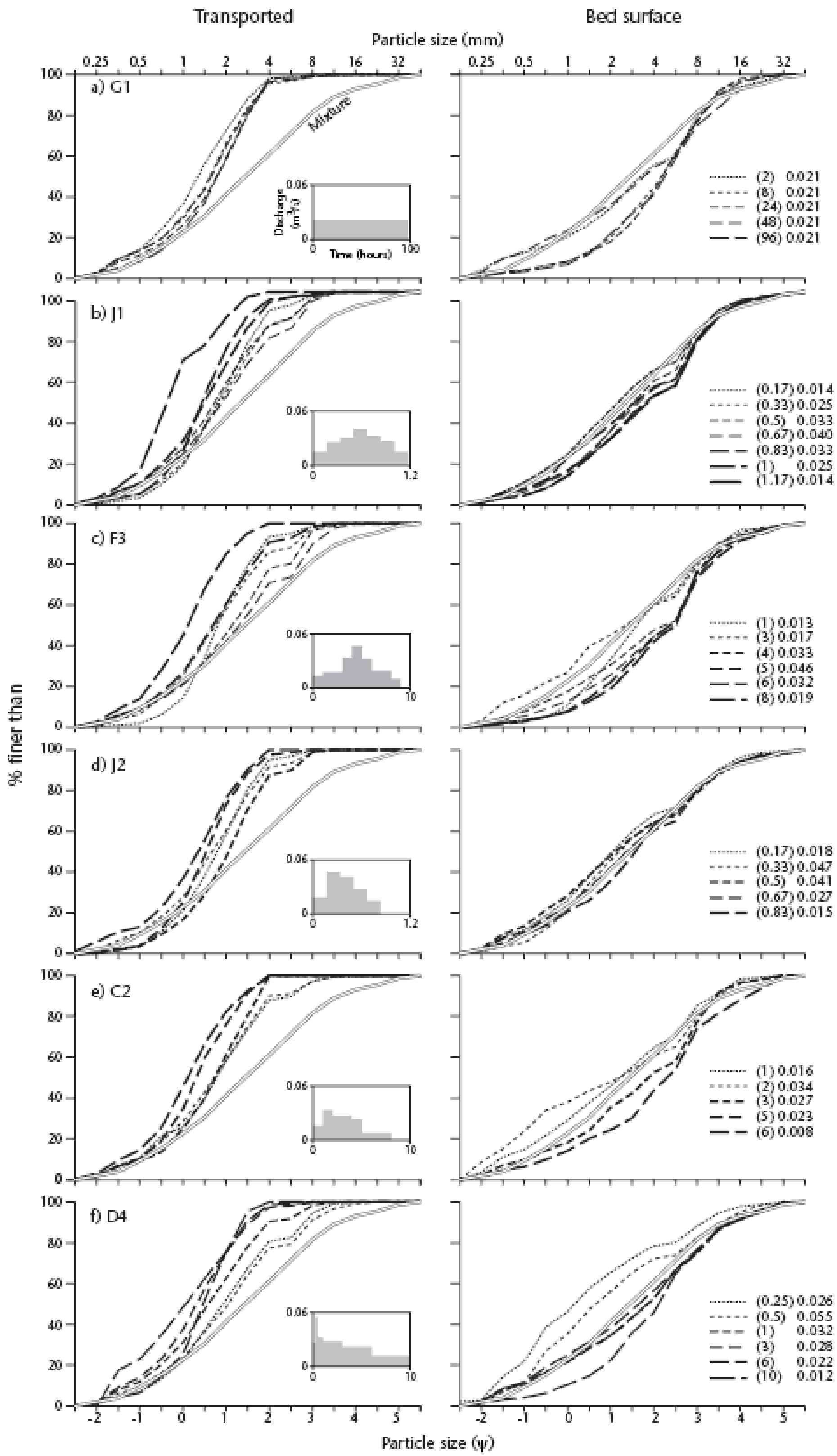

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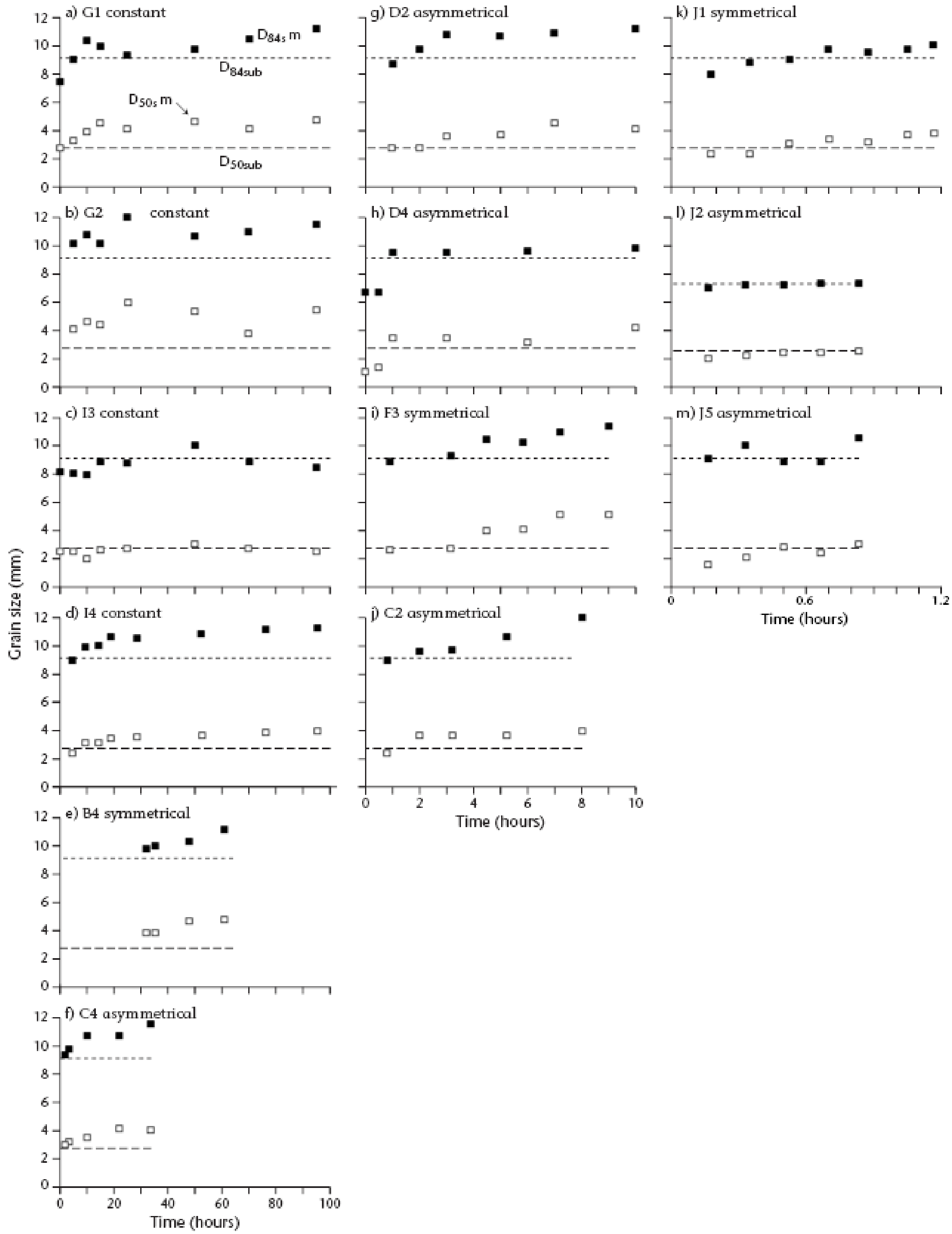

Figure 6 (Hassan et al.)

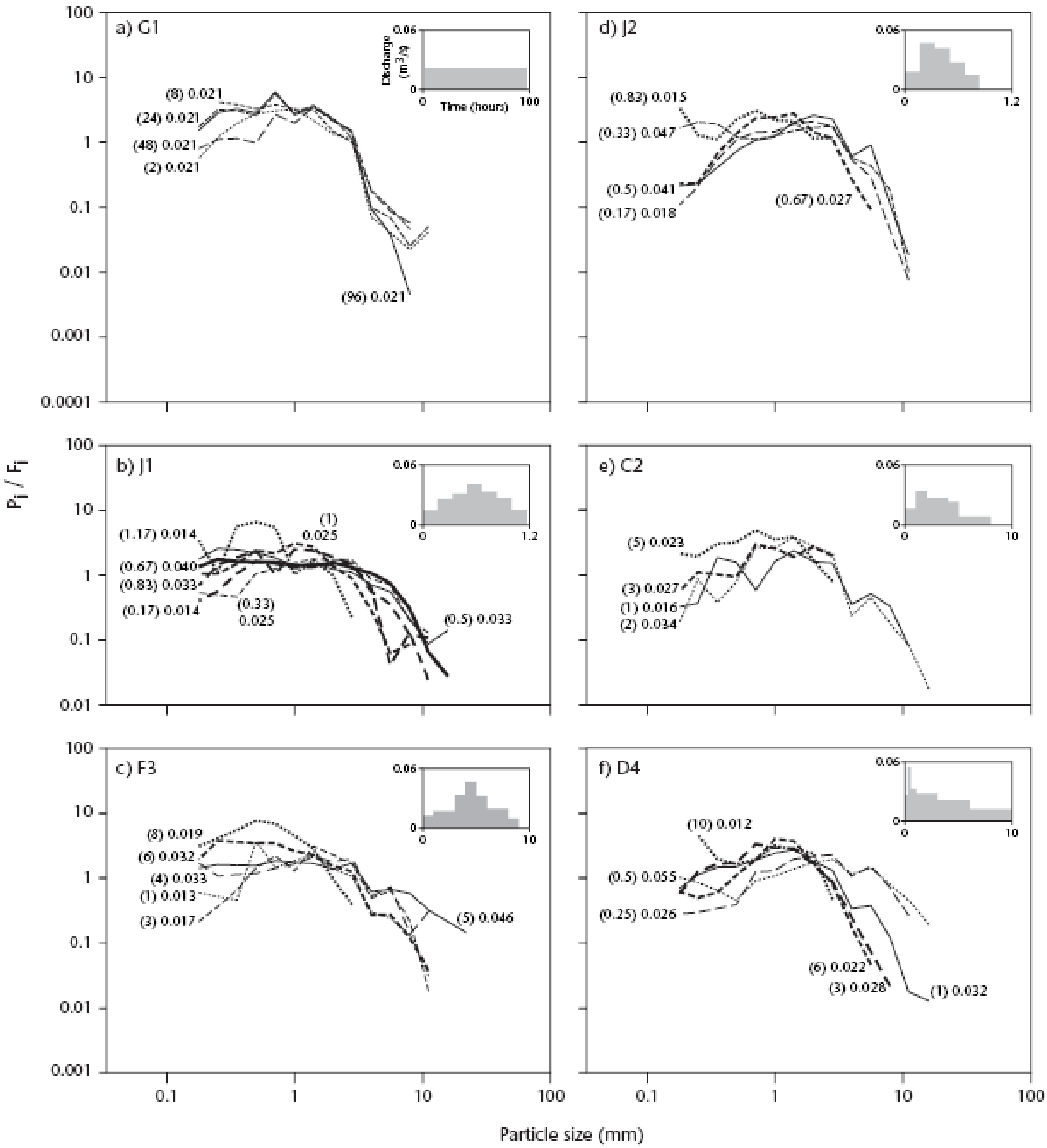

Figure 7 (Hassan et al.)

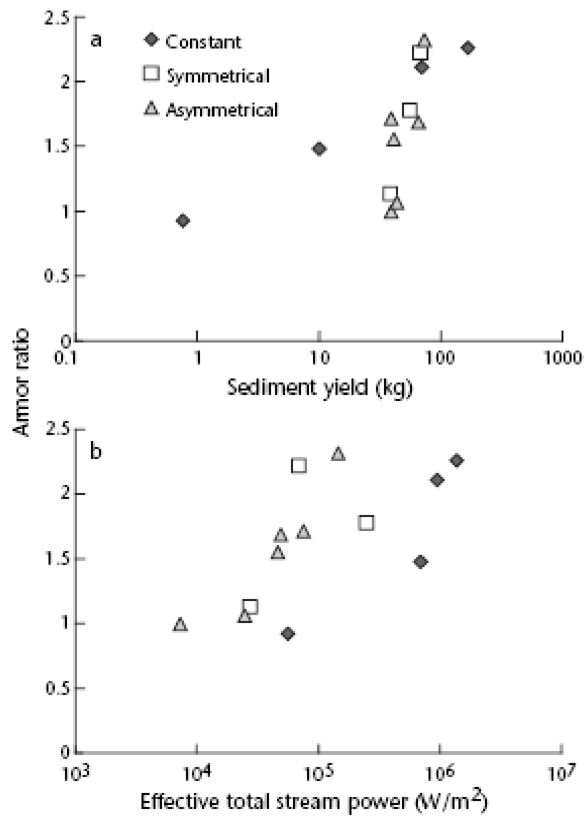

Figure 8 (Hassan et al.)

Table 1: Characteristics of arid streams.

Stream	Drainage area (km^2)	Annual rain (mm)	Mean annual flood (m^3/s)	Mean number of flow events	Number of samples	D_{50sub} (mm)	D_{50s} (mm)	Source
Ashalim	70	< 75	5	1	1	46	29	
Arava	6500	< 75			1	8	9	
Avia	6	50-100			1	8	8	
Barak	10	< 50			1	10	8	
Boker	97	< 100			1	13	7	
Darga	147	100-500	11	2	1	21	30	
Eshtamoa	112	200-500	12	7		19	18	Powell et al., 2001
Gvanim	8	< 75			1	5	5	
Hebron	250	200-500	17	3	23	38	68	
Hemar	450	50-150	15	2	4	19	24	
Nekarot	697	50-100	19	3	1	6	12	
Og	100	100-500	10	5	15	19	38	
Paran	3350	< 50	17	1-2	1	13	9	
Sayf	7	< 50			1	2	2	
Shahak	13	< 50			1	5	7	
Shilhav	5	< 50			1	2	3	
Yael	0.6	< 25	2*	< 1	4	10	11	
Yaham	14	< 50			1	14	7	
Yattir	136	200-300	14	7		19	18	Laronne et al., 1994
Zihor	171	< 50			1	5	7	
Zin	1400	50-100	22	4	21	5	7	

Notes: * estimated based on short record, D_{50s} median size of surface material, D_{50sub} median size of subsurface (bulk) material.

Table 2: Hydraulic and sediment data.

Exp.	Duration (hours)	Q range (m^3/s)	R_b range (m)	S ($x10^3$)	τ_b range (Pa)	Time to peak (hours)	D_{50t} (mm)	D_{50s} (mm)	# of flow steps to peak	Total number of steps	Hydrograph shape
G1	96	0.021	0.066	8	5.1	---	1.74	4.8	---	1	Constant
G2	96	0.032	0.083	7.6	6.2	---	1.5	5.4	---	1	Constant
I3	96	0.014	0.063	1.4	0.9	---	1.3	2.5	---	1	Constant
I4	96	0.019	0.036	6.5	2.3	---	1.4	4.0	---	1	Constant
B4	64	0.012 - 0.038	0.048 - 0.084	5	2.3-4.2	32	0.98	4.8	4	7	Symmetrical
F3	9	0.010 - 0.046	0.042 - 0.092	5.7	2.1 – 5.1	4	1.08	5.2	4	7	Symmetrical
J1	1.17	0.014 - 0.040	0.037 – 0.095	5	1.8 – 4.7	0.50	1.35	3.8	4	7	Symmetrical
C4	34	0.010 – 0.031	0.043 - 0.071	5	2.1 – 3.5	1	1.3	4.0	2	5	Asymmetrical
C2	8	0.008 - 0.034	0.04 – 0.079	5	2.0 – 3.9	1	1.08	4.1	1	7	Asymmetrical
D2	10	0.013 – 0.050	0.048 – 0.104	5	2.3 – 5.1	1	0.81	4.1	2	6	Asymmetrical
D4	10	0.012 - 0.055	0.050 – 0.105	5	2.5 – 5.1	0.25	1.04	4.2	2	6	Asymmetrical
J2	0.83	0.015 - 0.047	0.045 – 0.093	5	2.2 – 4.5	0.17	1.47	2.7	2	5	Asymmetrical
J5	0.83	0.016 – 0.039	0.029 – 0.065	19	7.0 – 12.1	0.17	0.96	3.0	2	5	Asymmetrical

R_b = hydraulic radius, Q = discharge, S = water surface slope, τ_b = shear stress, D_{50t} = median size of transported material, D_{50s} = median size of bed surface material . D_{50t} and D_{50s} refer to values measured at the end of the experiments; the number of steps to peak includes the peak flow. τ_b is estimated by ρgSR_b.