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Upstream sediment input effects on experimental dune trough scour in sediment mixtures

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[1] Understanding causes of dune irregularity, especially dune trough scour, is important for the modeling of vertical sorting of sediment mixtures in morphological models of rivers with sediment mixtures. Sediment in dunes is generally sorted in a fining-upward manner, which affects the sediment transport composition depending on the scour depth distribution of the dunes. Why dunes become more irregular and develop deep scour holes in some conditions is only partially understood. Moreover, there is a feedback between vertical sorting and dune irregularity. In gravelly sands, erosion-resistant coarse layers may form that decrease or inhibit dune trough scour. The causes of dune irregularity and the feedback by coarse sediment layers are explored in experiments and are demonstrated to be related partly to the upstream sediment boundary condition determined by the experimental setup: sediment feeding or recirculating. Sediment recirculation flumes promote fining of the transported sediment and formation of a less or immobile gravel lag layer in the dune troughs. Sediment feed flumes may force the transported sediment at the flume entry to be equal to the bed sediment (equal mobility condition) and hence allow no lag layer formation. Experiments show that the dune trough scour in recirculation is less deep than in feed flumes, and the vertical sorting and transport sediment composition are different. The experiments also indicate that dune irregularity in feed flumes is related to dimensionless shear stress similarly as in uniform sediments. Interpretation of experiments of dune dynamics in sediment mixtures should therefore account for differences in the upstream sediment supply condition. More in general, it is hypothesized that the upstream sediment supply condition (resembling either recirculation or feed flumes) in rivers may affect dune and vertical sorting dynamics.

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1. Introduction

[2] Morphological modeling of channel beds with sediment mixtures has made strong progress in the past decade. To model the sediment transport process and the exchange between transported and bed sediment mixtures in rivers with dunes correctly, the bed level variations due to migrating dunes must be accounted for [*Ribberink*, 1987; *Paola and Borgman*, 1991; *Parker et al.*, 2000; *Leclair and Bridge*, 2001] as well as the vertical sediment sorting in the dunes [*Parker et al.*, 2000; *Kleinhans*, 2001, 2002] (see http://www.geog.uu.nl/fg/mkleinhans). Bed level variation is caused by dune migration and hence related to dune irregularity. Following the definition of *Costello and Southard* [1981], regular dunes are called two-dimensional (2-D) and the irregular 3-D. This can be expressed quantitatively in the vertical direction as a probability distribution of trough depths or a probability distribution of bed level variations [*Parker et al.*, 2000], and in the horizontal direction as the sinuosity of the dune crest lines and connectivity (or length) between crest lines. Sediment is generally sorted in dunes in a fining-upward manner, which in turn affects the sediment transport composition depending on the scour depth distribution of the dunes at a later point in time. Both the bed level variation and sediment sorting must therefore be implemented in model concepts [*Parker et al.*, 2000; *Blom*, 2003], but are not yet well predictable for various flow conditions and sediments [e.g., *Leclair and Blom*, 2005].

[3] Dunes in uniform sediment become more irregular in horizontal and vertical directions with increasing shear stress up to the transition to upper stage plane bed where the dunes flatten again [*Reineck and Singh*, 1973; *Boothroyd and Hubbard*, 1975; *Costello and Southard*, 1981; *Terwindt and Brouwer*, 1986]. *Southard and Boguchwal* [1990] presented bed form stability diagrams in which the dune stability field is divided into 2-D and 3-D regimes based on experiments. Although the exact division is arbitrary, it indicates a transition from 2-D to 3-D dunes with increasing shear stress (or flow velocity at a given water depth). This diagram is also valid for gravels [*Carling*, 1999]. When dunes have a highly variable trough scour depth, the set thickness of the dune deposits is larger and highly

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Table 1. Experimental Parameters of the Experiments

Exp	u, m/s	h, m	S, 10^{-3}	D_{50}, 10^{-3} m	D*	D_{90}, 10^{-3} m	τ', Pa	θ'	Temperature, °C	Description
Equ1	0.51	0.048	4.1	1.26	28	5.27	1.89	0.093	12.2	Armoring, "plane" bed, repeated as Non1
Equ2	0.78	0.132	3.6	1.26	28	5.27	3.00	0.147	12.2	2-D dunes
Equ3	1.08	0.209	3.6	1.40	31	5.61	5.03	0.222	11.5	3-D dunes
T10	0.54	0.16	1.11	1.28	29	9.29	1.88	0.091	14	Barchans
T5	0.70	0.23	1.47	1.06	24	9.49	2.50	0.146	14	Transitional barchans to 2-D dunes
T7	0.80	0.35	1.52	1.21	27	10.25	2.89	0.148	14	2-D dunes
T9	0.70	0.26	1.69	1.39	31	9.44	2.41	0.107	14	2-D dunes

spatially variable in thickness [*Harms and Fahnestock*, 1965; *Reineck and Singh*, 1973; *Paola and Borgman*, 1991; *Leclair and Bridge*, 2001]. Since vertical sediment sorting is generated within a set [*Kleinhans*, 2001], set thickness variability decreases the net vertical sorting in the bed averaged over several dune lengths and set lengths. On reentrainment of these fining-upward sets by passing dunes, the depth and variability of the trough scour determines the entrainment of the coarser, deeper sediments.

[4] For dunes in sediment mixtures, two complicating factors are known. First, lower mobility or immobility of the coarser sediment leads to armoring, which in turn leads to sediment supply-limited conditions. This means that the amount of mobile sediment above the armor layer is insufficient to build dunes up to their equilibrium dimensions for the given flow and characteristics of the mobile sediment. Instead, flow parallel sand ribbons or barchan dunes develop. Barchan dunes are highly 3-D in the horizontal direction but trough scour is inhibited by the armor layer [*Kleinhans et al.*, 2002]. Second, during high discharge when large dunes form, coarse sediment concentrates in the troughs of the dunes. If this coarse lag layer is coarse or thick enough, a situation comparable (but not equal) to armoring might develop [*Kleinhans*, 2001]. The lag layer just below the active dunes hinders dune growth and sediment entrainment from the bed below the active dunes [*Klaassen*, 1991], and inhibits the formation of deep scour holes that are characteristic for irregular dunes [*Hooke*, 1968; *van der Zwaard*, 1973]. Thus the trough scour depth variation, which determines lag layer formation and thus vertical sorting, is itself strongly coupled to vertical sediment sorting. This multivariate interaction has already been explored by *Leclair and Blom* [2005] and will be further explored herein.

[5] A gravel lag layer forms when the gravel is slightly less mobile than the sand. The sediment mobility differences between grain size fractions are commonly related to a hiding exposure effect: the hiding of small grains in the lee of large grains and the exposure of large grains to the flow. A well-known mobility condition in unimodal sediments is equal mobility, in which the sediment composition of bed load (temporarily "stored" in dunes) and sediment underlying the surface sediment are equal. This implies that the critical shear stress is equal for all grain size fractions, which is attained by mobile armoring in the (nearly) plane bed case [*Parker and Klingeman*, 1982]. Bimodal or very widely distributed sediments, on the other hand, commonly exhibit smaller mobility of the coarser sediment [*Wilcock*, 1993; *Kuhnle*, 1993]. A basic question for the plane bed or bed load sheet case is whether the composition of the bed surface armor layer changes with changing flow or with a change in composition of the upstream sediment supply. *Wilcock* [2001] hypothesized that the nature of the sediment supplied from upstream controls the mobility differences between grain size fractions.

[6] A new hypothesis is developed here to extend *Wilcock*'s [2001] hypothesis to duned beds. The above mentioned mobility differences between grain size fractions strongly affect the lag layer development, which in turn determine the dune irregularity due to trough scour. In short: the nature of the sediment supplied from upstream controls dune irregularity. This is highly relevant for experimental studies of dune migration in sediment mixtures, because two fundamentally different methods for upstream sediment supply have been used: by feeding a constant sediment mixture or by recirculating the transported sediment from the tail end of the flume to the entrance (periodic boundary condition). In both flumes, the discharge, water depth and the initial slope are specified (and uniform flow can be maintained). In the sediment feed flume, the rate and composition of the sediment entering the flume is specified, while in the recirculating flume, it is determined by the (selective) transport process; thus the transport rate and composition is a dependent parameter [*Parker and Wilcock*, 1993].

[7] The aims of this paper are to investigate experimentally whether (1) dune trough scour irregularity in sediment mixtures without lag layers is similarly related to the shear stress magnitude as in uniform sediment and (2) the upstream sediment supply has an effect on lag layer formation and therefore on dune trough scour.

2. Methods

2.1. Methodology

[8] The difference between the two types of experimental setups is employed to contrast two cases: one with equal mobility (feed flume) and one with higher mobility of finer sediment (recirculation flume). Low and high shear stress equilibrium experiments were done in a feed flume to test whether the 2-D versus 3-D bed form irregularity is related to shear stress as it is in uniform sediment. The use of the feed flume with unimodal sediment ensures that no gravel lag is formed, so the effect of shear stress on dune irregularity can be isolated from the effect of gravel lags on dune irregularity. A second set of experiments was done in a recirculating flume to demonstrate the effect of a gravel lag (in addition to shear stress) on dune irregularity and to compare this condition to one without a gravel lag.

[9] Summary parameters are given in Table 1. The depth-averaged flow velocity (u) was determined by calibrated flow discharge measurement, the width of the flume (w) and the average water depth (h) along the measurement section as $u = Q/(wh)$. Subcritical flow ($Fr < 0.84$) was maintained,

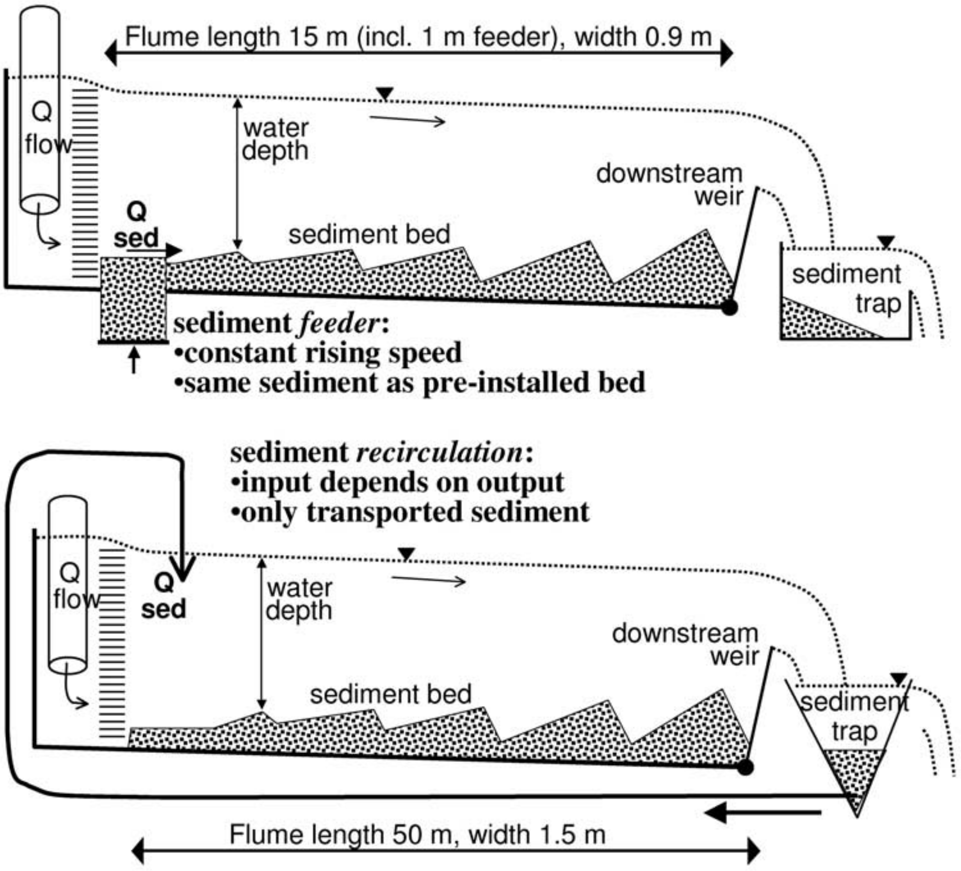

Figure 1. Experimental setup of the (top) sediment feed flume and (bottom) sediment recirculation flume. Water discharge is entered through a turbulence-damping grating. The downstream water level is controlled with a tailgate, which may either be upstream or downstream of the sediment trap. The relevant difference between the flumes is in the upstream sediment supply.

with $Fr = u/(gh)^{0.5}$ (g = gravitational acceleration). From the slope (S) and the hydraulic radius (R_c) the total shear stress (τ) was determined with $\tau = \rho g R_c S$ (ρ = density of water). The hydraulic radius was corrected for sidewall roughness with the method of Vanoni-Brooks. The dimensionless shear stress on grains can be computed as $\theta'_{50} = \tau'/[(\rho_s - \rho)gD_{50}]$, in which ρ_s = density (of sediment), g = gravitational acceleration and D = sediment diameter (50th percentile), τ' = shear stress on the grains, computed as $\tau' = \rho g[u/C']^2$ in which u is the depth-averaged flow velocity, C' is the grain-related Chézy coefficient: $C' = 18\log[12R_c/k'_s]$, with k'_s the grain roughness, assumed to be equal to the D_{90} of the sediment mixture as installed in the flumes. By assuming grain shear stress, the effect of bed forms on roughness and shear stress is removed. The median grain size is made dimensionless with $D^* = D_{50}[(\rho_s - \rho)g/(\rho\nu)]^{1/3}$ with ν the kinematic viscosity of water ($\sim 1.2\ 10^{-6}\ m^2\ s^{-1}$).

2.2. Setup of Experiments in a Sediment Feed Flume

[10] Three feed flume experiments were done in the Tilting Bed Flume at St. Anthony Falls Laboratory, which has a length of 14 m and a width of 0.9 m [*Kleinhans*, 2002] (Figure 1). Equ1 was a mobile armoring experiment for reference to the plane bed condition and Equ2 and Equ3 had dunes (Figure 2). Uniform flow was maintained by adjusting the downstream weir. The test section was between 4 and 13 m from the sediment feeder. Time series of the bed level at a fixed point (11 m from flume entrance) and water and bed surface profiles were collected in the middle of the flume with an ultrasonic device. The flow was maintained until the system was in equilibrium, which was defined as the condition at which the variations of bed form dimensions, sediment transport and average bed level change became smaller than the measurement accuracy and variability. The bed was remixed after each experiment. It should be noted that the flume was too short to attain equilibrium of the dune height for the largest flow depth; the dune height increased toward the downstream end of the flume as in most experiments with dunes reported in literature. The sediment was a log-normally distributed unimodal sediment (Figure 3), installed at a bed slope equal to that of the flume. Sediment of the same composition as the initial bed sediment was fed into the upstream end of the flume by a rising platform of 0.9 m wide and long, which rose at a constant and adjustable speed. Helley Smith measurements (ratio of nozzle exit area to entrance area 1.10, bag of 100 μm mesh size) were done at 13 m to check whether the transport rate and composition were equal to that of the feeder. In equilibrium conditions, the Helley Smith gave a mean transport rate within a few percent of the feed rate. The composition of transported sediment as measured with the Helley Smith is reported herein. Sus-

Figure 2. Photographs of the Equ experiments. For photographs of other experiments the reader is referred to *Kleinhans* [2002] and *Blom et al.* [2003].

pended load transport above the nozzle of the Helley Smith was negligible.

2.3. Setup of Experiments in a Sediment Recirculation Flume

[11] Four experiments (Table 1) were done in the Zandgoot flume at WL|Delft Hydraulics (Figure 1), which has a length of 50 m and a width of 1.5 m [*Kleinhans*, 2002; *Blom et al.*, 2003]. T10 and T5 had barchan to transitional dunes while T7 and T9 had dunes. The sediment was recirculated with sediment pumps. Suspended load transport was negligible. Bed and water surface profiles along the flume and bed load transport were automatically collected. The experiments were started with a mixed bed of slightly bimodal sediment, installed at a bed slope that is equal to the expected water surface slope of the experiments. The flow was maintained until the system was in equilibrium (T10 and T5). The next step on the bed of T5 was to generate a flow with a higher bed shear stress until a new equilibrium was reached (T7), and then again lower (T9) without remixing the bed. Samples have been taken from the transported sediment that was measured automatically in the recirculation system.

3. Results

3.1. Sediment Feed Flume

[12] Near the end of the Equ2 and Equ3 experiments (Figure 2), the composition of the transported sediment is almost equal to that of the original bed sediment and feeder sediment (Figures 3a and 3b). This shows that all the grain sizes were in motion in almost the same abundance as they occur in the bed sediment, approximating equal mobility with increasing discharge as expected. Small differences in fine grain sizes are due to suspended sediment not sampled in the Helley Smith.

[13] The dunes in Equ2 (lower shear stress) were much more regular than in Equ3 (high shear stress), in the sense that the latter had more curved crest lines and deep scour pits every now and then, while the regular ones were more straight crested and did not have pronounced scour pits (Figure 2). The dunes in Equ3 are about twice as high as in Equ2. From the time series taken at a single position, probability distributions of the bed level were computed (Figure 4a). These distributions indicate the variations of bed level due to passing dunes, normalized with respect to the average bed level at that position in that time period, and made dimensionless with water depth (Figure 4c). The Equ3 experiment has a skewed distribution with much deeper dune troughs than dune tops, while the distribution for Equ2 is about symmetrical. The narrow, symmetrical distribution of Equ1 is solely due to grain dynamics.

3.2. Sediment Recirculation Flume

[14] Experiments T10 and T5 had barchan dunes whereas T7 and T9 had slightly irregular 2-D dunes. There were no trough scour pits as was found after making trenches along the flume; the gravel lag was continuous and nearly plane. The bed load composition in all experiments is finer than the original bed sediment (Figures 3c and 3d), but the finest in T9 because most gravel was worked downward in T7 and was no longer entrained in the shallower dune troughs in T9. Consequently, the bed load compositions of T5 and T9 are different even though the shear stresses were approximately equal. The bed level distributions were computed from the downstream half of a number of profiles along the flume (in equilibrium conditions) after linear detrending of the profile. Comparison of T5, T7 and T9 reveals a close resemblance of T7 and T9 (Figure 4b) even though the shear stress in T7 is larger than in T9. So, relative to T5, the trough scour depth in T9 is much more

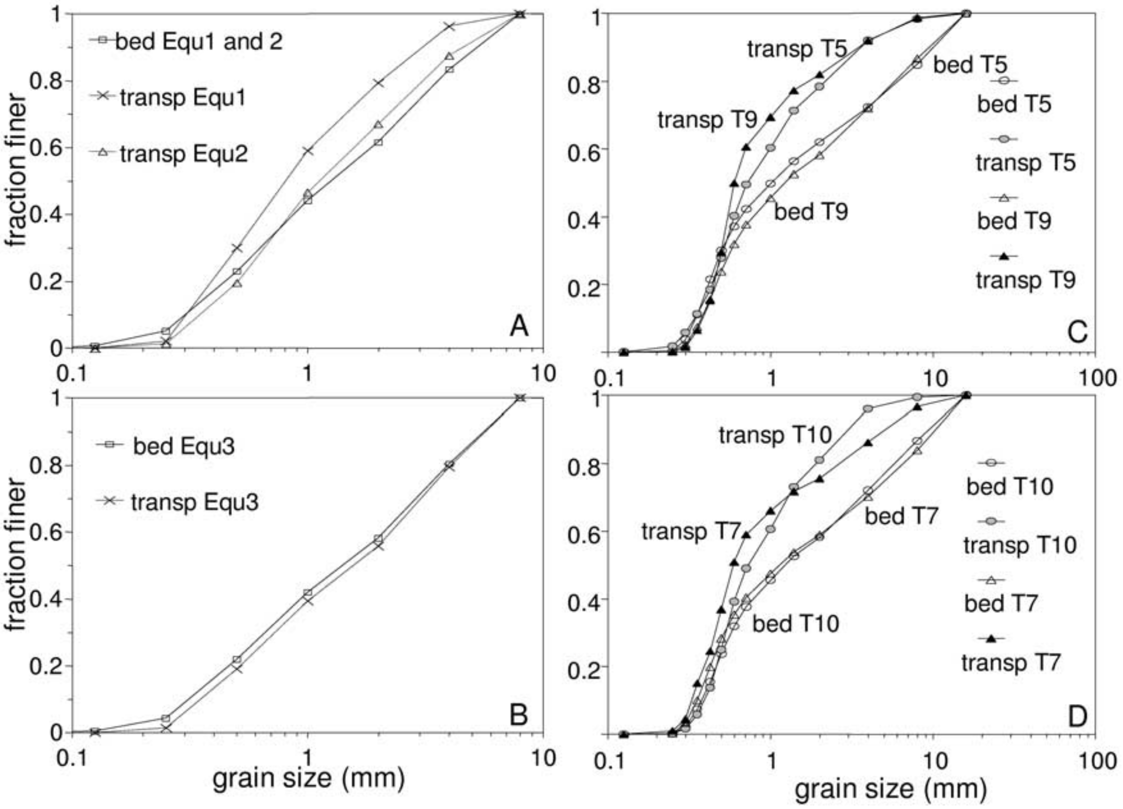

Figure 3. Comparison between grain size distributions of the bed sediment (equal to the feed sediment) and the bed load sediment at the end of the feed flume experiments and between the bed sediment and recirculated sediment of the recirculation flume experiments. The bed load sediments of (a, b) Equ2 and Equ3 approximate the bed sediments, demonstrating (near) equal mobility, whereas the bed load sediment of (c, d) T5, T7, T9 and T10 is much finer than the bed sediment, demonstrating higher mobility of the finer sediment.

pronounced, although still fairly regular. The reason is that in T5 and T7 there was a gravel layer beneath the troughs which hindered the trough scour, whereas in T9 the gravel had been worked down too deep for the dunes to be affected. See *Kleinhans et al.* [2002] and *Blom et al.* [2003] for more extensive descriptions and vertical sorting data.

4. Discussion

4.1. Causes of Dune Irregularity

[15] From the feed flume experiments, in which lag layer formation is not allowed, it can be concluded that the transition from 2-D to 3-D dunes in nonuniform sediments occurs with increasing shear stress similarly to uniform sediments. The probability distributions of bed levels for 3-D dunes (Equ3) at high shear stress have a much longer tail down into the bed than for 2-D dunes (Equ2) in lower shear stress (Figure 4). The choice for a grain size parameter in the dimensionless shear stress parameter is discussed by *Kleinhans et al.* [2002]. The effect of choosing grain size percentiles from bed sediment, transported sediment or lag layer sediment has a large effect on the magnitude of the shear stress, but the trends between experiments are the same except for T9. The (dimensionless) shear stress for T9 given in Table 1 is probably not correct as the chosen sediment diameter refers to the original sediment rather than the finer sediment activated in T9 by the dunes over time.

[16] The dunes in the Equ experiments become irregular at high shear stress as expected from literature. To further demonstrate the relation between three-dimensionality of the gravelly sand dunes and flow conditions, the available experiments reported in this paper and from literature are plotted in the bed form stability diagram of *Southard and Boguchwal* [1990, Figure 5] (Figure 5). This diagram is based on flow velocity rather than shear stress, but the limited depth range for which it is given means that a diagram with (dimensionless) grain shear stress gives similar results. The result for the diagram of *van den Berg and van Gelder* [1993] (based on dimensionless grain shear stress and D*) is indeed similar, but is not shown here because *van den Berg and van Gelder* [1993] never plotted the transition from 2-D to 3-D dunes in their diagram. The data follow the predicted increase of three-dimensionality in the diagram to some extent, even though the dunes have been classified somewhat arbitrarily in two- and three-dimensional and larger dune height relative to the flume width may obscure three-dimensionality in some experiments. However, the 29SAFL experiment deviates from the results and the reason for this is unclear and probably related to parameters not given in the diagram. Unfortunately no data are

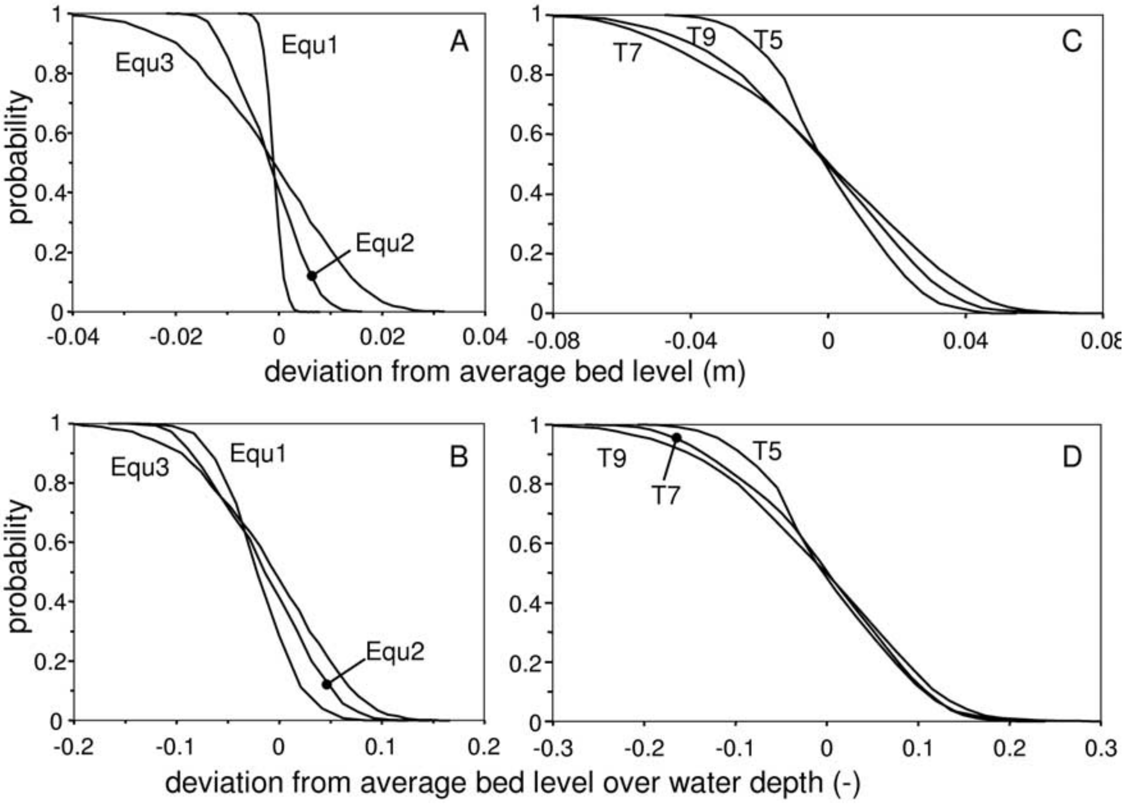

Figure 4. (a, c) Probability distributions of the bed surface. The long (left) tail of the Equ3 distribution indicates high dune trough irregularity. T9 has relatively deep troughs because of the much finer sediment in transport than in T5 and T7 (see text). (b, d) Made dimensionless with water depth.

available for 2-D dunes in sediment mixtures with grain sizes of 0.4—0.7 mm.

4.2. Mixture Feedbacks on Dune Irregularity

[17] While the results in the feed flume indicated that dune irregularity depends on shear stress in the same way as for uniform sediment when the formation of coarse layers is inhibited, the recirculation flume experiments demonstrated the two ways in which such a coarse layer affects dune irregularity.

[18] First, in extreme cases (very wide mixtures, low shear stresses and fine sediment supply), isolated barchan dunes migrate over a stable armor layer [*Kleinhans et al.*, 2002], and the trough-scouring flow is ineffective (experiment T10). Thus the exchange of sediment between the bed load and substrate sediment through the armor layer is insignificant. The dunes are ''irregular'' in planform (barchanoid) but do not have widely varying scour depths. In this case the mixture feedback on trough scour-related irregularity is strong and outweighs the shear stress control on (vertical) irregularity. Moreover, the irregularity is completely controlled by either the bimodality of the sediment and/or the upstream sediment supply (recirculation) which is much finer than the bed sediment, both resulting in the low mobility of coarse sediment.

[19] Second, for the same initial combination of slope, discharge and water depth and sediment mixture properties the feed and recirculation flumes give different results. Starting with a fully mixed bed and a relatively low shear stress, in a recirculating flume only the finer sediment is entrained and migrates over the immobile coarse sediment. The sediment entering the flume is this same fine sediment. The result is therefore fine mobile sediment (possibly barchan dunes) migrating over immobile coarse gravel (lag deposit), which is a strong deviation from equal mobility. In a feed flume the coarse fractions in the feed sediment cannot be transported and therefore are deposited in the upstream part of the flume. This leads to an increase in bed slope (and, maintaining uniform flow, also water surface slope), and consequently to an increase of the bed shear stress, until the coarser sediment is transported as well. The feed system is eventually forced (in equilibrium) to transport all the sediment that is fed in. At moderate discharge, this equal mobility condition is only attained when a mobile armor layer is formed [*Parker and Klingeman*, 1982]. So, in a recirculation flume or with a fine upstream sediment supply or without sediment supply at all, the armor layer becomes stable whereas in a feed flume an armor layer is mobile. A mobile armor layer is able to adapt to changing conditions, whereas the stable armor layer usually needs a shear stress above a high critical value before it is broken up.

[20] Equivalently for the duned bed, the coarse layer formed at the base of dunes can be characterized as mobile or stable. In stable coarse layer-forming conditions when the sediment supply is limited and/or finer than the substrate (recirculating flume), the immobility of the lag layer will outweigh the tendency of dunes to scour their troughs, and

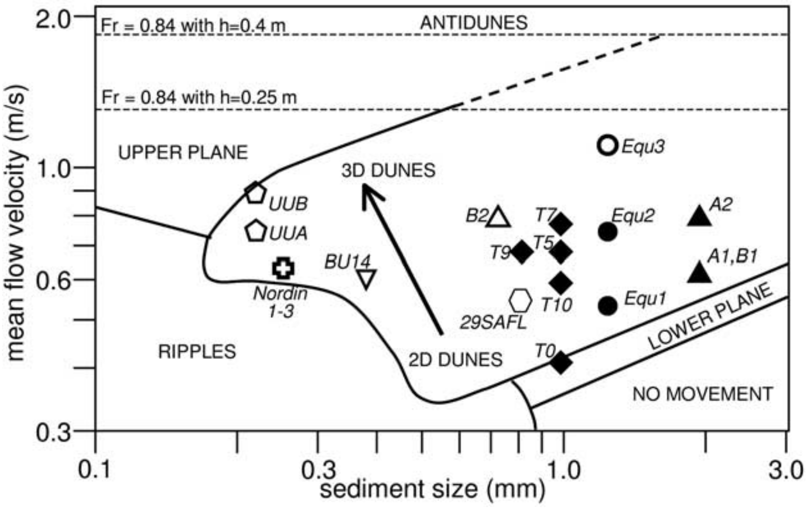

Figure 5. Bed form stability diagram of *Southard and Boguchwal* [1990] from their Figures 10.3 and 10.8 for water depths of 0.1–0.4 m. Open symbols represent 3-D dunes, and closed symbols represent 2-D dunes. The transition from dunes to antidunes occurs above Froude numbers of 0.84, which is given for two water depths in the graph. The experiments plotted are Equ1–3 (feed flume) of *Kleinhans* [2002], the barchan dunes of A1 and B1, 2-D dunes of A2 and 3-D dunes of B2 (recirculation flume) from *Blom et al.* [2003], lower plane bed of T0, barchan dunes of T5 and T10 and 2-D dunes of T7 and T9 (recirculation flume) from *Kleinhans et al.* [2002] and *Blom et al.* [2003], 3-D dunes of BU14 and 29SAFL (recirculation flume) from *Leclair and Blom* [2005], 3-D dunes in uniform sand runs UUA and UUB (recirculating flume) from J. H. van den Berg and I. van Enckevort (personal communication, 2003), and 3-D river dunes (runs 1–3) of *Nordin* [1971] with uniform sediment. All these data were collected in water depths of 0.15–0.35 m.

in extreme cases the dunes remain isolated barchanoids. In "mobile lag layers" (feed flume) dunes will be able to scour their troughs according to the tendency to become more irregular, and there barely is a feedback of a gravel lag on dune trough scour. In other words, the mobility of the coarse sediment in the trough zone is not only a function of the shear stress and the trough depth variation, but also of the composition of upstream supplied sediment relative to the sediment in the (active) bed as hypothesized. This extends the findings of *Wilcock* [2001] for plane beds and *Leclair and Blom* [2005] for duned beds, and must be taken into account when experimental bed level probability distributions from sediment feed and recirculation setups are compared and interpreted with the aim to apply the resulting model to rivers.

[21] For instance, *Leclair and Blom* [2005] compared the probability distributions of the bed surface levels for the experiments A1 and A2 of *Blom et al.* [2003] and 29SAFL of *Leclair and Bridge* [2001], both in a recirculation flume, of which the former were done with a wide sand-gravel mixture while the latter was done with a narrow sand mixture. The wide mixture had a more or less symmetric probability distribution, while the narrow mixture had a long tail from the deep irregular scour. *Leclair and Blom* [2005] attributed the difference between the 3-D dunes in the narrow mixture (29SAFL) and the 2-D dunes in the wide mixture (A1, A2) to the presence of coarse sediment in the trough zone which is less mobile due to the low dimensionless shear stress. In the light of the analysis above, the cause may also have been a combination of both low sediment mobility and lag formation, where the lag formation is due to the recirculating flumes of A1,A2 rather than the sediment mobility. This suggests that an experiment similar to A2 in a feed flume would give deeper dune trough scours in the absence of a lag layer.

[22] The differences between upstream sediment boundary conditions may also be relevant for rivers and modeling in general. The feed flume likely represents field conditions with equilibrium sediment transport and sediment composition best because the gravel is not worked down irreversibly below the active layer (also see *Parker and Wilcock* [1993] for discussion). The recirculating flume, on the other hand, may better represent bed sediment dynamics during floods, where hysteresis in armor layer and dune development cause the vertical sorting and composition of sediment in transport to be different before and after the flood peak [*Klaassen*, 1991; *Kleinhans*, 2001]. Bimodal sediments commonly show nonequal mobility [e.g., *Wilcock*, 1993], which, as an upstream sediment input condition similar to a recirculating flume, might cause lag layer formation or downstream fining [*Paola et al.*, 1992] more often than unimodal sediments.

5. Conclusions

[23] The two common experimental setups of sediment feed and recirculation represent different, extreme cases of upstream sediment supply conditions compared to natural streams. Sediment recirculation flumes promote the formation of lag layers, contrary to feed flumes. The dune irregularity (expressed as a probability distribution of bed levels) in the absence of coarse sediment layer formation as

in feed flumes is related to dimensionless shear stress similarly as uniform sediment. A negative feedback by vertical sorting (coarse layer formation) is likely to occur in mixtures with nonequal mobility, as in conditions where the sediment supplied upstream is finer than the substrate as in recirculation flumes. This must be taken into account in the use of experimental data of both vertical sorting and dune irregularity for future models.

Notation

C	Chézy roughness coefficient ($m^{0.5}\ s^{-1}$).
D	sediment diameter (m).
D^*	dimensionless sediment diameter.
g	gravitational acceleration (9.81 $m\ s^{-2}$).
h	water depth.
k_s	Nikuradse equivalent sand roughness (m).
R_c	hydraulic radius corrected for sidewall roughness (m).
S	slope.
u	depth-averaged flow velocity ($m\ s^{-1}$).
θ	dimensionless shear stress (Shields parameter).
ρ	density of water ($kg\ m^{-3}$).
ρ_s	density of sediment ($kg\ m^{-3}$).
τ	total shear stress (including form and grain drag) ($N\ m^{-2}$).
ν	kinematic viscosity ($m^2\ s^{-1}$).

Subscripts and superscripts

$'$	referring to skin friction, grain roughness.
50	50% percentile.
90	90% percentile.

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