Emergence of abrupt gravel to sand transitions along rivers through sorting processes

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ABSTRACT

Gradual downstream fining along gravel-bed rivers is often followed by a relatively abrupt change to a sand bed. This has usually been explained by the breakdown of pebbles of certain lithologies to sand, but it is not restricted to particular rock types and can occur over distances too short for significant abrasion. An alternative explanation is that as shear stress declines downstream, size sorting is enhanced through nonlinearities and thresholds in bedload transport and deposition mechanisms. This hypothesis is tested by numerical modeling of an idealized channel with a mixed gravel and sand bed. Abrupt and persistent gravel fronts with associated breaks of slope develop from a range of smooth initial states when a new initial-motion equation is used, but not with a conventional equation. The results suggest an emergent phenomenon, but one that is sensitive to process specification rather than initial or boundary conditions.

Keywords: geomorphology, modeling, gravel front, bedload transport.

INTRODUCTION

River beds become finer grained downstream through a combination of grain abrasion and size-selective transport and deposition. Downstream fining is usually strongest from a grain size of ~10 mm to ~1 mm, giving a relatively abrupt change from gravel- to sand-bed conditions (Yatsu, 1957; Howard, 1980; Shaw and Kellerhals, 1982; Sambrook Smith and Ferguson, 1995; Dade and Friend, 1998). This gravel to sand transition defines a fundamental boundary between river types (gravel or sand bedded) that are seen as distinct by geomorphologists, sedimentologists, ecologists, and river engineers. Abrupt transitions are apparent in some ancient sandstones as sharp gravel fronts, and their frequent occurrence in modern rivers provides a constraint on basin-filling models (Paola, 2000, p. 143). Geomorphologists seeking to explain this discontinuity in bed caliber have generally invoked the disintegration of pebbles of certain lithologies into sand-sized crystals during weathering or transport (Yatsu, 1957; Wolcott, 1988; Kodama, 1994). However, abrupt transitions are not restricted to particular lithologies, and can occur over distances too short for significant abrasion: 30 km along major rivers (e.g., McLean et al., 1999), 0.1 km in small rivers (Sambrook Smith and Ferguson, 1995), and 1 m in laboratory experiments (Paola et al., 1992). In such cases an alternative explanation is that bedload transport and deposition act in a more highly size selective way than usual. In this paper I test speculations by Ferguson et al. (1998) and Wilcock (1998) that nonlinearities and feedbacks in the processes of bedload transport might provide a mechanism for the emergence of gravel fronts along rivers.

Gravel to sand transitions are most common where relatively steep mountain rivers emerge onto valleys or plains with much lower slope, and the reduction in fluid shear stress (τ) forces the river to deposit most of its bedload. Ferguson et al. (1998) noted that size sorting is enhanced in such situations because differences in the critical shear stresses to move different grain sizes become relatively greater as τ declines downstream. This creates a series of positive feedbacks. First, the preferential mobility of smaller sizes increases, so bedload becomes much finer than the bed. Then, where this fine bedload is deposited farther downstream, the bed becomes finer still, so that subsequent bedload is yet finer because of the reduced availability of coarse fractions. Finally, once the deposited load contains >30% sand, it forms sand patches and eventually a continuous sand matrix with embedded or overpassing gravel, rather than a gravel framework with interstitial sand; this further increases the effective availability of sand.

The last of these mechanisms was also invoked by Wilcock (1998) to explain the strong influence of bed sand fraction (F_s) on the critical stresses τ_{cg} and τ_{cs} to move gravel (treated collectively) and sand. Wilcock and Kenworthy (2002) quantified these trends after doing additional flume experiments in the critical range of F_s, and they and Wilcock (1998) speculated that preferential mobility of sand could trigger abrupt gravel to sand transitions.

My test consists of using a one-dimensional numerical model to simulate the space-time evolution of a two-fraction stream bed, using either the Wilcock and Kenworthy (2002) threshold equation or a more conventional one. The model is run with initial conditions of little or no downstream fining, or substantial but gradual fining, to test in what conditions abrupt gravel fronts develop.

NUMERICAL MODEL

The model simulates bed aggradation or degradation, and fining or coarsening, using finite-difference versions of the standard overall (Exner) and fractional (Hirano) sediment continuity equations. The latter assumes that any deposited bedload is mixed within an active bed layer of constant thickness and porosity; the grain-size distribution in the bed therefore changes if the deposited bedload is finer or coarser than the bed, but stays the same during degradation. In my model the bed consists of gravel and sand of diameters D_g and D_s; the initial sand fraction varies linearly between F_{s0} and F_{s1} over L km; and the initial slope declines linearly from S_0 to S_1. The values of F_{s1} and S_1 are extended for a further 0.1 km to allow progradation. Water is fed at a specified unit discharge q and local shear stress is calculated from q and S using the Manning equation. Gravel and sand are fed at capacity rates so that the bed at 0 km does not alter.

The reported simulations used $L = 1$ km, $D_g = 23$ mm, $D_s = 0.5$ mm, $S_0 = 0.005$, $S_1 = 0$, $q = 0.7$ m^{2}s^{-1}, and $F_{s0} = 0.1$. These values are based on Allt Dubhaig, a small river in Scotland that has a strongly concave long profile above a local base level, an abrupt gravel to sand transition with F_s increasing from ~0.2 to ~0.9 within 0.1 km, and an associated break of slope (Sambrook Smith and Ferguson, 1995; Ferguson et al., 1996). Sensitivity to the chosen values is discussed later.

Because channel slope and transport capacity decline to zero, the entire sediment flux entering the reach must be deposited along the profile, which straightens and progrades toward an asymptotic flume-like equilibrium or grade with constant slope, no downstream fining, and the same sand and gravel fluxes everywhere. Different simulations approach grade at different rates, so the stage of development is indicated better by the mean aggradation depth a over the 1.1-km-long domain than by elapsed time. Complete straightening would require $a = 49$ cm.

BEDLOAD TRANSPORT EQUATIONS

The critical shear stress to mobilize a river bed scales with the geometric-mean grain size D_b, but the critical stress to move an individual size fraction centered on diameter D_i depends more on relative

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than absolute size because of hiding and exposure effects. It is commonly represented by a power law equivalent to

$$\tau_{ci} \propto D_i^{\beta} D_b^{1-\beta}. \tag{1}$$

Field measurements suggest that $\beta \approx 0.1$ in rivers with predominantly gravel beds, making transport only slightly size selective (e.g., Ashworth and Ferguson, 1989; Parker, 1990), but there is uncertainty over the appropriate value for bimodal gravel and sand. Wilcock (1998) estimated τ_{cg} and τ_{cs} for strongly bimodal beds, mainly in flume experiments but with some field data, and found they declined with F_s in a curvilinear way. Wilcock and Kenworthy (2002) fit it using a negative exponential function equivalent to

$$\tau_{ci} = \tau_{ci1} + (\tau_{ci0} - \tau_{ci1})\exp(-14F_s), \tag{2}$$

where subscripts 0 and 1 denote values for $F_s = 0$ and 1 (pure gravel and pure sand). Two of the end-member thresholds take the usual form ($\tau_{cg0} \propto D_g$ and $\tau_{cs1} \propto D_s$), but τ_{cg1} is lower than τ_{cg0} because exposed gravel rolls freely over a sand bed, and $\tau_{cs0} = \tau_{cg0}$ because trace quantities of sand in a gravel framework cannot move until the gravel does.

The functions 1 and 2 are compared in Figure 1A, in which all stresses are normalized against the value for pure gravel. Both τ_{cg} and τ_{cs} decline with increasing F_s in each scheme, but the Wilcock and Kenworthy (2002) function is effectively flat for $F_s \geq 0.4$, whereas the power law falls throughout the range. In addition, the ratio τ_{cs}/τ_{cg} decreases from 1 to <0.2 in the Wilcock and Kenworthy scheme, but is constant at ~0.7 in the power law. These differences give contrasting patterns of preferential mobility of sand at the low excess stresses characteristic of gravel-bed rivers: the bedload sand fraction P_s exceeds the bed fraction F_s by much more in the Wilcock and Kenworthy (2002) scheme, and most so at F_s ~0.3 instead of ~0.1 (Fig. 1B). For this plot and in model simulations the transport rates of sand and gravel have been computed using the equation Wilcock and Kenworthy fitted to their data. This is a two-part nonlinear function of τ/τ_{ci}, not dissimilar in shape to Parker's (1990) function, and gives low but nonzero flux at $\tau < \tau_{ci}$, so that there is no abrupt computational cutoff of transport over low slopes. As in other fractional transport equations, for a given flow the flux of each size is directly proportional to its volumetric availability in the bed. At the start of my simulations, with $F_s = 0.1$, the downstream decline in τ causes P_s to increase from 0.26 at 0 km to 0.88 at 1 km when using Wilcock and Kenworthy's threshold, or from 0.29 to 0.66 with the power law.

EMERGENCE OF ABRUPT GRAVEL TO SAND TRANSITIONS

Simulations using the Wilcock and Kenworthy (2002) threshold and starting with no or slight downstream fining (F_{s1} = 0.1, 0.2, or 0.3) gave very similar results, illustrated in Figure 2 for F_{s1} = 0.1. The gravel-rich sediment feed is initially deposited in the upstream part of the reach, but the aggradational front advances and sandy deposition occurs at the break of slope beyond it. By a = 3 cm an incipient gravel to sand transition is visible, with a doubling of F_s and halving of bed slope between 0.8 and 0.85 km. At this stage the bed at 1.1 km is unaltered, but thereafter the entire distal bed is aggrading and sandy. The proximal bed meanwhile coarsens slowly, so that the transition increases in amplitude and abruptness. It and the break of slope migrate slowly downstream; by a = 19 cm they are close to 0.9 km and F_s exceeds 0.9 throughout the distal 0.2 km.

These results support the hypothesis that the preferential mobility of sand can cause development of strong downstream fining where little or none exists initially, so long as the bed slope decreases downstream, and that the fining becomes concentrated into a zone of abrupt increase in F_s. Moreover, the gravel to sand transition is long lasting: Figure 2

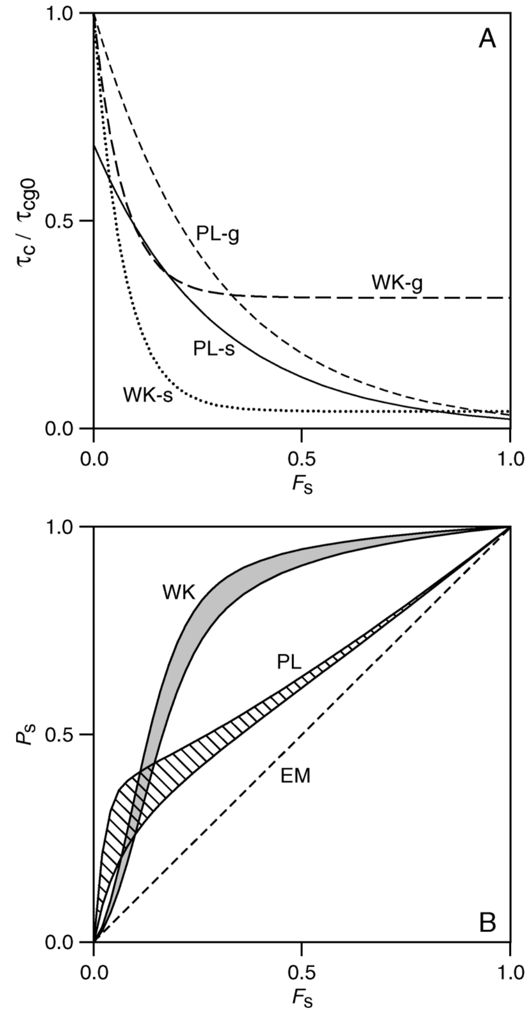

Figure 1. A: Alternative threshold functions used in two-fraction model. PL denotes power law (equation 1 in text); WK denotes Wilcock and Kenworthy (2002) (equation 2 in text, with D_g/D_s = 45). Curves show change in critical shear stresses τ_{cg} for gravel (labeled g) and τ_{cs} for sand (s) as bed sand fraction F_s increases. Stresses are scaled by critical stress τ_{cg0} for gravel in absence of sand. B: Preferential mobility of sand with PL and WK threshold functions. Shaded bands show sand fraction P_s in bedload for different sand fractions F_s in bed, at relative shear stresses τ/τ_{cg0} between 1 and 1.5. EM denotes equal mobility, achieved at very high stresses.

shows that it is still present and just as abrupt at a = 42 cm, by which time the long profile above the break of slope is almost straight. The gravel front finally advances past the end of the model domain at a = 45 cm.

Figure 3 shows the simulated evolution of a channel identical in all respects except that it starts with strong but progressive downstream fining (F_{s1} = 0.9). A sharp gravel front emerges even more rapidly and ~0.2 km farther upstream. The trigger mechanism is no longer fining at the distal end of an aggradational front, but proximal degradation and coarsening due to the rapid downstream increase in mobility of gravel and, even more so, sand at higher F_s. There is an incipient break of slope between the degrading proximal reach and slightly aggrading distal reach. The proximal degradation ceases at $a \approx$ 5 cm; thereafter the channel evolves in the same way as in Figure 2 with proximal gravel aggradation and slow coarsening, and sandy distal aggradation. The gravel front advances relatively rapidly to ~0.8 km but

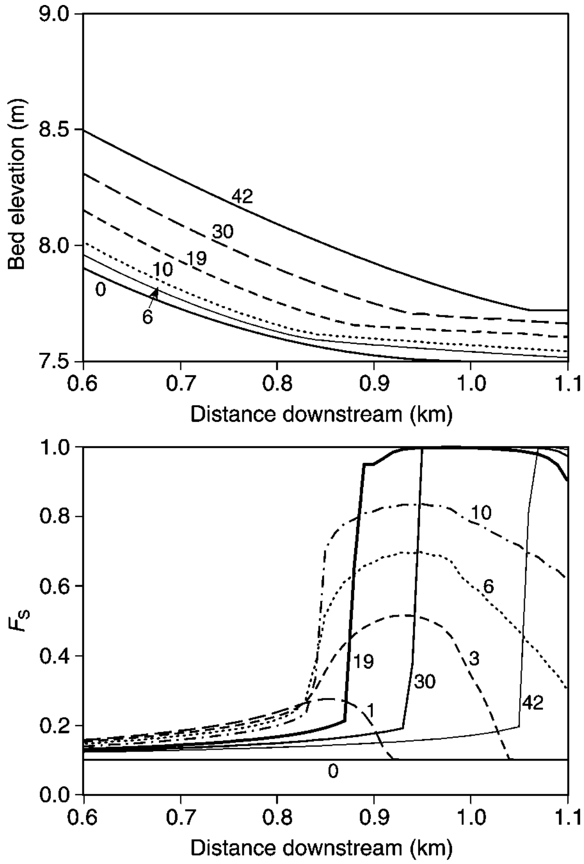

Figure 2. Evolution of long profile (elevation *z*, upper plot) and bed fining (indicated by sand fraction F_s; lower plot) in simulation using Wilcock and Kenworthy (2002) threshold function and starting with no downstream fining; see text for other details. Numbers by curves are mean aggradation (in cm). Only lower part of channel is shown.

then more slowly, to 0.9 km at $a = 16$ cm and 1.0 km at $a = 25$ cm, before exiting the domain at $a \approx 35$ cm.

In both simulations the amplitude and abruptness of the changes in slope and sand content are similar to those illustrated for the prototype by Sambrook Smith and Ferguson (1995) and Ferguson et al. (1996).

EFFECT OF CHOICE OF HIDING FUNCTION

Figure 4 shows the outcome of a run identical to that in Figure 2 except that the Wilcock and Kenworthy threshold function is replaced by the conventional power law, equation 1. As in Figure 2, aggradation extends progressively farther downstream; there is fining toward the aggradational front so that the maximum value of F_s increases and shifts downstream, exceeding the threshold for a sand-matrix bed before $a = 4$ cm. However, there are three major differences: an abrupt local increase in F_s never develops, nor does an abrupt break of slope, and beyond a certain stage ($a = 15$ cm in Fig. 4) the proximal coarsening extends to the end of the channel so that the sand peak collapses. Runs with $F_{s1} = 0.2$ or 0.3 are very similar. With $F_{s1} = 0.9$ the collapse phase is reached almost immediately, and the sand peak falls to half its initial value by $a = 15$ cm, in sharp contrast to the results in Figure 3 using the Wilcock and Kenworthy threshold. In all four cases the entire channel has reverted to a gravel bed before it has aggraded halfway to a straight long profile. A higher value of the hiding exponent β gives slower aggradation, but the same qualitative results. Thus the conventional power-law threshold equation does not generate abrupt or lasting gravel to sand transitions. Because the same

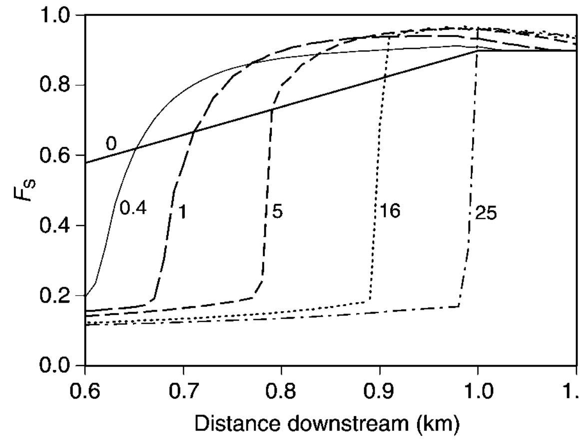

Figure 3. Evolution of fining in simulation like Figure 2 except for strong but progressive initial downstream fining. F_s is sand fraction in bed.

transport law and boundary conditions were used for both sets of simulations, the different outcomes are unambiguously the consequence of the choice of threshold function.

PHYSICAL EXPLANATION

Emergent phenomena can usefully be regarded as the product of coupled, context-dependent interactions in a dynamic system (Holland, 1998, p. 121). The interaction in the gravel to sand transition is between the preferential mobility of sand and the local aggradation rate as they vary in space and time. This can be seen best by writing the continuity equation for sand in the nonstandard form

$$\frac{\partial F_s}{\partial t} = \frac{(P_s - F_s)}{L}\left(\frac{\partial z}{\partial t}\right) - \frac{q}{(1-\lambda)L}\left(\frac{\partial P_s}{\partial x}\right), \tag{3}$$

where *t* is time, *z* is bed elevation at distance *x*, *q* is total bedload flux, *L* is active-layer depth, and λ is porosity. The first term on the right side quantifies deposition of bedload sandier than the bed and the second quantifies winnowing of sand from the bed. It is apparent that bed fining requires aggradation and size-selective transport ($P_s > F_s$), and is favored by the rapid aggradation and strongly selective transport in distal gravel-bed channels with low and falling τ as base level is approached. In contrast, bed coarsening by winnowing is favored by proximal conditions: high τ, hence high gravel flux, and opportunity for P_s to increase downstream.

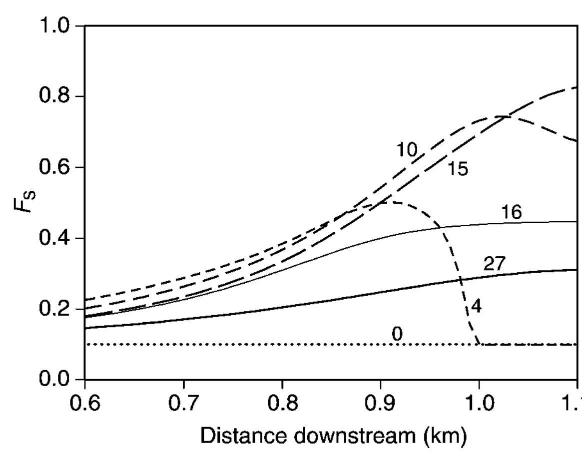

Figure 4. Evolution of fining in simulation identical to Figure 2 except for use of power-law threshold function. F_s is sand fraction in bed.

In the present simulations both terms have the same order of magnitude in most places, so that their difference is small and the bed changes only slowly. The balance is negative proximally so that the bed slowly coarsens, but as P_s increases downstream the first term increases (more so with the Wilcock and Kenworthy threshold scheme than the power law; see Fig. 1B) while the second decreases, becoming negligibly small once $P_s \rightarrow 1$. The bed fines rapidly here, creating a sharp gravel to sand transition. Once $F_s \rightarrow 1$ all terms in equation 3 are very small and the bed is stable (apart from minor oscillations in numerical solutions). However, the beginning of the gravel to sand transition is subject to winnowing because of the high downstream gradient of P_s, and the gravel front therefore migrates downstream (in simulations using Wilcock and Kenworthy's [2002] threshold equation) or collapses completely (in power-law simulations).

DISCUSSION

These findings confirm the speculation of Ferguson et al. (1998) that nonlinearities in bedload transport mechanisms can cause an abrupt gravel to sand transition to develop, without any contribution by abrasion, as downstream changes in bed composition are amplified by a strong decline in shear stress. They also support Wilcock's (1998) more specific speculation that the abruptness of the transition reflects how small increases in bed sand content lead to big increases in the mobility of both sand and, to a lesser extent, gravel. The simulated transitions resemble those in the prototype stream from which initial and boundary conditions were taken.

To check whether the results are restricted to these particular conditions, I repeated the simulation shown in Figure 2 with higher and lower discharge (1.0 and 0.5 m^2s^{-1}), coarser and finer gravel (32 and 16 mm), lower proximal slope (0.0025), and thus lower concavity, and fixed rather than capacity sediment feed. The feed specification made no difference to the evolution of the middle and lower parts of the system. The other changes altered the rate of aggradation but gave identical qualitative results: the Wilcock and Kenworthy (2002) threshold generated abrupt and lasting gravel fronts in all cases, whereas the power law never did. The only quantitative difference was that after a given amount of aggradation the gravel front was somewhat farther upstream for higher q, higher D_g, or lower S_0; this suggests that the discontinuity develops where τ declines to a critical value relative to D_g, and that its location will be sensitive to changes in the basin environment.

Abrupt gravel to sand transitions along alluvial rivers may therefore be another example of the emergence of characteristic landform phenomena through spatial self-organization, where nonlinear process laws operate in context-dependent dynamic systems (e.g., Hallet, 1990; Murray and Paola, 1994; Werner, 1999). Emergence is often regarded as a consequence of sensitive dependence on initial conditions, but my results show that abrupt gravel fronts develop on concave river profiles with a range of combinations of discharge, grain size, slope, and sediment feed. Instead, their emergence (or not) seems sensitive to process specification: whether transport thresholds are represented by the traditional power law, or by the new scheme of Wilcock and Kenworthy (2002). This is in contrast to Murray and Paola's (1994) suggestion that river braiding is not sensitive to the detailed specification of flow and sediment transport laws. It implies that, in this case at least, we cannot completely abandon reductionist concern with the details of the processes acting. Conversely, the existence of abrupt gravel fronts provides indirect support for Wilcock and Kenworthy's (2002) threshold specification because it predicts their development, whereas the power law does not.

The emergence of slope and grain-size discontinuities in a two-fraction fluvial system demonstrates the potential for nonlinearities to amplify small differences in transport conditions. Whether the result generalizes to multiple size fractions remains to be seen. Cui and Parker (1998) simulated abrupt gravel fronts in such a system, but only by using a different bedload/bed exchange scheme for sand than for the gravel fractions. Other factors not taken into account in the present model are bed patchiness (Paola and Seal, 1995), basin subsidence, which has the potential to fix the position of what would otherwise be an advancing gravel front (Cui and Parker, 1998; Paola, 2000), and settling of sand from suspension (Ferguson et al., 1998; Dade and Friend, 1998). The results nevertheless support the hypothesis that abrupt gravel to sand transitions along rivers can emerge from nonlinear sediment dynamics without appealing to discontinuities in rock breakdown or external sediment inputs.

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Notes