Persistence of armor layers in gravel-bed streams

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[1] Streambed surfaces are typically coarsened, or armored, at low flows, but there is little evidence of their condition during floods, when significant hydraulic and ecologic disturbance occurs. Some flume experiments have been used to conclude that armor layers wash out during floods, although other experiments have produced a persistent armor layer. In the absence of clear field or flume evidence, we use a surface-based transport model in an inverse prediction of surface grain size as a function of transport rates observed in the field. The predicted surface grain size matches that observed at low flow and indicates that low-flow armor layers persist at large flows. In the field, transport grain size increases with transport rate, reducing or eliminating adjustments in bed surface grain size as flow and transport increase. A persistent armor layer considerably simplifies the prediction of sediment transport, hydraulic roughness, and habitat disturbance during floods.

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1. Introduction

[2] The bed surface of gravel-bed rivers is often coarsened, or armored, relative to the subsurface. Streambed armoring strongly influences channel hydraulics, mediates the exchange of water between flow and bed, defines the habitat for aquatic insects, salmonid spawning, and juvenile fish, and determines the sediment available for transport. The grain size of the bed surface can be observed at low flows when little or no transport is occurring, but is generally inaccessible during high flows producing transport. Very little is known of how the composition of the bed surface changes during flows producing sediment transport and bed disturbance. The basic question "does the stream bed change over a flood?" does not have a clear, corroborated answer. This paper examines available experimental evidence and applies a sediment transport model to transport observations in the field to evaluate the persistence of armor layers during floods.

[3] It is commonly held that the armor layer evident at low flow 'washes out', becoming finer grained during floods and reforming on waning flows [*Parker and Klingeman*, 1982]. Experiments in which sediment of a constant size is fed into a laboratory flume have demonstrated such an inverse relation between bed grain size and transport rate and, hence, flow strength [*Dietrich et al.*, 1989; *Kuhnle*, 1989; *Lisle et al.*, 1993]. Field observations of stream bed fining in response to large sediment inputs have also been used to argue that the degree of armoring varies inversely with the rate of sediment transport [*Lisle and Madej*, 1992].

[4] There is competing evidence suggesting bed surface grain size changes little, or not at all, over a flood. When transported sediment is recirculated in flume experiments, a coarse surface layer develops but the bed surface grain size does not change with increases in flow and transport rate [*Wilcock et al.*, 2001]. It is also typically observed that sediment transport in the field coarsens with transport rate [e.g., *Jackson and Beschta*, 1982], which can act to suppress bed surface fining as flow increases [*Wilcock*, 2001].

2. Laboratory Evidence

[5] In the absence of field observations of the bed surface at high flows, much of the evidence cited for armor persistence comes from laboratory observations. There are two typical modes of flume operation. In one, sediment is fed into the flume, typically at a constant rate. In the other, sediment entrained from the flume bed is recirculated and used as the feed.

[6] When sediment is fed into a flume, the system responds by adjusting the bed surface composition, flow depth and slope to carry the imposed load. If the sediment contains a range of grain sizes, larger, less mobile sizes accumulate on the bed surface until all sizes are transported at the rate at which they are supplied [*Parker and Klingeman*, 1982]. Because mobility differences among grain sizes tend to decrease with increasing transport rate, bed coarsening in feed flumes diminishes with increasing transport rate (Figure 1a) [*Dietrich et al.*, 1989; *Kuhnle*, 1989; *Lisle et al.*, 1993; *Parker et al.*, 1982]. Data are presented by *Wilcock* [2001] and are available as an auxiliary on-line supplement[1] to this paper. The variation in surface gain size with transport rate observed in sediment feed flumes is primary evidence that has been used to argue that low-flow armor layers wash out during floods. Sediment feed experiments typically use a range of sediment feed rates, but a constant feed composition. This can be a poor representation of the field case, for which transport grain size typically increases with transport rate [*Jackson and Beschta*, 1982].

[7] In a recirculating flume, sediment entrained in the flume is immediately returned at the upstream end. The rate and composition of the "feed" depends on the flow and the relative mobility of the various sizes in the bed. Transport rate and grain size, as well as the grain size and slope of the bed surface, are free to adjust. Experiments with widely sorted sediment show that the transport grain size tends to increase with increasing flow, while the composition of the

[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2004GL021772.

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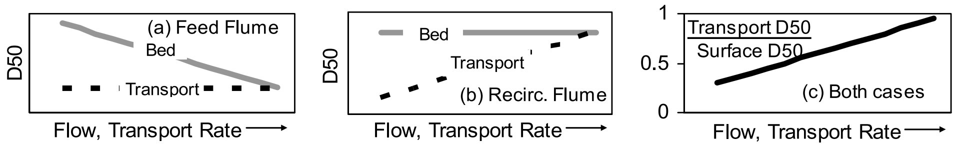

Figure 1. Schematic bed surface and transport grain size adjustments. (a) Feed flume: change only in bed surface. (b) Recirculating flume: change primarily in transport. (c) Both cases: transport coarsens relative to the bed surface.

bed surface remains relatively constant (Figure 1b; data presented by *Wilcock et al.* [2001] and in the auxiliary online supplement to this paper). Although the degree of bed coarsening is not observed to vary with flow strength, bed coarsening is observed in recirculating flumes. Because differences in grain mobility between the feed and the flume are essentially zero, this armoring is caused by a kinetic sieving process in which small grains move downward to fill gaps vacated by the entrainment of large grains [*Parker and Klingeman*, 1982].

[8] In both feed and recirculating flumes, transport coarsens relative to the bed surface as flow and transport rate increase, although the underlying variation in the transport and bed grain sizes are essentially inverse (Figure 1). For the feed case, variations in grain size are isolated to the bed surface because the grain size of the sediment feed is held constant. The bed coarsens as transport rates drop. In the recirculating case, changes in surface grain size are small or zero, whereas the transport becomes coarser as transport rates increase. Because the difference between the two systems is in the upstream boundary condition, rather than any fundamental transport or sorting processes, the same general trend of bed coarsening relative to the transport is observed in both cases, even though the difference in boundary conditions produces different equilibrium states.

[9] Flume experiments do not resolve the question of armor persistence in the field. If a stream behaved as a feed system, changes in relative grain mobility would be accommodated by adjustments in the bed surface: a coarsened low-flow surface would vanish at high flows. If a stream behaved as a sediment recirculating system, changes in relative grain mobility would be accommodated primarily by changes in the transport grain size: a coarse low-flow surface would persist at high flows. The two flume configurations represent very different upstream boundary conditions. Neither exactly simulates natural conditions, nor can they be directly compared [*Parker and Wilcock*, 1993].

3. Equilibrium Armor Model

[10] Given inconclusive evidence from flume experiments and an absence of clear field documentation, the immediate opportunity to examine surface sorting variation in alluvial channels is to use a sediment transport model to explore the possible range in grain size of armor layers. To be useful, such a model must be defined relative to the bed surface. A recent model [*Wilcock and Crowe*, 2003] is the first to be developed from extensive coupled observations of flow, transport, and bed surface grain size [*Wilcock et al.*, 2001]. The model predicts the transport rate of individual size fractions as a function of bed shear stress and bed surface grain-size distribution.

[11] Here, the Wilcock and Crowe model is used in an inverse calculation, wherein the bed surface grain size and boundary shear stress are predicted as a function of the rate and size distribution of the transport. That is, the inverse calculation predicts the bed shear stress and bed surface composition needed to produce the specified sediment transport. Because stress and the grain size of the bed and transport are interdependent, the solution to the inverse calculation is implicit. *Parker* [1990] presents a solution from an earlier surface-based transport model and *Parker and Wilcock* [1993] present a solution procedure to demonstrate that a general solution exists.

[12] A credible evaluation of equilibrium armor composition requires highly accurate transport data. The predictions are particularly sensitive to error in coarser sizes, which tend to have small transport rates and are the most difficult to sample accurately. We use two field data sets: Oak Creek, OR [*Milhous*, 1973] and Goodwin Creek, MS [*Kuhnle*, 1992]. These represent perhaps the best measurements available of sediment transport in gravel-bed rivers because, in each case, the entire transport load was collected or sampled within a confined trough, providing an unambiguous description of the transport composition at different flows. The two sites differ considerably in channel size (channel width 3.7 m and 20.7 m for Oak Creek and Goodwin Creek, respectively), bed slope (0.014 and 0.0033), and bed grain size (median 20 mm and 8.3 mm). In both cases, transport samples within a narrow range of transport rate or boundary shear stress have been combined as weighted averages in order to reduce the variability inherent in natural transport [*Kuhnle*, 1992; *Wilcock*, 1998].

[13] For Oak Creek, the grain size of the transport consistently increases with transport rate (Figure 2a) from a median size of 2.2 mm at transport rate q_b = 0.00025 kg m^{-1} s^{-1} to 22.2 mm at q_b = 0.11 kg m^{-1} s^{-1}. When the observed transport rates and grain sizes are used in the inverse prediction, the calculated surface median size is between 40 mm and 55 mm and is nearly invariant over all transport rates (Figure 2b). The calculated surface grain size is also essentially identical to the bed surface grain size measured at low flow [*Milhous*, 1973]. This is remarkable because Oak Creek data were not used in developing the transport model. The absence of variation and the similarity of predicted and observed bed surface grain sizes are also remarkable given the temporal and spatial complexity typical of any natural stream. We do not expect that the bed surface grain size remains constant at all locations on a spatially variable bed, but we can suggest that the observed transport rates do not force adjustment of the mean surface grain size as flow increases.

[14] If transport of constant grain size is used in inverse transport predictions for Oak Creek (simulating, in effect, a sediment feed flume), the calculated bed surface size is very

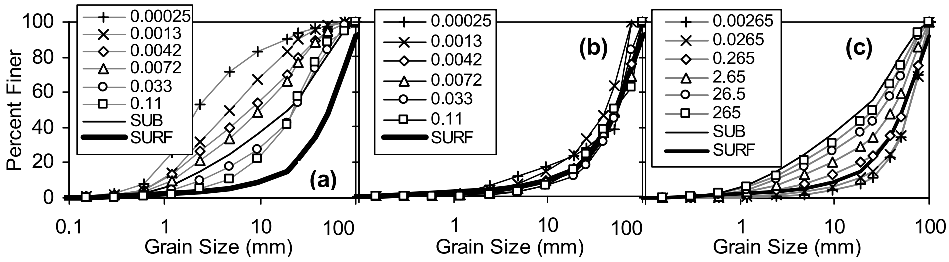

Figure 2. Transport and bed surface grain size, Oak Creek, OR. (a) Transport grain size at six different transport rates indicated in kg m^{-1} s^{-1} and grain size of the bed surface and subsurface. (b) Surface grain size predicted for the six cases given in Figure 2a. (c) Surface grain size calculated using a constant transport grain size equal to the subsurface and a wide range of transport rates.

coarse at small transport rates (coarser than the observed bed surface) and progressively fines as transport rate increases (Figure 2c). Similar results were found in an earlier inverse prediction of the Oak Creek surface [*Parker*, 1990]. These conditions (constant transport grain size and bed surface fining with increasing transport rate) correspond poorly with the variation in transport grain size observed in the field.

[15] Prediction of the bed surface grain size at transport rates larger than observed requires speculation regarding the size distribution of that transport. If one argues that the transport grain size approaches, but does not exceed that of the subsurface (because the subsurface is the source of the transport), comparison of Figures 2a and 2c suggests that the predicted bed surface will become finer as transport rates exceed approximately 1.0 kg m^{-1} s^{-1}, which is roughly one order of magnitude larger than maximum observed. If, on the other hand, one argues that the transport grain size can become coarser than the subsurface (due, for example, to an increasing proportion of the finer fractions traveling in suspension; see *Lisle* [1995] for a range of observations), then any fining of the bed surface would be damped or eliminated.

[16] For Goodwin Creek, the transport grain size again consistently increases with transport rate (Figure 3a) from a median of 0.5 mm at q_b = 0.0021 kg m^{-1} s^{-1} to 7.2 mm at q_b = 0.71 kg m^{-1} s^{-1}. The surface grain size calculated from the observed transport is nearly invariant over all transport rates (Figure 3b) with median size of approximately 20 mm. Again, a persistent armor size is predicted in association with increasing size in the transport.

[17] The predicted surface grain size is coarser than observed (median 20 mm vs. 12 mm, Figure 3b). One explanation is that the reported surface size is based on a sample of the bed surface to the depth of the largest surface particle [*Kuhnle*, 1992]. Such samples may be expected to include finer subsurface material contained in interstices between the largest surface grains. The predicted and observed surface size distributions truncated at 8 mm are essentially identical, indicating that the difference between the two can be attributed to a larger proportion of fine material in the field sample. A second explanation for the difference between predicted and observed surface size distributions at Goodwin Creek concerns the appearance of dunes during large transport rates [*Kuhnle*, 1992]. Trough scour and grain mixing within these dunes would tend to eliminate any surface sorting. As flow recedes and the dunes wash out, a surface layer will become reestablished, although the duration of these lower transport rates may not be sufficient to fully develop a coarse armor.

[18] If transport with a constant grain size is used for the inverse prediction of surface size on Goodwin Creek, the predicted surface size at small transport rates is much coarser (median 32 mm) than observed and, as with Oak Creek, becomes finer with increasing transport rate (Figure 3c).

4. Discussion

[19] The general observation that the grain size of sediment transport in natural streams increases with transport rate, combined with the prediction of a persistent surface grain size over all transport rates observed for two streams with exceptionally well measured transport, suggest that low-flow armor layers persist over typical floods. This is consistent with the one available observation of surface grain size during active transport. Surface grain size on

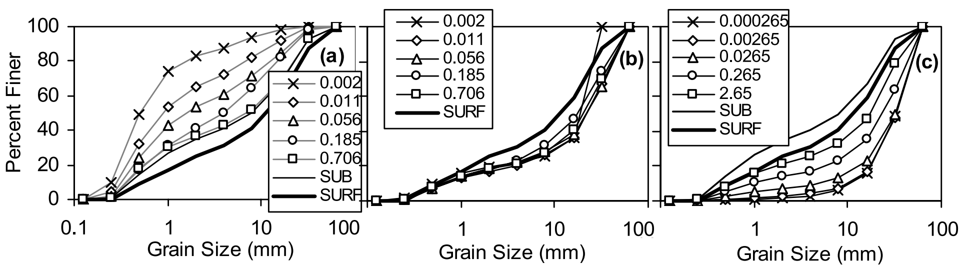

Figure 3. Transport and bed surface grain size, Goodwin Creek, MS. (a) Transport grain size at five different transport rates indicated in kg m^{-1} s^{-1} and grain size of the bed surface and subsurface. (b) Surface grain size predicted for the five cases given in Figure 3a. (c) Surface grain size calculated using a constant transport grain size equal to the subsurface and a wide range of transport rates.

Sagehen Creek CA was nearly identical during a snow-melt flood and one month later when the discharge was four times smaller and transport had largely ceased [*Andrews and Erman*, 1986]. Although the peak transport rates were relatively modest, observations in later years [*Andrews*, 1994] show that the transport grain size increases over the range of flow corresponding to the two bed surface samples (e.g. transport median size increased 65% [*Wilcock*, 2001]), as found on Oak Creek and Goodwin Creek.

[20] Supporting field evidence for a persistent armor layer is found from studies using marked tracer grains. In one stream, more than half of the bed area was mapped as either largely immobile or partially mobile (i.e. some grains on the bed surface remain in place over the flood) for a flood with a two-year recurrence interval [*Haschenburger and Wilcock*, 2003]. In another stream, only 30% of the tracer grains larger than the median size of the bed surface moved during a flood with recurrence interval slightly greater than two years [*Church and Hassan*, 2002]. Although tracers do not provide a complete description of the bed surface, the large proportion of inactive grains supports the idea that the bed surface is persistent during typical floods.

[21] A persistent armor layer does not indicate that the surface grains are immobile. Tracer observations on Sagehen Creek and time-series observations in a recirculating flume [*Wilcock and McArdell*, 1997] demonstrate that a coarsened bed surface coexists with the transport of all sizes of surface grains [*Parker and Klingeman*, 1982]. The surface actively exchanges grains with the transport while maintaining a coarsened composition, although not all grains may be in motion.

[22] A persistent armor layer suggests that the bed surface grain size measured at low flows can be used to make predictions at high flows when the bed is not accessible. This is very useful for the application of transport models defined relative to the bed surface. Such models are necessary to accurately predict general transport, including transient conditions, but require the specification of surface grain size. A persistent armor layer also simplifies the prediction of hydraulic roughness, aquatic habitat, and the exchange of fluid between the bed and the water column during floods.

[23] An important exception to a persistent armor layer concerns the onset of dunes, which tend to scour and mix the sorted surface layer. Although dunes are rarely reported in gravel-bed rivers, the cases available indicate that dunes form at high transport rates. Further progress regarding bed surface composition during floods requires not only direct observation of surface layers, but a reliable means of predicting the onset, growth, and dimensions of dunes in gravel-bed rivers [*Task Committee*, 2002].

[24] In as much as transport in natural streams shows an increase in grain size with increasing transport rate, a recirculating flume would appear to provide a more representative simulation of streambed behavior over the course of a flood. Clearly sediment supply must control the system at larger time scales because streams ultimately must carry the sediment delivered to them from the watershed. In the absence of exceptional localized inputs of sediment, as from a landslide or debris flow, it appears that mutual adjustment among the flow, the bed, and the transport produce a variable transport grain size and a persistent bed surface grain size over individual floods.

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References

Andrews, E. D. (1994), Marginal bed load transport in a gravel bed stream, Sagehen Creek, California, *Water Resour. Res.*, *30*, 2241–2250.
Andrews, E. D., and D. C. Erman (1986), Persistence in the size distribution of surficial bed material during an extreme snowmelt flood, *Water Resour. Res.*, *22*, 191–197.
Church, M., and M. A. Hassan (2002), Mobility of bed material in Harris Creek, *Water Resour. Res.*, *38*(11), 1237, doi:10.1029/2001WR000753.
Dietrich, W. E., J. W. Kirchner, H. Ikeda, and F. Iseya (1989), Sediment supply and the development of the coarse surface layer in gravel-bedded rivers, *Nature*, *340*, 215–217.
Haschenburger, J. K., and P. R. Wilcock (2003), Partial transport in a natural gravel-bed channel, *Water Resour. Res.*, *39*(1), 1020, doi:10.1029/2002WR001532.
Jackson, W. L., and R. L. Beschta (1982), A model of two-phase bedload transport in an Oregon coast range stream, *Earth Surf. Processes Landforms*, *9*, 517–527.
Kuhnle, R. A. (1989), Bed-surface size changes in gravel-bed channel, *J. Hydraul. Eng.*, *115*, 731–743.
Kuhnle, R. A. (1992), Fractional transport rates of bedload on Goodwin Creek, in *Dynamics of Gravel-Bed Rivers*, edited by P. Billi et al., pp. 141–155, John Wiley, Hoboken, N. J.
Lisle, T. E. (1995), Particle size variations between bed load and bed material in natural gravel bed channels, *Water Resour. Res.*, *31*, 1107–1118.
Lisle, T. E., and M. A. Madej (1992), Spatial variation in armouring in a channel with high sediment supply, in *Dynamics of Gravel-Bed Rivers*, edited by P. Billi et al., pp. 277–293, John Wiley, Hoboken, N. J.
Lisle, T. E., F. Iseya, and H. Ikeda (1993), Response of a channel with alternative bars to a decrease in supply of mixed-size bed load: A flume experiment, *Water Resour. Res.*, *29*, 3623–3629.
Milhous, R. T. (1973), Sediment transport in a gravel-bottomed stream, Ph.D. thesis, Oreg. State Univ., Corvallis.
Parker, G. (1990), Surface-based bedload transport relation for gravel rivers, *J. Hydraul. Res.*, *28*(4), 417–436.
Parker, G., and P. C. Klingeman (1982), On why gravel bed streams are paved, *Water Resour. Res.*, *18*, 1409–1423.
Parker, G., and P. R. Wilcock (1993), Sediment feed and recirculating flumes: A fundamental difference, *J. Hydraul. Eng.*, *119*, 1192–1204.
Parker, G., S. Dhamotharan, and H. Stefan (1982), Model experiments on mobile, paved gravel bed streams, *Water Resour. Res.*, *18*, 1395–1408.
Task Committee (2002), Report of the ASCE task committee on flow and transport over dunes, *J. Hydraul. Eng.*, *128*, 726–729.
Wilcock, P. R. (1998), Two-fraction model of initial sediment motion in gravel-bed rivers, *Science*, *280*, 410–412.
Wilcock, P. R. (2001), The flow, the bed, and the transport: Interaction in flume and field, in *Gravel-Bed Rivers V*, edited by M. Mosley, pp. 183–219, N. Z. Hydrol. Soc., Wellington.
Wilcock, P. R., and J. C. Crowe (2003), A surface-based transport model for sand and gravel, *J. Hydraul. Eng.*, *29*, 120–128.
Wilcock, P. R., and B. W. McArdell (1997), Partial transport of a sand-gravel sediment, *Water Resour. Res.*, *33*, 233–245.
Wilcock, P. R., S. T. Kenworthy, and J. C. Crowe (2001), Experimental study of the transport of mixed sand and gravel, *Water Resour. Res.*, *37*, 3349–3358.

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