

## Reply

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### 1. Overview

We thank *Wilcock* [this issue] and *Millar and Rennie* [this issue] for their keen interest in our work and for the opportunity to clarify our model framework and results. While they make many valuable suggestions and addendums to our research, many of their objections are based on misinterpretation of our thesis and extension of our findings beyond their intended scope. We hope that our responses will dispel these misconceptions and decrease the potential for misapplication of our research.

### 2. Reply to Comment by Wilcock

#### 2.1. Purpose of the Analysis Framework

*Wilcock* [this issue] (hereinafter referred to as *Wilcock*) suggests that our approaches for examining the effects of hydraulic roughness and sediment supply on surface grain size are incomplete because they do not include all of the salient physical controls on bed material texture (i.e., a detailed sediment budget that accounts for spatial and temporal divergence of flow, momentum, shear stress, sediment transport, and bed material supply), nor do our models specify all of the physical boundary conditions that may limit surface grain size. *Wilcock* further asserts that because the models are incomplete, they cannot be used to conclusively interpret current environmental conditions or assess cause and effect (i.e., assess past channel disturbances and consequent responses leading to current conditions). Here we clarify the purpose of our analysis framework and make a distinction between assessing current channel conditions versus predicting or reconstructing channel response.

Our intent was to investigate the relationships between surface grain size, hydraulic roughness, and bed material supply in channels that are otherwise similar. Consequently, we developed simple physical relationships between these factors and presented analysis frameworks that standardized the data in terms of boundary shear stress (total stress for the case of hydraulic roughness and bed stress for the case of sediment supply). Our approach is a static comparison of differences in grain size between channels with different magnitudes of hydraulic roughness and bed material supply, but with similar boundary shear stress [*Buffington and Montgomery*, 1999b, Figure 3; *Buffington and Montgomery*, 1999c, Figure 2]. This static framework allows assessment of current environmental conditions (i.e., magnitudes of hydraulic roughness or equilibrium transport rate) but is not a dynamic model for predicting or reconstructing paths of channel response leading to any of the states observed in our data set. As *Wilcock* correctly points

out, a perturbation of hydraulic roughness or sediment supply will cause complex responses among mutually adjusting factors of channel morphology, hydraulics, sediment transport, and supply. Consequently, one cannot predict the response of a single factor (e.g., grain size) in isolation of the others. However, it was not our intent to model channel response to perturbation, nor did we intend to suggest that the only response would be a change in surface texture.

Although we do not present dynamic process-response models, we can, however, suggest general trends of textural response to altered sediment supply or hydraulic roughness based on observations within our analysis frameworks. For example, we expect that surface textures will generally fine in response to increased inputs of wood debris (see section 3.2. for further discussion), but as discussed above, our analysis framework provides no information on exact response paths. We agree with *Wilcock* regarding the need for more complete models to predict or reconstruct channel response, but we disagree with *Wilcock's* assertion that our models cannot be used to interpret current environmental conditions. Our simple, albeit incomplete, frameworks demonstrate distinct relationships between surface grain size, roughness, and sediment supply.

#### 2.2. Other Models

*Wilcock* recommends *Parker's* [1990] state diagram as an alternative approach for examining channel response to altered sediment supply and hydraulic discharge. *Parker's* model is particularly useful because it accounts for channel response to changes in the size distribution of the sediment supply and explicitly defines and links equations for discharge, sediment transport, and channel slope. However, our framework for examining textural response to sediment supply includes most of the basic factors contained in *Parker's* model (i.e., mutual interactions amongst the rate of bed material supply, grain size, bed load transport rate, and shear stress as modified by hydraulic roughness). Furthermore, relationships between sediment supply and surface grain size observed in our framework support those hypothesized by *Parker* [1990].

In addition to *Parker's* approach, there are a variety of other conceptual models for predicting and interpreting channel response to different disturbance scenarios [*Lane*, 1955; *Nunally*, 1985]. These other approaches use simple proportional relationships between channel characteristics (slope, grain size, discharge, sediment supply, etc.) to qualitatively predict potential channel response to a change in one or more of the identified channel characteristics. Regardless of which approach one might choose to use for predicting and interpreting changes in channel characteristics, *Wilcock* correctly points out that in their current form, none of these approaches are models for predicting or reconstructing precise paths of channel response; they merely indicate trends of likely response.

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### 2.3. Grain Size and the Shields Equation

Wilcock objects to our use of the Shields equation to predict grain size because “the underlying physical mechanism producing a change in ... grain size ... is absent.” We disagree. Alluvial rivers hydraulically sort the sediment supplied to them, as is evidenced by the well-known occurrence of downstream fining (a process of size-selective deposition resulting from downstream reductions in channel slope, boundary shear stress, and competence). Particle size and downstream fining also can be influenced by other factors, such as abrasion, chemical weathering, and local variations in the rate and size of bed material supplied from hillslopes, channel banks, and tributaries. Nevertheless, boundary shear stress is a primary control on channel competence and grain size through a river network. The Shields equation is a physically based force balance that can be used to predict the competent median grain size for a given boundary shear stress. Therefore the Shields equation is a zero-order prediction that describes the primary hydraulic control on channel competence.

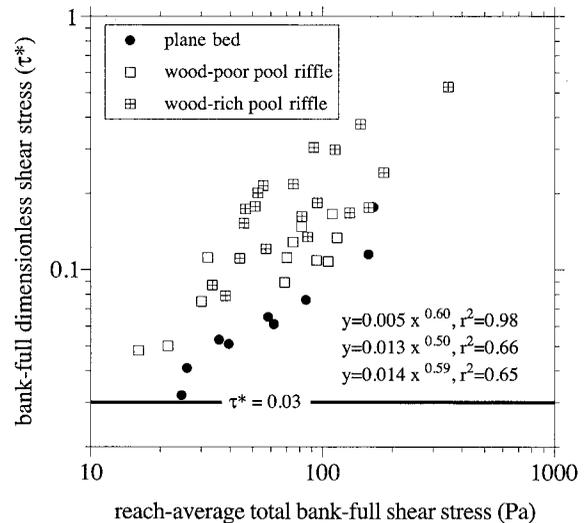
The relationship between grain size and boundary shear stress is modulated by the availability of particle sizes. Consequently, the competent grain size predicted from the Shields equation is a hypothetical value, as emphasized in our papers. The purpose of this calculation is not to predict the actual median grain size of a river bed but rather to establish a theoretical end-member condition against which to compare observed grain sizes in channels with different morphologies and different associated scales and magnitudes of hydraulic roughness. The hypothetical grain size may never be realized due to the factors discussed above and due to site-specific channel morphology and associated hydraulic roughness [Buffington and Montgomery, 1999b, pp. 3514–3515].

A mechanistic explanation of the processes of textural change and the feedback between shear stress and particle size is provided [Buffington and Montgomery, 1999b, pp. 3507, 3508; 1999c, pp. 3523, 3528]. The Shields equation does not explicitly parameterize those processes but rather predicts the end result for a bed surface in equilibrium with bank-full channel hydraulics (a morphologically significant discharge), bearing in mind the caveats regarding particle-size availability.

### 2.4. Shields Stress $\tau^*$ Versus $D_{50}$

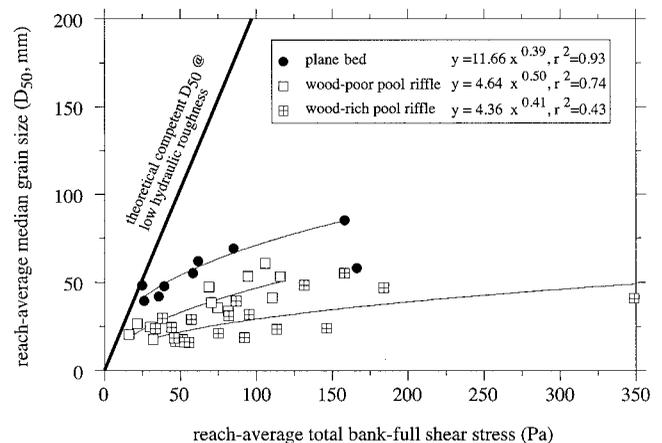
Wilcock proposes that we present our basic data in terms of the bank-full Shields stress ( $\tau^*$ , noncritical values) instead of in terms of the reach-average median grain size ( $D_{50}$ ). Doing so yields further insight to our data (Figure 1). As expected, the data demonstrate that for a given bank-full shear stress channels with more roughness have smaller median grain sizes and thus larger  $\tau^*$  values. However, for each channel type, there is a systematic increase in  $\tau^*$  with greater bank-full shear stress. The increase in  $\tau^*$  values is partially driven by a nonlinear increase in median grain size with bank-full shear stress (Figure 2). Each channel type shows a systematic departure from the slope of the reference grain-size prediction at higher values of bank-full shear stress (Figure 2), producing finer than expected grain sizes and thus an increase in  $\tau^*$  relative to the reference value (0.03) (Figure 1).

The nonlinear relationship between median grain size and boundary shear stress (Figure 2) is somewhat surprising and, to our knowledge, has not been previously documented. There are several possible explanations for the observed nonlinearity. First, for each channel type, there may be a systematic increase in hydraulic roughness with greater bank-full shear stress. At

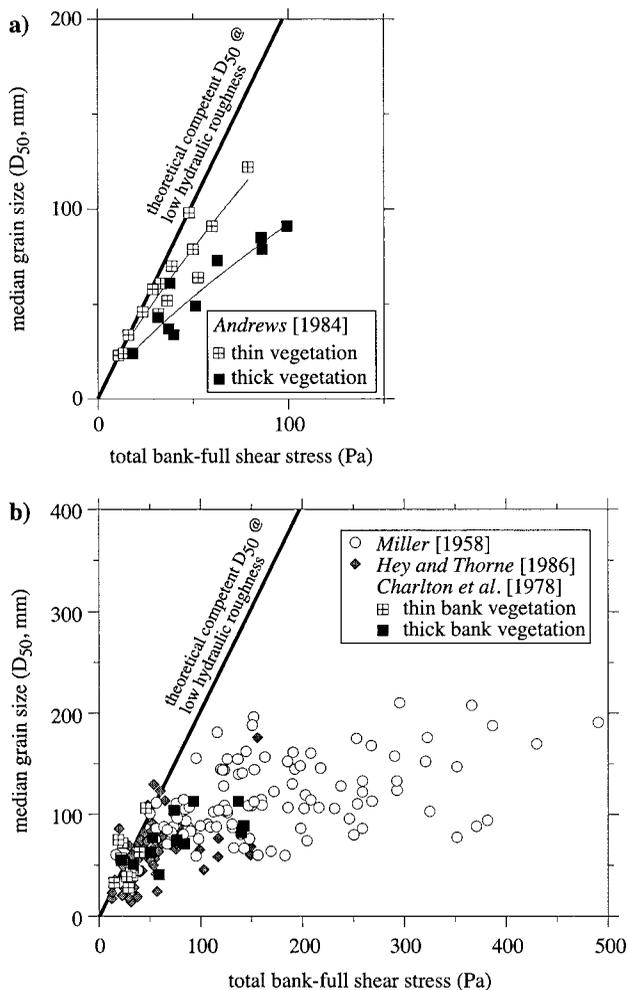


**Figure 1.** Bank-full dimensionless shear stress ( $\tau^* = \tau_0 / (\rho_s - \rho)gD_{50}$ ) versus reach-average total bank-full shear stress ( $\tau_0 = \rho ghS$ ). The line is the reference dimensionless shear stress (0.03) for low hydraulic roughness [Buffington and Montgomery, 1999b]. Respective regression equations for each channel type are shown. The plane bed regression does not include the anomalous Alder Creek [see Buffington and Montgomery, 1999b].

our study sites, increasing bank-full shear stress corresponds with steeper channels that tend to have lower flow depths and larger particle sizes, causing a general increase in relative roughness ( $D_{84}/h$ ) which may reduce bed stresses and channel competence, as well as cause an apparent increase in critical dimensionless shear stress (see review by Buffington and Montgomery [1997]). Values of  $D_{84}/h$  systematically increase from about 0.05 to 0.2 for each of our channel types as slope and boundary shear stress increase. Similarly, width-to-depth ratios systematically decrease from  $\sim 25$  to 10 for each channel type as slope and boundary shear stress increase. Declining width-to-depth ratios may reduce both bed stress and channel competence, producing smaller than expected particle sizes. Note, however, that differences in width-to-depth ratio between the



**Figure 2.** Reach-average median grain size versus total bank-full shear stress. The heavy line is the reference state prediction for low hydraulic roughness [Buffington and Montgomery, 1999b]. Plane bed regression is as per Figure 1 caption.



**Figure 3.** Median grain size versus total bank-full boundary shear stress for gravel-bed rivers in (a) Colorado [Andrews, 1984] and (b) New Mexico [Miller, 1958] and the United Kingdom [Charlton et al., 1978; Hey and Thorne, 1986]. The heavy line is defined in Figure 2.

three channel types studied are not statistically significant [Buffington and Montgomery, 1999b] and are unlikely to cause the observed systematic textural fining across the channel types.

Second, for each channel type, there may be a systematic increase in the volume of bed load material supplied to the channel or a decrease in the caliber of sediment supply at steeper slopes. Surface textures are sensitive to both the rate and size of sediment supplied to the channel [Buffington and Montgomery, 1999c].

Third, the rate of increase in total boundary shear stress may outpace the availability of coarse particle sizes at steeper slopes. The result being that the bed is finer than predicted and is mobilized at flows less than bank-full.

The nonlinear relationship between grain size and bank-full shear stress is observed to varying degrees in other data sets as well and may be a general characteristic of many coarse-grained rivers (Figure 3; also see Figure 12 of Buffington and Montgomery [1999b]). Consequently, further investigation of the nonlinear relationship between bank-full shear stress and  $D_{50}$  is warranted.

### 2.5. The Bed Load Transport Equation

Wilcock correctly points out that a bed load transport equation, in itself, is an insufficient means of predicting general channel response. Nevertheless, we maintain that such an equation can be used to develop and test general relationships between surface texture and rate of bed load supply under controlled conditions (as detailed by Buffington and Montgomery, [1999c]). Without these controls, relationships between surface texture and rate of bed material supply [Buffington and Montgomery, 1999c, Figures 1 and 2] may be obscured by competing responses to changing boundary conditions (e.g., textural response to changes in the size distribution of bed material supply, nonequilibrium transport). We choose strict controls in order to isolate relationships between surface texture and bed material supply, openly acknowledging the limitations for application of our approach to natural channels [Buffington and Montgomery, 1999c, pp. 3528–3529]. Where applicable, our approach allows quantitative assessment of sediment supply with less investment of time and money than would be required for a typical bed load sampling project.

## 3. Reply to Comment by Millar and Rennie

### 3.1. Channel Response Path

Millar and Rennie [this issue] (hereinafter referred to as Millar and Rennie) interpret our reference state framework as a model for predicting channel response paths and conclude that we envision textural response to hydraulic roughness to occur vertically with a constant total boundary shear stress (their Figure 1). Because we do not present a dynamic process response model, we do not discuss likely paths of channel response to specific perturbations, other than the general expectation of textural fining with greater hydraulic roughness. Nevertheless, we would not expect the total stress to remain constant for any perturbation of roughness, discharge, or sediment load, contrary to Millar and Rennie’s interpretation of our paper. The specific response path followed by a particular reach depends on a variety of factors, including the type, magnitude, and duration of disturbance; channel and basin characteristics, including basin hydrology (frequency and magnitude of discharge events); feedback among mutually adjusting channel processes and boundary conditions; timescales for morphologic adjustment; and the disturbance history of the channel. Nowhere do we state that textural changes occur vertically with a constant total boundary shear stress. In effect, Millar and Rennie object to a self-fabricated interpretation of our paper.

### 3.2. Effects of Hydraulic Roughness: Surface Texture Versus Total Boundary Shear Stress

Millar and Rennie correctly note that supplementary form drag caused by the addition of hydraulic roughness will increase flow depth and/or slope, resulting in greater total boundary shear stress. They suggest that hydraulic roughness can increase the total boundary shear stress with no corresponding change in surface texture (horizontal vector, their Figure 1). Moreover, they propose that our data demonstrate this sort of relationship, rather than a textural response to hydraulic roughness. We tested their hypothesis using data published in our paper.

Overall, our data demonstrate a textural response to hydraulic roughness, rather than the response to total boundary shear

stress as claimed by Millar and Rennie. Mean values of  $D_{50}$  for each channel type are statistically different from one another ( $P < 0.05$ ,  $t$  test) and are systematically finer in channels with greater roughness, while there are no statistically significant differences ( $P > 0.05$ ) in channel depth, slope, or total shear stress among the channel types (as a whole). For a given value of  $D_{50}$ , channels with more hydraulic roughness do have larger values of total boundary shear stress (their Figure 1), but this is expected for hydraulic equilibrium. Statistically, there is no significant relationship between channel type and total boundary shear stress (for the ensemble data set), but there is a significant relationship between channel type and grain size. Differences in grain size between channel type result from associated differences in hydraulic roughness at our study sites and do not appear to be related to any systematic covariance of channel type with either the rate or size of bed material supply [Buffington and Montgomery, 1999b, pp. 3516–3518].

While Millar and Rennie's "horizontal vector" (their Figure 1) is a possible response path to the addition of hydraulic roughness, it is not likely in unconfined channels with extensive floodplains, as is typical of our study sites. Overbank flow will limit the amount of change in channel depth and/or slope caused by the addition of hydraulic roughness, forcing a decrease in the bed stress, channel competence, and surface grain size as the channel relaxes toward hydraulic equilibrium. Moreover, the flow depth and slope of the total bank-full shear stress (that of interest in our investigation) will show the least amount of change because of the mitigating effects of overbank flow at bank-full stage. Consequently, some degree of textural change is expected in response to altered hydraulic roughness in floodplain channels. For the converse problem (where hydraulic roughness is removed from channels), most field studies indicate some degree of textural coarsening [Lisle, 1995], rather than maintenance of a constant surface grain size.

The horizontal and vertical vectors shown in Millar and Rennie's Figure 1 define end-member paths of possible textural response to the addition of hydraulic roughness. In gravel-bed channels with extensive floodplains, textural response to roughness likely follows some downwardly oblique, nonlinear path within the space bracketed by these two vectors.

### 3.3. Armoring

Millar and Rennie raise an interesting question about the relative degree of armoring between the three channel types studied. One might expect a systematic reduction in armoring if hydraulic roughness decreases channel competence and surface grain size. Conversely, one might expect a higher degree of armoring in channels that have less roughness and correspondingly greater values of bed stress and competence. On the basis of this expectation, Millar and Rennie interpret the observed lack of armoring across the three channel types studied as evidence that hydraulic roughness has no effect on surface texture. The interpretation being that an unarmored surface indicates no hydraulic modification of the bed material supplied to the channel.

The observed lack of armoring is partially a result of how the data were analyzed. In particular, the fine tails of the size distributions were truncated to isolate bed load material (as opposed to suspended load). Assuming that the surface and subsurface material have the same parent population, truncating the fine tail causes the two distributions to become increasingly similar (appear unarmored). Using the untruncated distributions produces larger ratios of surface-to-subsurface grain

size (stronger armoring), with 28% of the data having ratios  $>2$  (compared to 6% for the truncated distributions). Moreover, the mean ratio of surface-to-subsurface median grain size systematically declines from  $2.2 \pm 0.38$  in plane bed channels to  $1.6 \pm 0.16$  in wood-rich pool riffle channels. The decrease in armoring from plane bed to wood-rich pool riffle channels is consistent with our hypothesis that hydraulic roughness inhibits armoring by reducing bed shear stress and channel competence, thereby causing deposition of finer bed load material and possibly decreasing the degree of surface winnowing [Buffington and Montgomery, 1999b].

Nevertheless, differences in armoring between channel types are not as strong as one might expect. This is because hydraulic roughness and altered competence affect not only the surface grain-size distribution but also the subsurface distribution, as evidenced by the covariance of surface and subsurface sizes at our sites [Buffington and Montgomery, 1999b, Figure 10]. Coarser-grained textural patches typically have correspondingly coarser subsurface material, while finer-grained patches typically have finer subsurface sizes. This is true for both truncated and untruncated size distributions [Buffington and Montgomery, 1999a, Figure 9]. Moreover, when reach-average subsurface median grain sizes are plotted in the reference state framework, they also show a systematic decrease in median grain size with increasing hydraulic roughness, as was observed for the surface material [Buffington and Montgomery, 1999b, Figure 3]. The influence of hydraulic roughness on both the surface and subsurface material at our sites further demonstrates the tendency for alluvial rivers to hydraulically sort and modify the sediment delivered to them. This sorting is not simply a modification of the surface layer but of the entire bed material supply.

Millar and Rennie suggest that the ratio of surface-to-subsurface grain size is a better indicator of textural response to hydraulic roughness than our reference state framework. However, the covariance of surface and subsurface material at our sites cause armoring to be less sensitive to channel type and associated hydraulic roughness than one might expect. Consequently, the ratio of surface-to-subsurface grain size may not be as reliable an indicator of textural response to hydraulic roughness as Millar and Rennie's recommendation would suggest. In contrast, the reference state approach does discriminate textural response to hydraulic roughness. The point of our approach is to provide a theoretical reference condition against which to compare observed grain size. Our reference condition is that of maximum competence, which can be objectively determined from the bank-full shear stress. Millar and Rennie's proposed reference condition is effectively the subsurface grain size, which is less attractive because it may covary with hydraulic roughness (as discussed above), and it is site-specific (a function of imposed sediment supply and downstream hydraulic sorting) and therefore cannot be predicted a priori. Moreover, a change in the grain-size distribution of the bed material supply (and thus the subsurface size distribution) may cause an apparent change in the ratio of surface-to-subsurface sizes even when no change in the surface texture has occurred.

## 4. Closure

On the basis of our observations we propose general trends of textural response to both hydraulic roughness and bed material supply but do not offer predictions of specific magnitudes

of textural response or predictions of specific changes in channel hydraulics or morphology that might result from a particular channel perturbation. Because natural channels are non-linear, dynamic systems, a variety of responses may occur, and a change in any one factor cannot be predicted in isolation of the others. Nevertheless, our simplified analysis framework offers a context within which to develop an understanding of potential trends in textural response to altered boundary shear stress and bed material supply, thereby adding to our “tool box” for river analysis.

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