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Key Points:

- Rivers with beds of coarse sand and fine gravel are notably absent worldwide
- At a shear velocity of 0.1 m/s, wash load competency of sand plummets
- Wash load fallout explains an absence of rivers with beds of 1 to 5 mm diameter sediment

Supporting Information:

- Supporting Information S1

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The grain size gap and abrupt gravel-sand transitions in rivers due to suspension fallout

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Abstract Median grain sizes on riverbeds range from boulders in uplands to silt in lowlands; however, rivers with ~1–5 mm diameter bed sediment are rare. This grain size gap also marks an abrupt transition between gravel- and sand-bedded reaches that is unlike any other part of the fluvial network. Abrupt gravel-sand transitions have been attributed to rapid breakdown or rapid transport of fine gravel, or a bimodal sediment supply, but supporting evidence is lacking. Here we demonstrate that rivers dramatically lose the ability to transport sand as wash load where bed shear velocity drops below ~0.1 m/s, forcing an abrupt transition in bed-material grain size. Using thresholds for wash load and initial motion, we show that the gap emerges only for median bed-material grain sizes of ~1–5 mm due to Reynolds number dependencies in suspension transport. The grain size gap, therefore, is sensitive to material properties and gravity, with coarser gaps predicted on Mars and Titan.

1. Introduction

As rivers flow from uplands to lowlands, their beds tend to systematically fine downstream [*Sternberg*, 1875]. Downstream fining is generally gradual; however, there is often a relatively abrupt change in the grain size of riverbeds from medium gravel to medium sand [*Yatsu*, 1955; *Shaw and Kellerhals*, 1982; *Sambrook Smith and Ferguson*, 1995] (Figure 1a). This is the only abrupt and persistent transition in bed grain size known to occur in the fluvial system. Moreover, there is a general absence of rivers on the planet that have riverbeds composed of 1–5 mm diameter sediment (Figure 1b) [e.g., *Udden*, 1914; *Pettijohn*, 1949; *Trampush et al.*, 2014]. Due to the lack of granule and pebble beds, this grain size gap has led most alluvial rivers to be classified as either sand or gravel bedded, which is a foundational division for fluvial engineering, sedimentology, and geomorphology. For example, different sets of semiempirical equations have been developed for sand- and gravel-bedded rivers including those for flow resistance, sediment transport, and river morphology [*Garcia*, 2008]. The gravel-sand transition is also a fundamental boundary used to characterize the depositional architecture of sedimentary basins [*Paola et al.*, 1992a; *Marr et al.*, 2000]. An explanation for the grain size gap that relates specifically to fine gravel and coarse sand has remained elusive.

Early workers attributed the grain size gap to enhanced comminution of sediment in the gap range [*Yatsu*, 1955; *Kodama*, 1994] or to in situ weathering of bedrock at the sediment source [*Wolcott*, 1988], arguing that these particles break down rapidly into sand. Although there is a subset of rivers with rock types conducive to these mechanisms [*Kodama*, 1994], the grain size gap exists worldwide (Figure 1b) across rivers that sample many different lithologies. Alternatively, *Jerolmack and Brzinski* [2010] propose that viscous damping of particle collisions limits breakdown of particles finer than 10 mm and the production of gap-sized sediment. However, experiments show that collisions are not damped in this size range owing to energetic transport of particles in suspension [*Scheingross et al.*, 2014]. Moreover, the magnitude of fining in many rivers and flume experiments, especially across gravel-sand transitions, is too high to be explained by abrasion alone [*Paola et al.*, 1992b; *Sambrook Smith and Ferguson*, 1995]. Finally, other sedimentary environments, including energetic shallow marine and beach settings, can be composed of sediments in the gap range [*McLean*, 1970; *Jennings and Shulmeister*, 2002] (e.g., Figure 1c). If the grain size gap results from rock material properties, then these particle sizes also should be missing from beaches where abrasion mechanics are similar to rivers. These arguments shed doubt on the comminution hypotheses as universal explanations for the grain size gap, and instead point to the importance of particle size sorting processes in rivers.

In most models, downstream fining occurs through size-selective bed load transport [*Parker*, 1991; *Hoey and Ferguson*, 1994; *Cui and Parker*, 1998; *Parker and Cui*, 1998], and an abrupt gravel-sand transition can occur but

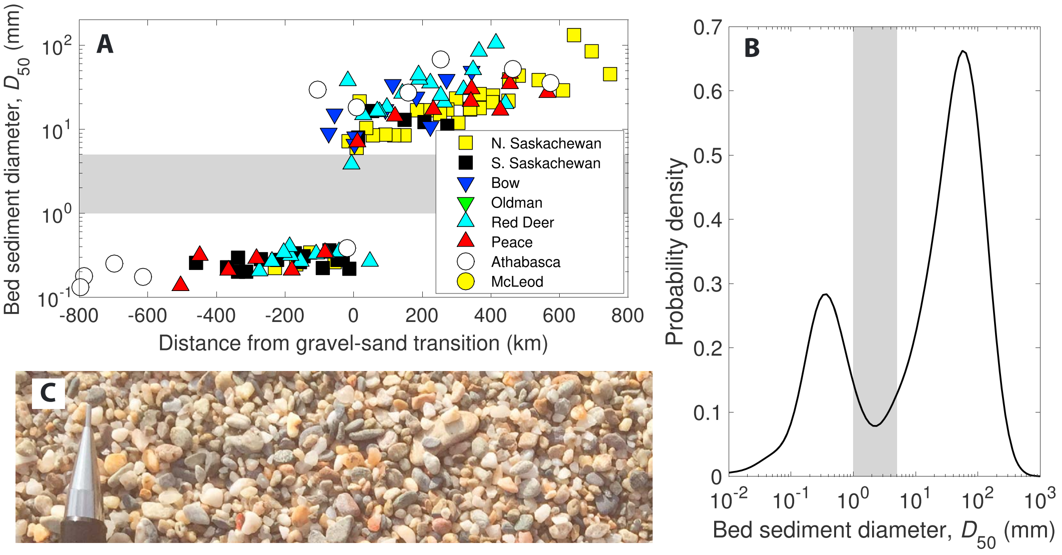

Figure 1. (a) Downstream fining of median grain size in eight large rivers in Alberta, Canada, five of which cross a gravel-sand transition (from *Kellerhals et al.* [1972] and *Shaw and Kellerhals* [1982]). (b) Probability distribution of median bed grain size of 541 single thread rivers worldwide (from *Trampush et al.* [2014]). The shaded box in Figures 1a and 1b denotes the inferred grain size gap of $1 < D_{50} < 5$ mm. (c) Beach sediment from Githio, Greece, with grains that range in diameter from ~1 to 5 mm. Chrome part of pencil tip is 20 mm long.

only through the a priori assumption of a grain size gap. For example, often, sand and gravel are defined as two separate classes and modeled using different approaches [*Paola et al.*, 1992a; *Wilcock*, 1998; *Ferguson*, 2003]. Strong bimodality can cause gravel-sand transitions to be sharp because of sorting effects during bed load transport [*Sundborg*, 1956; *Wilcock and Kenworthy*, 2002; *Ferguson*, 2003], but different phenomenological rules are applied to the gravel and sand modes, which contributes to the effect. Models that consider a full sediment size distribution must omit sediment within the grain size gap to force an abrupt gravel-sand transition [*Cui and Parker*, 1998; *Parker and Cui*, 1998], or impose an abrupt change in channel bed gradient or channel width [*Ferguson and Church*, 2009]. Importantly, bed-load size-sorting effects are principally a function of the breadth or bimodality of the grain-size distribution and should apply equally to any absolute size range [*Parker*, 1990], even though they are sometimes framed in terms of sand and gravel specifically [*Wilcock and Kenworthy*, 2002]. Thus, these models do not explain why the grain size gap occurs specifically for gravel and sand.

Although bed-load sorting processes have dominated recent discussions on gravel-sand transitions, some workers have suggested that suspended or wash load sediment may be important [*Iseya and Ikeda*, 1987; *Sambrook Smith and Ferguson*, 1995; *Ferguson et al.*, 1998]. This idea is supported by experimental work examining downstream fining of bimodal mixtures of gravel and sand, in which the collapse of the flow's ability to suspend sand across the gravel front was inferred to cause sharp gravel-sand transitions [*Paola et al.*, 1992b; *Seal et al.*, 1997; *Toro-Escobar et al.*, 2000]. In addition, *Venditti and Church* [2014] showed that there is a sharp decline in shear stress across the gravel-sand transition in the Fraser River, which leads to rapid sand deposition from wash load immediately downstream of the gravel front [*Venditti et al.*, 2015].

Herein we develop a theory to explore the hypothesis that sharp gravel-sand transitions may emerge as a consequence of downstream changes in wash load transport. In particular, it appears from experimental and field observations that, where fine gravel falls below the threshold of motion, sand also transitions from wash load (suspended sediment that is poorly represented on the bed) to bed material load (bed load and suspended load sourced from the bed). This may cause a rapid change in the median bed-material grain size [*Paola et al.*, 1992b; *Venditti and Church*, 2014]; however, a quantitative model of this process has yet to be proposed.

2. Grain Size Gap Model

Downstream fining due to selective deposition can occur in alluvial rivers where, for example, there is a downstream decrease in bed stress to transport sediment (i.e., $d\tau_b/dx < 0$, in which τ_b is the bed shear stress

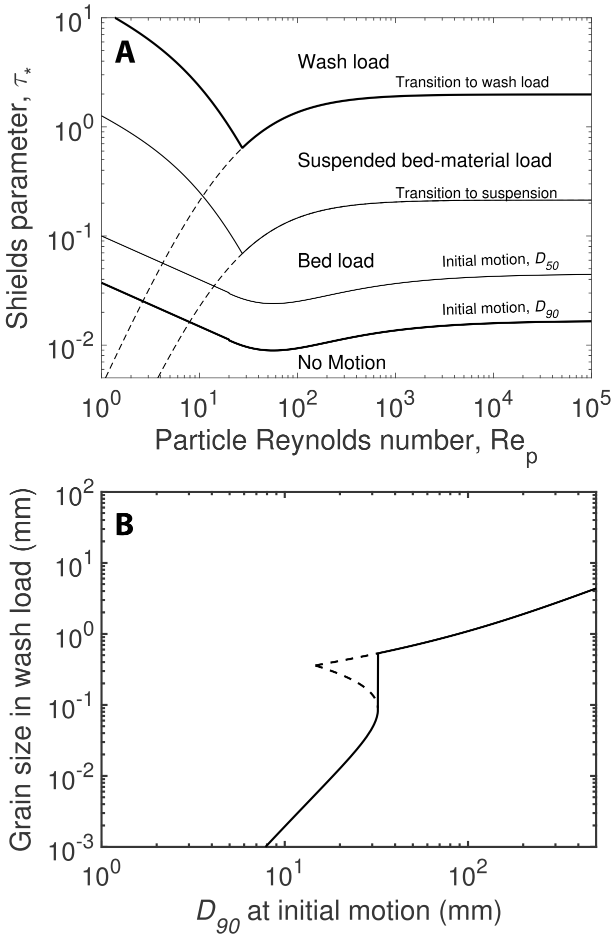

Figure 2. (a) Modeled thresholds for initial motion for median particle diameter, D_{50} [*Brownlie*, 1983; *White*, 1970] and D_{90} (equation (3)). Modeled thresholds for incipient suspension by *Nino et al*. [2003] (equations (4a) and (4b); solid line) and incipient wash load (equations (5a) and (5b)). The dashed lines are predictions assuming that u_*/w_s is constant for all Re_p [*Bagnold*, 1966]. (b) Predicted grain diameter at incipient wash load (equations (5a) and (5b)) for shear stress conditions in which a certain grain size is at initial motion (assumed to be D_{90}). Where model solutions have multiple values (dashed line), we assume that the finer size represents the threshold of wash load (solid line).

and x is the downstream direction), which reduces the river's ability to transport the coarser fraction of the sediment load, resulting in deposition. Selective deposition can occur through loss of competency (i.e., the river's inability to mobilize certain particles because they are too large) [*Paola et al*., 1992a] or loss of capacity (i.e., the river's inability to transport the supplied sediment load) [*Parker*, 1991; *Hoey and Ferguson*, 1994]. Modeling the loss of capacity while coupling bed load, suspended load, and wash load is not straightforward [*Grams and Wilcock*, 2014], and wash load in particular depends on the sediment supply, which is difficult to constrain. Although it is likely an oversimplification, here we model downstream fining by loss of competency because fining can be predicted as a simple function of bed shear stress and transport thresholds. Following *Paola et al*. [1992a], we assume that downstream fining occurs due to deposition of the coarsest fraction of the sediment load where bed shear stresses fall below the threshold of motion for that size class.

The threshold for sediment motion is typically formulated as a critical Shields number (τ_c^*) that is a function of particle Reynolds number (Re_p) [*Shields*, 1936],

$$\tau_c^* = \frac{u_*^2}{RgD} \tag{1}$$

$$Re_p = \frac{(RgD)^{1/2}D}{\nu} \tag{2}$$

in which $u_* = \sqrt{\tau_b/\rho}$ is bed shear velocity, ρ is fluid density, R is submerged specific density of sediment, g is acceleration of gravity, D is particle diameter, and ν is kinematic viscosity of the fluid. The Shields curve (Figure 2a) is usually cast in terms of the median bed grain size (D_{50}), and can be modified to apply to the coarser end of the bed-material size distribution (e.g., D_{90}; Figure 2a) using a hiding function for the *i*th grain size class as [*Parker*, 1990]

$$\tau_{c_i}^* = \tau_c^* \left(\frac{D_i}{D_{50}}\right)^{-\gamma} \tag{3}$$

where $0 \leq \gamma \leq 1$ determines the relative mobility of different size fractions.

At conditions of suspended sediment transport, particles are entrained from the bed by coherent flow structures that produce bursts of upward moving fluid and, as the structures dissipate, particles settle toward the bed due to gravity [e.g., *Bennett et al*., 1998]. The water column tends toward an equilibrium concentration profile due to a dynamic balance between upward and downward fluxes of particles [*Rouse*, 1937]. The conditions at which predominantly bed-load transport transitions to suspension (i.e., incipient suspension) is often assumed to be $u_*/w_s = \alpha$, in which w_s is the particle terminal settling velocity and $\alpha \approx 0.4$ to 1 [*Bagnold*, 1966; *van Rijn*, 1984]. However, several workers have shown that the Bagnold threshold ($u_*/w_s = \alpha$) fails to accurately predict the transition from bed load to suspension for low-particle Reynolds numbers [*van Rijn*, 1984]. For example, *Nino et al*. [2003] show that the transition to suspension becomes increasingly difficult at small particle Reynolds numbers, which they attribute to effects related to the viscous sublayer during particle reentrainment. Their criteria for the transition to suspension for particles transported over a bed of similar sized particles is

$$u_*/w_s = 21.2 Re_p^{-1.2} \quad \text{for } 1 < Re_p < 27.3 \tag{4a}$$

$$u_*/w_s = 0.4 \quad \text{for } Re_p > 27.3 \tag{4b}$$

The *Nino et al*. [2003] relation predicts that, for small Re_p, suspension occurs at shear stresses that exceed those required for initial motion, indicating a regime of bed-load transport at small Re_p (Figure 2a). *Van Rijn* [1984] developed a similar relation with a break from the Bagnold curve at $Re_p = 32$. The Bagnold curve, in contrast, plummets below the Shields curve for small Re_p implying that sediment at small Re_p moves only by suspension, which is counter to observations of a regime of bed load transport [*van Rijn*, 1984; *Nino et al*., 2003] (Figure 2a).

Nino et al. [2003] did not address the transition to wash load, but it is common to assume that the transition to wash load occurs at an α value that is about threefold that required for the transition to suspension [*Bridge*, 2003]. Thus, we multiply equations (4a) and (4b) by a factor of $\beta = 3$ to convert between the threshold for suspension and wash load, and combine equations (1), (4a), and (4b) to formulate the critical Shields number for wash load as

$$\tau_{wl}^* = 4320 Re_p^{-2.4} \frac{w_s^2}{RgD} \quad \text{for } 1 < Re_p < 27.3 \tag{5a}$$

$$\tau_{wl}^* = 1.54 \frac{w_s^2}{RgD} \quad \text{for } Re_p > 27.3 \tag{5b}$$

in which $\frac{w_s^2}{RgD}$ is inversely proportional to a drag coefficient, which we compute for all D from the settling velocity model of *Ferguson and Church* [2004] for natural sediment (Figure 2a). Although by definition wash load is poorly represented on the bed [*Einstein*, 1950; *Bagnold*, 1966], it is often conceptualized incorrectly as having no interaction with the bed. However, the classic experiments of *Einstein* [1968] show that to achieve steady state wash load transport (with u_*/w_s as large as 7000), reentrainment of grains from the bed is necessary to balance the slow and continuous downward flux due to gravitational settling. These particles can be reentrained immediately after contact with the bed, preventing a large fraction of them from being incorporated into the bed material. Thus, while the *Nino et al*. [2003] model is for the transition from bed load to suspension, modified here for transition from suspended-bed material to wash load, near-bed entrainment mechanics are still relevant for both of these transitions, even under supply-limited conditions [*Lamb et al*., 2008a].

Following our conceptual model, we recast the transport thresholds in Figure 2a by assuming that the coarse fraction of the bed material is at initial motion during formative discharge (e.g., bankfull) events and fine sizes are at the threshold for wash load. We use D_{90} as a metric of the bed material size that is marginally mobile and lost to the transport system by selective deposition at formative flows, following *Paola et al*. [1992a]. We use D_{10} as a metric of the bed material that will be marginally mobile into wash load and poorly represented on the bed, following the common definition of wash load [*Einstein*, 1950; *Bagnold*, 1966]. Combining equations (1) and (3) and accounting for form drag in the momentum balance results in a prediction of the formative bed shear velocity when D_{90} is at initial motion,

$$u_{*f}^2 = f RgD_{90} \tau_{c_{50}}^* (D_{90}/D_{50})^{-\gamma} \tag{6}$$

in which f is the ratio of total bed stress relative to the bed stress available to move sediment, thus accounting for macroscale form drag [*Lamb et al*., 2008b]. Using equations (5a), (5b), and (6), we now can find the sediment size at the threshold of wash load for the formative discharge event in which the coarsest sizes are at the threshold of motion (Figure 2b). We set $f = 1.5$ following the analysis of *Lamb et al*. [2008b], $\gamma = 0.9$ after

Parker [1990], and $D_{90}/D_{50} = 3$, which is typical of gravel-bedded rivers and consistent with our data compilation in section 3.

Finally, given that most riverbed grain-size distributions can be fit with a lognormal distribution, we calculate D_{50} as the geometric mean of the two predicted bounds on the bed-material grain-size distribution (i.e., D_{90} and D_{10}). We make no assumption about the transport stage of D_{50} at bankfull, except that implicitly it must be above the threshold of motion (since that is set for D_{90}) and below the threshold of wash load (which is set for D_{10}). Importantly, we set all parameters such as f and γ to be constants for all sediment sizes such that we make no explicit distinctions in bed forms, form drag, or sorting between sand and gravel, or any other size classes that could influence the emergence of a grain size gap. Model sensitivity to these parameters is discussed in section 5.

3. Data Compilation

We use the compiled bed grain-size distributions and bankfull measurements of formative bed shear velocity as u_f^* for a worldwide compilation of rivers [*Trampush et al*., 2014] (Figure 1b). We also compare the model against several rivers in Western Canada that cross the grain size gap (Figure 1a). In the Fraser River, B.C., we use observations of bed shear stress reported in *Venditti and Church* [2014] for bankfull flow in the gravel and sand bed reaches, which have been shown to entrain the gravel bed surface and move sand as wash load in the gravel reach [*McLean et al*., 1999]. For the Alberta rivers, we require a continuous downstream profile of total boundary shear stress to estimate the shear velocity at the bed-material sampling sites (Figure 1a). *Kellerhals et al*. [1972] reported shear stress for 2 year and 5 year return interval flood flows ($n = 36$) at discharge gauging stations in each river system shown in Figure 1a, and less frequently for the 10 year and bankfull flood flows. In these formerly glaciated drainage basins, reported bankfull flows have return periods of 2.5 (1 site), ~10 (5 sites), ~25 (2 sites) and >100 (7 sites) years. We elected to use exponential fits to 5 year return interval shear stress and downstream distance to provide continuous downstream profiles of shear stress, which could be matched to bed-material samples.

4. Results

Model results show, in general, a positive correlation at formative bed shear stresses between the coarse particles at the threshold of motion and the fine sediment at the threshold of wash load (Figure 2b). Thus, in a river undergoing downstream fining of the coarse load due to selective deposition, there also will be a fining of the material that transitions from wash load to bed-material load. However, the relation between initial motion and wash load particle sizes is not monotonic where grains at initial motion range in size from ~10 to 25 mm. In this region, there is a remarkable decline in the competency to transport wash load sediment ranging in size from 0.05 to 0.8 mm—a size range that makes up much of the sand load. The full solution (dashed line in Figure 2b) predicts that multiple sizes simultaneously may be at the threshold of wash load. For cases with multivalued solutions, we choose the finer size (solid line in Figure 2b), to be consistent with the definition of wash load.

Figure 3a shows that, at initial motion, sediment size smoothly decreases with decreasing formative bed shear velocity. The particle sizes at the threshold for wash load, on the other hand, show a dramatic drop from coarse sand to silt at $u_f^* \sim 0.1$ m/s (solid line in Figure 3a) or a region of $0.08 < u_f^* < 0.12$ m/s for the multivalued solution (dashed line in Figure 3a). Because the predicted D_{50} is taken as the geometric mean of D_{90} and D_{10}, it too shows a discontinuity at $u_f^* \sim 0.1$ m/s in which D_{50} jumps from ~5 mm to ~1 mm within a very narrow range of bed shear velocities.

The model predictions of the existence of a grain size gap, the particle sizes in the gap, and bed shear velocities where the gap occurs compare well with data from rivers that cross the gravel-sand transition (Figures 3b and 3c) and the extensive bankfull compilation of rivers worldwide (Figure 3d). Importantly, field measurements for all cases also suggest that the grain size gap occurs for ~1–5 mm grains where $u_f^* \sim 0.1$ m/s. For example, in the Fraser River, the main channel-spanning shift from gravel- to sand-bedded conditions occurs where u_f^* first falls into the range 0.08 to 0.12 m/s (Figure 3b). The Peace, Red Deer, South Saskatchewan, and North Saskatchewan transition at u_f^* of 0.09, 0.114, 0.115, and 0.08 m/s, respectively (Figure 3c). The three rivers that do not experience formative shear velocities in the range 0.08 to 0.12 m/s

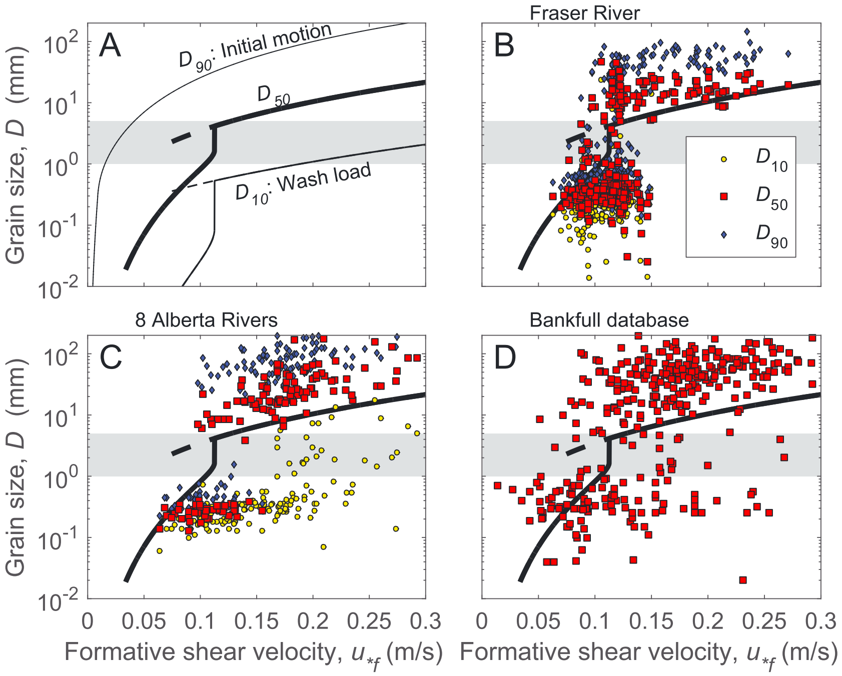

Figure 3. (a) Predictions, at the formative (e.g., bankfull) bed shear velocity, of grain size at initial motion (D_{90}), incipient wash load (D_{10}), and median bed grain size (D_{50}). The region of multivalued solutions for wash load and D_{50} are demarcated with dashed lines, and the preferred solution is demarcated by a solid line. The same model predictions for D_{50} overlaid by cross section-averaged data from the (b) Fraser River [*Venditti and Church*, 2014], (c) Alberta rivers plotted in Figure 1a, and (d) the compilation of *Trampush et al.* [2014]. In Figures 3b and 3c, different points represent different locations along each river, in which larger u_{*f} generally represents locations farther upstream, whereas in Figure 3d different points represent different rivers. The shaded box denotes the inferred grain size gap ($1 < D_{50} < 5$ mm).

do not transition to sand beds. The data are scattered, however, and away from the grain size gap the model tends to underpredict D_{50} in the gravel reaches and overpredict D_{50} in the sand reaches, which could be due to changes in form drag, f, due to bed forms or the hiding parameter, γ, across the gravel-sand transition. The model can be fit to better match the data (Figure S1 in the supporting information) but only by making assumptions specific to the gravel- and sand-bedded reaches, which is counter to our approach to make no assumptions about the behavior of distinct grain size classes.

5. Discussion and Conclusion

Our results suggest that rivers with median bed grain sizes between 1 and 5 mm should exist only under a very limited range of hydraulic conditions ($u_f^* \sim 0.1$ m/s, or ~0.08–0.12 m/s for the multivalued solution) because of the remarkable change in sand wash-load competency at that same shear stress. Slightly larger u_f^* will result in a rapid increase in the ability of the flow to transport sand as wash load, which will coarsen the bed material into the gravel range. A slightly smaller u_f^* will result in a rapid decrease in the ability of the flow to transport sand as wash load, which can be the bulk of the total sediment load, and will abruptly fine the bed material. In this way, the wash load hypothesis produces a grain size gap without the need to require rapid comminution of the fine gravel to produce sand, strong bimodality of the supplied grain-size distribution, or an imposed bed-slope break as in most previous models [*Parker and Cui*, 1998; *Ferguson*, 2003; *Ferguson and Church*, 2009].

The predicted grain size gap and the bed shear velocities across which it occurs may shift depending on particular assumptions for form drag, grain hiding, and other parameters in the model, but the existence of a grain size gap is robust. For example, model results vary little for the fractions assigned to wash load and initial motion (i.e., D_{10} and D_{90}) as long as they provide reasonable bounds on the bed-material size distribution. Larger ratios of the threshold for wash load relative to suspension (i.e., larger β) [e.g., *Komar*, 1980] produce a slightly coarser and wider grain size gap (Figure S1a), which is still consistent with observations for

β as large as 8. A smaller hiding coefficient, γ, shifts the predicted grain size gap to finer sizes but by less than 30% even for the limiting case of $\gamma = 0$ (Figure S1b). Results also are insensitive to D_{90}/D_{50} if γ is near unity (Figure S1c). The value of f does not affect the emergence of a grain size gap or the gap sizes, only the formative shear velocity where it occurs (i.e., $u_{*f} \propto \sqrt{f}$ following equation (6)).

Unlike the comminution hypothesis that predicts that grain size gap material should be absent, the wash load hypothesis predicts that grain size gap material is present, but it never dominates the bed-material size distribution. For $u_f^* > 0.1$ m/s, grain size gap material should be represented in the finer fraction of the grain-size distribution ($D \ll D_{50}$), and for $u_f^* < 0.1$ m/s it should be part of the coarser fraction ($D \gg D_{50}$). Moreover, our model implies that the gravel-sand transition is expected to occur over longer distances in larger, lower sloping rivers that can have long reaches where u_f^* is ~0.08 to 0.12 m/s and $|\partial u_*/\partial x|$ is small. These ideas are consistent with the Fraser River in that, both upstream and downstream of the main channel-spanning gravel-sand transition, there are patches partly formed of gap material [*Venditti et al.*, 2010a; *Venditti and Church*, 2014]. Upstream, the gap material is scarce, but downstream of the transition, u_f^* oscillates about the critical value of 0.1 m/s (Figure S2), which correlates with a 50 km sandy reach with gravel patches.

Abrupt gravel-sand transitions have been attributed in some cases to an abrupt change in channel-bed slope (and thus $\partial u_*/\partial x$) [*Sambrook Smith and Ferguson*, 1995, 1996]. To isolate this mechanism from the effects of wash load fallout, the magnitude of downstream fining can be written, using the chain rule, as $\frac{dD}{dx} = \frac{\partial u_*}{\partial x}\frac{\partial D}{\partial u_*}$, which reveals that fining patterns depend both on the downstream change in bed stress and the change in grain size relative to bed stress. Although it is possible that an externally set riverbed slope break may exist (e.g., due to tectonics or base level change), it is unclear why this slope break would occur at the particular grain size of $1 < D_{50} < 5$ mm. The wash load hypothesis, on the other hand, implies that an abrupt gravel-sand transition can occur even under gradual downstream changes in bed shear stress and channel slope (i.e., if $\partial u_*/\partial x$ is constant) because of dramatic changes in $\partial D/\partial u_*$ at the grain size gap (Figure 3).

Although a bed slope break and strong bimodality are not necessary to produce an abrupt gravel-sand transition following the wash load hypothesis, they are commonly associated with gravel-sand transitions [*Sambrook Smith and Ferguson*, 1995], and it is likely that both effects still emerge in concert with or because of wash load fallout, and reinforce the abruptness of the transition. For example, changes in grain size are expected to produce changes in alluvial bed slope through morphodynamic feedbacks [*Parker and Cui*, 1998]. In addition, discrete patches of gravel and sand that emerge in the transitional zone, $0.08 < u_f^* < 0.12$ m/s (Figure S2), likely induce bimodality, which in turn can enhance sorting, lead to preferential transport of coarser particles over a finer bed [*Venditti et al.*, 2010b], sharpen the gravel-sand transition [*Sundborg*, 1956; *Ferguson*, 2003; *Wilcock and Kenworthy*, 2002] and change suspension thresholds [e.g., *Grams and Wilcock*, 2014]. Bimodality might also occur under changing flow stage, as the sand fraction transitions temporally between wash load and bed-material load, as suggested by observations in the Fraser River [*McLean et al.*, 1999]. Other reinforcing effects include higher deposition rates as a result of wash load fallout, which should enhance the concavity of river profiles [*Paola et al.*, 1992a]; backwater effects in coastal rivers that can further enhance suspension fallout [*Lamb et al.*, 2012a]; and bed form development in sandy reaches that can increase form drag across the gravel-sand transition. Deposition due to loss of sediment transport capacity, even where the flow is competent to transport a certain grain size range, could also force the grain size gap to occur at high bed shear velocities and may explain, for example, why some sand bed rivers exist where $u_f^* > 0.1$ (Figure 3c).

In conclusion, abrupt gravel-sand transitions and the absence of rivers with median bed-material sizes in the range of 1–5 mm can emerge due to a collapse of a river's ability to transport sand as wash load where bed shear velocities drop below ~0.1 m/s—a collapse that is unlike any other size fraction. Ultimately, the grain size gap occurs for these particular sediment sizes because of the coincident nonlinear changes in the transport of sand as wash load due to Reynolds number effects. This suggests that the grain size gap nearly uniformly occurs for very coarse sand and pebbles on Earth because of the uniformity of fluid density, fluid viscosity, sediment density, and gravity. The specific gravity of sediment is lower on Mars and Titan [*Lamb et al.*, 2012b; *Grotzinger et al.*, 2013], for example, and there grain size gaps are predicted to widen and shift to coarser particles by a factor of 2 and 3, respectively (Figure S3).

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Supporting Information for

The grain size gap and abrupt gravel-sand transitions in rivers due to suspension fallout

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Figures S1- S3

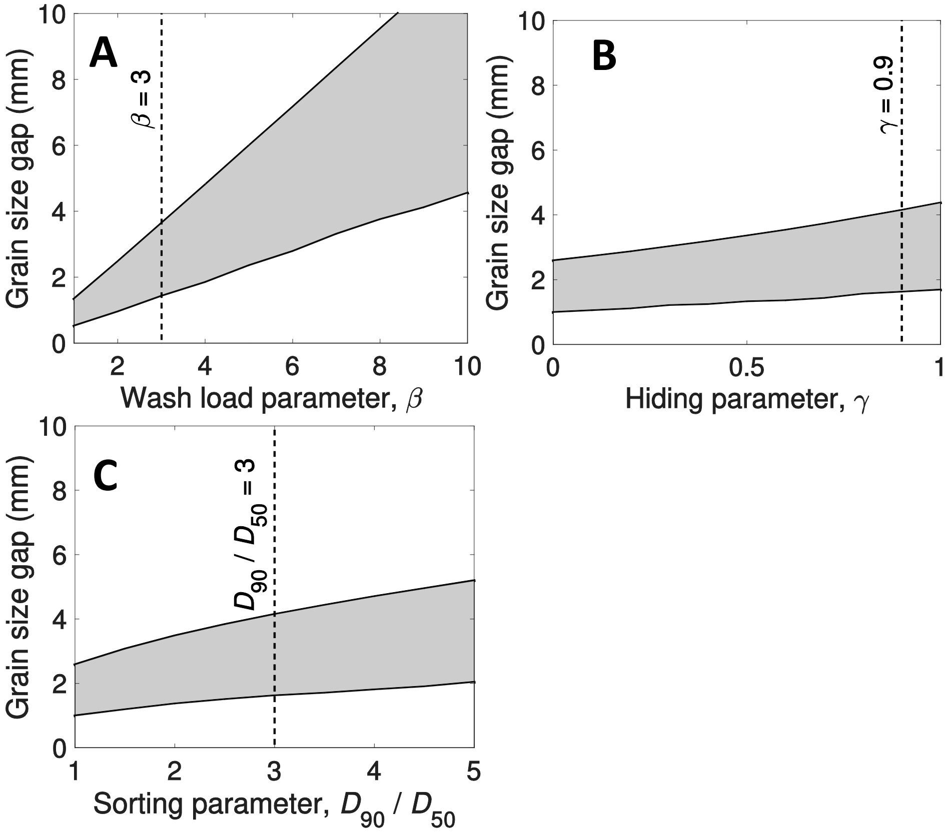

Figure S1. Sensitivity of the predicted grain size gap range (shaded region) to the model parameters: A) the threshold for wash load entrainment relative to that for entrainment into suspension, β, B) size-selective (γ = 0) versus size-independent (γ = 1) behavior at incipient sediment motion (into bed load), and C) the degree of sorting of the bed material, D_{90} / D_{50}. At β =1, all suspended sediment by definition is considered wash load (i.e., there is no suspended bed-material load). Besides the parameter varied on the horizontal axis, all other parameters are held constant at values used in the main text (i.e, β = 3, γ = 0.9 and D_{90} / D_{50} = 3).

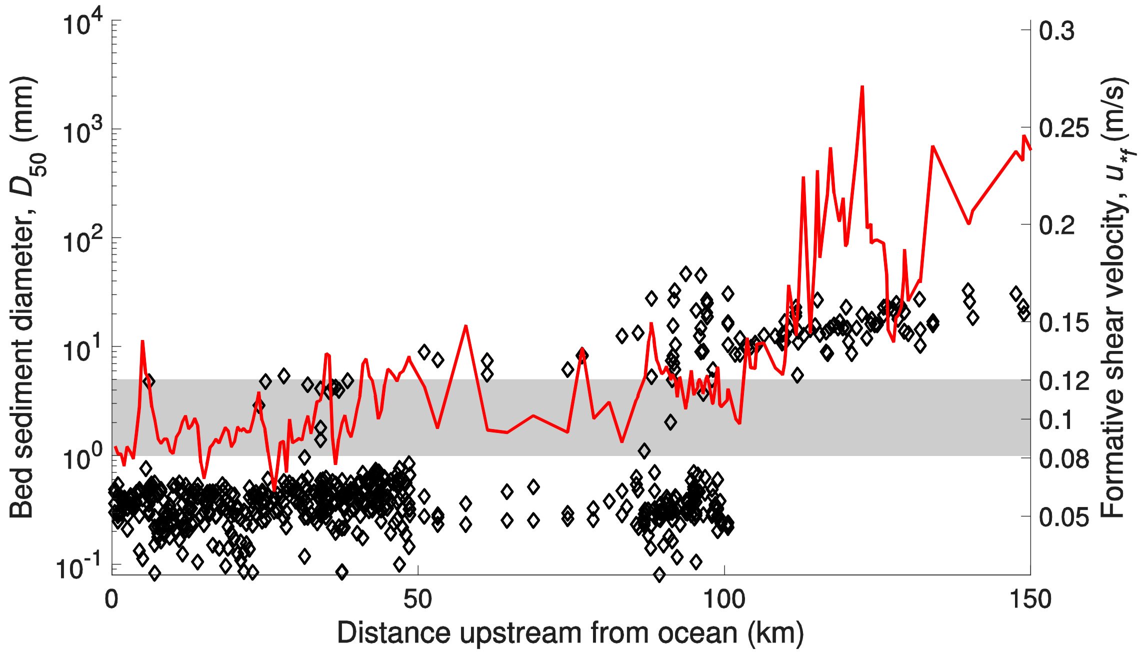

Figure S2. A) Downstream change in formative (bankfull) bed shear velocity (solid red line) and median bed grain size, D_{50}, (diamonds) in the Fraser River [*Venditti and Church*, 2014]. The shaded box denotes the inferred grain size gap ($1 < D_{50} < 5$ mm), and the shear-velocity axis has been aligned so that $0.08 < u_{*f} < 0.012$ m/s matches the grain size gap.

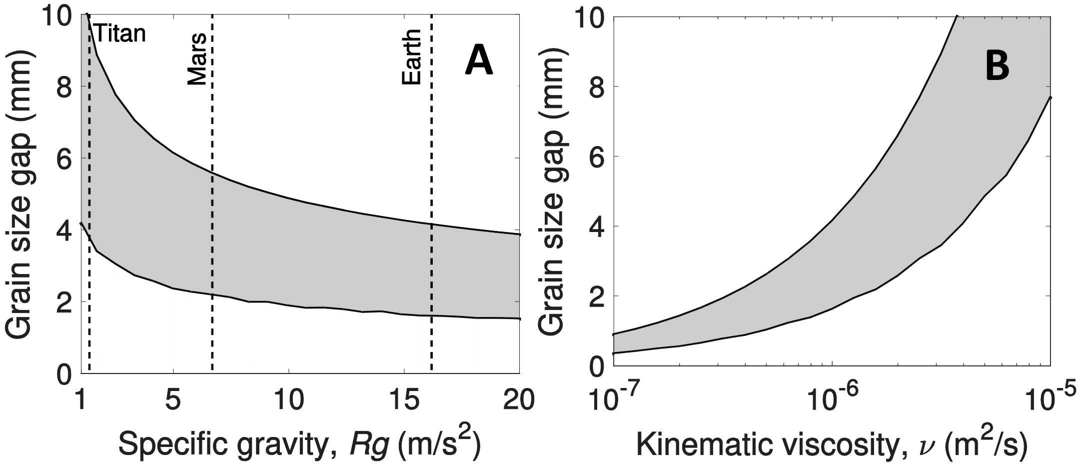

Figure S3. A) Model predictions of the grain size gap (shaded region) as a function of submerged specific gravity, *Rg*, with all other model parameters held constant at values specified in the main text. For siliciclastic sediment on Earth, *Rg* = 16.18 m/s^2, whereas basalt particles transported in freshwater flow on Mars have *Rg* = 6.68 m/s^2, and water-ice clasts transported in liquid methane on Titan have *Rg* = 1.35 m/s^2 (dashed lines). Fluid viscosity is set to 10^{-6} m^2/s for all cases, which is reasonable for liquid water and some estimates for Titan flows [*Grotzinger et al.*, 2013]. B) Model predictions of the grain size gap (shaded region) as a function of the kinematic viscosity of the fluid, with all other parameters held constant at values specified in the main text, and *Rg* = 16.18 m/s^2, corresponding to siliciclastic sediment on Earth. Kinematic viscosity can vary in water flows on Earth primarily due to temperature (e.g., ν = 1.6 x 10^{-6} m^2/s for 3 °C freshwater, and ν = 0.75 x 10^{-6} m^2/s for 33 °C), and can be as high as 10^{-5} m^2/s for viscous brines that have been considered on Mars [*Lamb et al.*, 2012b]. Thus, the grain size gap is predicted to be coarser and broader in colder rivers and in higher viscosity fluids.