Universal relation with regime transition for sediment transport in fine-grained rivers

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Fine-grained sediment (grain size under 2,000 μm) builds floodplains and deltas, and shapes the coastlines where much of humanity lives. However, a universal, physically based predictor of sediment flux for fine-grained rivers remains to be developed. Herein, a comprehensive sediment load database for fine-grained channels, ranging from small experimental flumes to megabravers, is used to find a predictive algorithm. Two distinct transport regimes emerge, separated by a discontinuous transition for median bed grain size within the very fine sand range (81 to 154 μm), whereby sediment flux decreases by up to 100-fold for coarser sand-bedded rivers compared to river with silt and very fine sand beds. Evidence suggests that the discontinuous change in sediment load originates from a transition of transport mode between unixed suspended bed load transport and suspension-dominated transport. Events that alter bed sediment size near the transition may significantly affect fluvio-coastal morphology by drastically changing sediment flux, as shown by data from the Yellow River, China, which, over time, transitioned back and forth 3 times between states of high and low transport efficiency in response to anthropic activities.

Significance

Fine-grained sediment transport systems (grain size under 2,000 μm) are ubiquitous over time and space on Earth and extraplanetary surfaces, and include rivers, deltaic coastal settings, and submarine, lahar, and subglacial systems. Forecasting the evolution of Earth’s surface requires a predictive algorithm for sediment transport. Herein we provide a universal relation for sediment transport in fine-grained rivers. Surprisingly, it is shown that sediment flux differs by up to 2 orders of magnitude as grain size changes only slightly near the boundary between very fine sand and fine sand. The universal applicability of the sediment transport formulation enables quantitative understanding of the sedimentology and morphology of fine-grained rivers.


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Here we compile a sediment transport database for fine-grained bed rivers including 783 field and 811 laboratory studies (SI Appendix, Table S1) to derive a universal transport relation. The relation is an improvement over previous work because it avoids case dependence and can be applied across a range of flow conditions, environments, and scales; meanwhile, it provides insight into the linkages between notably high sediment concentrations in silt-sand bed rivers and lower values in typical sand bed rivers.

**The Enigma of Exceptional Sediment Load in the Yellow River**

We start by highlighting the apparent sediment transport anomaly of rivers with beds of silt and very fine sand, focusing on data from the lower Yellow River, China. These data (26) have been used to establish a generalized EH formulation (GEH), comparable to data from medium and coarse sand-bed channels (27), including those used to establish the EH relation (11). Fig. 1A illustrates a drastic discrepancy between the Yellow River and the data behind the sand-bed EH. Both datasets can be fitted to the form

$$C_f q_s^* = \alpha \tau^m,$$

where $q_s^* = q_s / \sqrt{R g D^3} = \text{Einstein number}$; $\tau^* = \tau / (R g D)$ = Shields number; $C_f = g H S / U^2$ is the resistance coefficient (assuming steady, uniform flow); $q_s$ is volumetric sediment flux per unit width (square meters per second); $R$ is sediment submerged specific density; $g$ is gravitational acceleration rate (meters per square second); $D$ is median grain size or geometric mean grain size of bed material (meters); $\tau = p g H S / p C_f U^2 = p u^* +_2$ is bed shear stress (pascals) for steady, uniform flow; $p$ is water density (kilograms per cubic meter); $H$ is water depth (meters); $S$ is water surface slope; $U$ is depth-averaged velocity (meters per second); and $u^*$ is shear velocity (meters per second). Both the resistance coefficient $C_f$ and the Shields number $\tau^*$ are macroscale hydraulic factors that lump effects over grain and bedform scales (e.g., skin friction and form drag; SI Appendix, Text S2).

The values for coefficient $\alpha$ and exponent $n$ are drastically different for the standard sand-bed EH relation, that is, $(\alpha, n) = (0.05, \frac{5}{2})$, as compared to GEH relation for the Yellow River, that is, $(\alpha, n) = (0.9, \frac{5}{3})$. For the same shear stress, sediment transport predicted by the GEH relation much more efficiently utilizes shear stress to produce higher sediment concentrations; on the contrary, sediment transport utilizes shear stress less efficiently in the EH relation (SI Appendix, Text S2). The difference between the 2 predictions for sediment load is 1 to 2 orders of magnitude. Insofar as EH is the gold standard for sand-bed rivers (11, 12), we ask hypothetically, Is there something special about the Yellow River that makes it different from all other rivers? Our answer is no, but with an unexpected twist.

**The Yellow River Has Field and Laboratory Siblings**

The first step toward answering whether the exceptional load of the Yellow River is an anomaly is to search for analogs. Although many field examples of silt-sand bed rivers exist (7, 8, 18, 23, 28), few sediment transport data have been collected from them. One case with the necessary data—Indian Canal (28)—behaves similarly to the Yellow River (SI Appendix, Fig. S1), in which the water depth varies from 0.67 m to 3.35 m and median grain size is between 20 μm and 82 μm, values close to those obtained from the Yellow River bed. Beyond the limited field data, we compiled data from 5 experimental studies (24, 25, 29–31) for silt-sand bed material ($D_{50} = 11$ to 153 μm). Results show that the experimental studies, like Indian Canal, follow the GEH relation, and thus act like the Yellow River (Fig. 1 and Movie S1). Thus the Yellow River is not special or unique: Sediment transport data from laboratory-scale flumes using silt-sand mixed material (rather than sand only) are well quantified by the GEH formulation (Fig. 1), indicating a strong element of universality.

![Fig. 1. Discontinuous regime transition behavior based on laboratory flume experiments.](image-url) (A) GEH and EH formulations are compared to the databases (26, 27) that were used to develop them. (B) Comparison between sediment transport database and theoretical formulations in dimensionless space. Only laboratory data are shown here. Two distinct populations are evident, each of which is characterized by a similarity relation (power law), that is, GEH and EH. Data are colored to indicate the median grain size of the respective sediment bed; the corresponding color bar is shown inserted in the figure. Cases that agree with the GEH and EH formulations are shown in red and blue, respectively, on the lower bar. (C) Plot of dimensional sediment load (per unit width) and median grain size, which shows a discontinuous jump in sediment transport rate near $D_{50} = 100$ μm. Data within the range or parameter space ($u^*$, $C_f$) are shown in the plot. The mean values (overbars) of parameters are used to calculate the solid line for GEH and EH, and the uncertainty zones are calculated from the range of parameter space. This parameter space can be arbitrarily chosen to show the discontinuity, as also shown in SI Appendix. The difference between the 2 regimes is a factor of 11 to 18.
There is a clear discontinuity in sediment load between the typical sand-bed datasets that plot along the EH relation and the silt-sand mixed channels that plot along the GEH relation (Fig. 1 and Movie S1). This discontinuity cannot be explained by the difference of experimental techniques, because there were 2 groups of data from the same setup (25), in which the silt bed experiment ($D_{50} = 40 \mu m$) agrees with GEH and the coarser experiment ($D_{50} = 110 \mu m$) agrees with EH. Moreover, this discontinuity may be separated to first order by a relatively narrow range of $D_{50c}$: 88 to 153 $\mu m$ (Fig. 1B). In dimensional space, for similar hydraulic conditions, sediment load $q_s$ differs by a factor of 10 to 20 in the transitional zone of bed grain size (Fig. 1C). This discontinuous jump exists for every combination of hydraulic factors, and the discontinuity always occurs at the same grain size range (Fig. 1C and SI Appendix, Fig. S2). This behavior contradicts the assumption that a universal transport relation covering silt-sand and typical sand transport environments should be continuous (17, 25). We refer to this discontinuous relation between sediment load and grain size under similar hydraulic conditions as the Fine-grained Transport Regime Transition (FTRT), which separates the high transport efficiency regime for silt-sand beds that conform to GEH from the low transport efficiency regime for typical sand beds that follow EH.

**Quantification of Regime Transition**

The FTRT occurs over a narrow grain size range (Fig. 1), which suggests that grain size offers only first-order control, leaving at least one other parameter. Here we present and test 3 hypotheses, denoted H1 to H3, for the origin of the regime transition.

1. For H1, as bed material grain size declines, high-relief dunes of sand-bed rivers give way to low-relief bedforms generating little form drag, so that boundary shear stress is utilized maximally for sediment transport, prompting higher transport efficiency. Field evidence demonstrates that the high sediment load in a silt-sand system can coincide with a distinct change in bedform geometry (17). The transition between upper-regime plane bed and dune fields should also represent a discontinuous change related to hydraulic factors and grain size.

2. For H2, the FTRT arises where sediment transport makes a transition from a state of coexisting bed load and suspended load transport to predominantly suspension transport. This condition promotes low-relief bedforms, since the bed load necessary to construct large dunes is unavailable (32); hence, H1 and H2 are not mutually exclusive.

3. For H3, since the FTRT shows a remarkable dependence on grain size, a secondary parameter is hidden among factors associated with hydraulics or grain size distribution. Statistical information for grain size higher than first order, for example, the SD, may play an important role as a secondary parameter for demarcation of the 2 regimes of FTRT.

We test H1 with observations, since most of the flume experiments include documentation of bedforms. For this hypothesis to stand, it is necessary to show that high-relief bedforms lead to the EH regime, and low-relief bedforms lead to the GEH regime. However, while high-relief bedforms indeed lead to the EH regime, low-relief bedforms are a necessary but insufficient condition for GEH (Fig. 2A). Thus, H1 is not a complete explanation for the FTRT. Low-relief bedforms increase the effective shear stress for sediment transport; however, it may be that this condition is a consequence of augmented sediment transport rather than the cause.

The correspondence between bedform relief and transport regime, or lack thereof, sheds light on other possible hypotheses (H2 and H3). Several studies show that, when the ratio of suspended to total load is enhanced, high-relief bedforms give away to low-relief bedforms and a transition to upper-regime plane bed (32–34). However, upper-regime plane bed can also arise from bed load sheet flow in the absence or near-absence of suspended load (35, 36). This is another line of evidence indicating that low-relief bedforms define a necessary but insufficient condition for high ratio of suspended to total load. The implication is that the GEH may be linked to a high ratio of suspended to total load, as predicted in H2.

To test H2, we seek clues from theoretical and experimental studies. Theoretically, in order to suspend a sediment particle directly from the bed surface, the suspension number ($Z_g = \nu / \nu_f$, where $\nu_f$ is the settling velocity of the median bed material size) should be much greater than 2.5 (37). The widely adopted criterion, $Z_g > 3$, lacks justification (38). Nonetheless, a first test of this criterion shows that this value gives a lower bound for the transition to predominantly suspended load. $Z_g > 3$ is indeed necessary for the transition from EH to GEH, but the low-efficiency (EH, blue) and high-efficiency (GEH, red) points overlap in the range $3 < Z_g < 4$ (Fig. 2B). Notably, variation of $Z_g$ is largely controlled by grain size (settling velocity); therefore, this level of overlap cannot be simply explained by the experimental uncertainties, because the grain size can be well constrained in the experiments. Thus, an additional parameter is necessary to separate the 2 regimes.

For H3, we use laboratory data to identify primary and secondary parameters that can separate the high- (GEH) and low-efficiency (EH) transport regimes. Upon evaluating 13 dimensionless numbers (SI Appendix, Table S2), we find that the suspension number $Z_g$ (Fig. 2C) and the dimensionless grain size $D^* = (D_{50}/\nu_f)^{1/3}$ (SI Appendix, Fig. S3), where $\nu$ is kinematic viscosity (square meters per second) gives first-order controls on the FTRT. However, these 2 numbers are somewhat equivalent in their capacities to separate the 2 regimes, because variation of $Z_g = \nu / \nu_f$ comes mostly from the settling velocity, which is, in turn, dictated by grain size; either may be used, but combining them does not improve predictive capability. We show results of both candidates later on. The only other term which contributes to a separation between the 2 regimes is the gradation coefficient, that is, $\sigma = (D_{84}/D_{16})^{1/3}$, which scales the SD of the bed grain size distribution. Thus, bed sorting plays a role in determining the FTRT. Specifically, $Z_g$ or $D^*$ offers first-order control on the FTRT, and $\sigma$ (grain sorting or uniformity) offers second-order control (H3).

Using both laboratory and field data, we present the $Z_g = \sigma$ regime diagram demarcating the transition (Fig. 2C). Note that the transitional value of $Z_g$ ranges from a high of 9.5 for uniform sediment (EH regime) to a low of 3.0 for GEH. Equivalently, we show a $D^* = \sigma$ regime diagram demarcating the transition. The transitional value of $D^*$ varies from 2.05 to 3.91 (D ranges from 81 $\mu m$ to 154 $\mu m$ for quartz in water on Earth) as $\sigma$ varies from 1 to 2 (SI Appendix, Fig. S3). The principle used to develop the $Z_g = \sigma$ and $D^* = \sigma$ diagrams follows a criterion such that the diagram should minimize the number of statistical errors when predicting which transport regime each case belongs to.

The 2-parameter $Z_g = \sigma$ regime transition criterion can be collapsed into a single criterion by using the entire grain size distribution. Let $f_{GSD}(D)$ denote the probability density function (PDF) of bed material grain size $D$. In many rivers with beds of sand and finer material, and, in particular, in the case of the lower Yellow River, this distribution can be approximated as log-normal (SI Appendix, Fig. S4), so that $\sigma$ becomes synonymous with the geometric SD (39–42). For any given bed grain size distribution, the average value of the suspension number, here termed $Z_{eff}$, can be defined as $Z_{eff} = \int f_{GSD}(D)u^*/\nu_f(D) dD = u^*/\nu_f(D)$, where the effective fall velocity $\nu_f(D)$. Data analysis reveals a critical suspension number $Z_{eff} = 9.0 \pm 0.6$, such that the GEH regime prevails when $Z_g > Z_{eff}$, and the EH regime prevails when $Z_g < Z_{eff}$ (Fig. 2D and SI Appendix, Fig. S5). The fact that the FTTRT is highly dependent on the critical transport number supports H2, namely, that the FTTRT corresponds to a transition between coexisting bed load and suspended load transport (EH) and predominantly suspension transport (GEH).
effect of gradation is such that poorly sorted sediment facilitates a transition from mixed bed and suspended load to a suspension-dominated mode at a higher median grain size $D$ or a lower median suspension number $Z_{eff}$ within the transitional range ($D = 81$ to 154 μm or $Z_{eff} = 3$ to 9.5). The critical suspension number can also explain why the 2 regimes cross at high stresses in Fig. 1. At such a high stress, $Z_{eff}$ is likely to exceed $Z_{eff,c}$ and thus the 2 regimes would merge into the GEH regime (SI Appendix, Text S3 and Fig. S24).

**Universal Fine-Grained Sediment Transport Equation**

We now join the EH and GEH formulations into a Universal EH relation (UEH) for fine-grained bed rivers (silt to sand bed). Based on Eq. 1 and Fig. 2D,

$$C_{df}^* = \alpha \tau^{-n},$$

$$((\alpha, n)_{EH} = (0.05, 5/2) \text{ when } Z_{eff} < Z_{eff,c}$$

$$((\alpha, n)_{GEH} = (0.9, 5/3) \text{ when } Z_{eff} \geq Z_{eff,c})$$

where $Z_{eff} = \int_{fGSD(D)u^*/v_s(D)dD = u^*/v_{s,eff}}$ and $Z_{eff,c} = 9.0$. $fGSD(D)$ is the PDF of bed grain size and $v_{s,eff} = 1/fGSD(D)/v_s(D)dD$. In alternative forms, Eq. 2B can be written by defining the transition based on either $Z_{eff}$ or $D^*$ (Fig. 2C and SI Appendix, Fig. S3). In the $Z_{eff} = \beta_D$ diagram, $Z_{eff} < f_D(\sigma_D)$ for EH ($\alpha = 0.05$, $n = 5/2$) and $Z_{eff} > f_D(\sigma_D)$ for GEH ($\alpha = 0.9$, $n = 5/3$), where

$$f_D(\sigma_D) = \begin{cases} 3 & \sigma_D > 2 \\ 21.06 - 9.3\sigma_D & 1.3 \leq \sigma_D \leq 2 \\ 9.5 & \sigma_D < 1.3 \end{cases}$$

In the $D^* = \beta_D$ diagram, $D^* > f_D(\sigma_D) = 2.05 + 1.85/\{1 + \exp[-10(\sigma_D - 1.75)]\}$ for EH ($\alpha = 0.05$, $n = 5/2$) and $D^* < f_D(\sigma_D)$ for GEH ($\alpha = 0.9$, $n = 5/3$).

We test this formulation against our databases (Fig. 3), in which almost all of the data are independent of those used in the GEH and EH formulations. Results (Fig. 3 and SI Appendix, Table S3) show that the proposed universal sediment transport equation is roughly accurate to within a factor of 2 for any scale (geometric SD of discrepancy ratio less than 2), flow condition, and grain size, over 7 orders of magnitudes in Einstein number $q_s^*$. Such a strong agreement cannot be obtained using other formulations (SI Appendix, Text S1, Fig. S6, and Table S3), and no previous relations for fine-grained rivers (13, 17, 25) incorporate the FTRT.
In Situ Measurements of Regime Transition

Rivers impacted by dams are likely locations to observe an FTRT, because the channel bed downstream tends to coarsen as fine sediment is winnowed out by clear water. We provide a case study from the lower Yellow River of China, where Sanmenxia Dam was constructed in 1960 and Xiaolangdi Dam was constructed in 1999 (SI Appendix, Fig. S7).

For Sanmenxia Dam, most of the upstream sediment was retained in the reservoir, so that water released was relatively clear. Over several years, the channel bed at Huayuankou (located ~275 km downstream) coarsened from \( D_{50} \approx 70 \) μm to \( D_{50} \approx 300 \) μm. As sediment from the Loess Plateau (SI Appendix, Fig. S7) filled the reservoir rapidly, sediment bypassing was implemented in 1968. By the 1970s, the bed at Huayuankou recovered to its predam grain size composition (\( D_{50} \approx 70 \) μm) (43). Clear water releases are conducted yearly at Xiaolangdi Dam as part of the Water and Sediment Regulation operation, to degrade the bed and lower downstream flood stage. As a result, the bed at Huayuankou (~150 km downstream of Xiaolangdi Dam) again coarsened from \( D_{50} \approx 70 \) μm to currently \( D_{50} \approx 200 \) μm (ref. 44 and SI Appendix, Table S4). Our FTRT criteria predict that such changes in bed material size will result in alternation of the lower Yellow River between regimes of high (GEH) and low (EH) sediment transport efficiency.

Indeed, the FTRT is reflected in the order of magnitude variations in sediment transport rates measured at Huayuankou (Fig. 4): For 1961–1966 (bed \( D_{50} \) 194 to 400 μm) and 2001–2002 (bed \( D_{50} \) 200 to 210 μm), the data unambiguously fall in the EH regime (as predicted by UEH, i.e., Eq. 2). Comparatively, for 1980–1990 (bed \( D_{50} \) range 30 to 158 μm), the data fall in the GEH regime (as predicted by UEH). Therefore, our analyses indicate that there were 3 regime transitions induced by Sanmenxia and Xiaolangdi Dam operations: in the 1960s, GEH→EH due to Sanmenxia Dam construction; in the 1970s, EH→GEH due to the sediment bypass of Sanmenxia Dam and the recovery of the lower Yellow River to a silt-sand bed state; and lastly, in the late 1990s, GEH→EH due to Xiaolangdi Dam construction. The sediment transport data collected at Huayuankou in 2001 and 2002 (i.e., 2 to 3 y after Xiaolangdi Dam; SI Appendix, Table S4) are in the EH regime, corresponding to rapid coarsening of the channel bed following dam construction.

**Discussion**

The FTRT corresponds to a critical suspension number \( Z_{eff,c} = 9.0 \), which satisfies the theoretical condition \( Z_{eff,c} >> 2.5 \) for direct suspension of bed particles (37). This finding indicates that the FTRT corresponds to a transition from mixed bed load and suspended load transport (EH) to suspension-dominated transport (GEH) (Fig. 2B). Experiments indicate that fine particles sheltered by large roughness structures can be directly entrained into a fluid without passing through a bed load layer, when the local viscous sublayer is penetrated by turbulent sweeps (45), indicating that the phenomena hypothesized to correspond with GEH indeed exists. The case where upper-regime plane bed is associated with the EH regime (low efficiency) can be explained by the presence of a substantial bed load layer, for example, an intense salination layer or sheet flow. This would lower overall suspension in 2 ways: 1) extracting momentum and dissipating flow energy, thus lowering the mean shear stress at the fluid/bed load layer interface, and 2) diluting the sediment concentration at this interface relative to the underlying bed (35, 36). Alternatively, as the bed sediment becomes sufficiently fine, turbulent flow may become strong so that bed particles can be directly suspended into fluid without a bed load transitional layer (GEH).

There are limits to the UEH. First, the UEH, like other sediment transport formulae, is applicable for equilibrium transport of bed material load. Further developments are needed to describe nonequilibrium transport (46, 47). Second, the UEH relation has no critical shear stress and is not designed for the case of bed load only. This may explain the deviation between UEH and laboratory data, where very low sediment flux was observed (Fig. 3). Third, scatter may originate from inherent uncertainties associated with the flume and field data. The major uncertainties in the flume experiments include channel slope and bedform characterization. Moreover, difficulties in the measurement of bed material grain size, in both flume and field, may impede accurate discernment of bed material load. Fourth, the database compiled here comprises noncohesive sediment transport under turbulent flow conditions. Cohesive and hyperconcentrated sediment transport (48–50) is not considered. Sediment cohesion can reduce sediment entrainment (51, 52) and thus may reduce transport fluxes from those predicted by UEH.
Conclusions
Sediment transport flux in fine-grained rivers does not vary smoothly as grain size increases. Instead, there exists a discontinuity in the range of very fine sand (81 to 154 μm) where sediment load decreases by 1 to 2 orders of magnitude (FTRT). The high-efficiency regime (GEH) has been observed in large rivers and canals, and is also present in experiments where the bed material is silt to fine sand. Theoretical and data analyses indicate that the FTRT corresponds to a transition in the sediment transport mode from suspension-dominated (GEH) to a mixed bed load and suspended load regime (EIH). A dynamic transition between the high- and low-efficiency regimes, mediated by dam operation, has been observed 3 times within the Yellow River, China. Our UEH sediment transport relation, validated for fine-grained rivers with grain sizes varying from 11 μm to 1080 μm, incorporates this FTRT.

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