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Transient response in longitudinal grain size to reduced gravel supply in a large river

Michael Bliss Singer[1,2]

[1]School of Geography and Geosciences, University of St Andrews, Irvine Building, North Street, St Andrews, KY16 9AL, UK*

[2]Institute of Computational Earth System Science, University of California Santa Barbara, Santa Barbara, CA 91306, USA

ABSTRACT

The first extensive dataset on subaqueous bed material grain size in a large river subject to reduced sediment supply is investigated alongside bathymetry, modeled flow, and sediment flux. Results suggest that following sediment supply decline and a shift to a finer sediment supply, the gravel-sand transition (GST) in fluvial systems extends and subsequently migrates upstream. The non-abrupt (~125 km) GST in the Sacramento River corresponds with a hump in the long profile, indicating recent downstream redistribution of sediment that impacts grain sizes. The hump is composed of sediments winnowed from upstream gravel beds that accumulate downstream where slope declines. This increases local sorting values and coarse sediment flux rates in the GST, leading to further gravel loss by burial and net efflux. Thus, in a transient response to sediment supply changes, whether anthropogenic or natural, the GST extends upstream as a longitudinally patchy bed modulated by bedload sheet transport that favors the loss of gravel.

INTRODUCTION

Longitudinal grain size in fluvial systems generally declines exponentially downstream (if lateral sediment sources are insignificant) until fine grains overwhelm gravels in a zone of low shear stress [*Ferguson*, 2003]. There an abrupt gravel-sand transition (GST) forms in a fixed position, which has been identified in worldwide datasets [*Gomez et al.*, 2001; *Sambrook Smith and Ferguson*, 1995; *Yatsu*, 1955], in laboratory simulations [*Sambrook Smith and Nicholas*, 2005], and by numerical modeling [*Cui and Parker*, 1998; *Ferguson*, 2003]. These and other studies confirm the existence and persistence of an abrupt GST in fluvial systems with constant and/or relatively high sediment supply. However, other research investigating the impact of sediment supply on river beds suggests that grain size change is a first-order response to shifts in magnitude and caliber of supply [*Dietrich et al.*, 1989; *Iseya and Ikeda*, 1987], which creates internal feedbacks between grain size, sediment transport, and channel morphology. These factors and simple modeling of GST sensitivity to boundary conditions [*Cui and Parker*, 1998; *Ferguson*, 2003; *Paola et al.*, 1992] imply that the location of the abrupt GST will not persist following changes to sediment supply [*Knighton*, 1999]. A fluvial system which is not at grade (i.e., where slope is not adjusted to sediment supply), may be used to investigate system response to such perturbations [*Hoey and Bluck*, 1999]. This paper presents an investigation of a bed material grain size dataset collected in a river that has undergone major supply decline recently due to anthropogenic activity and therefore serves as a natural laboratory in which to explore the character and evolutionary processes of the GST following a recent and dramatic decline in sediment supply.

Prior research presented a new dataset of subaqueous bed material sediment extracted from the Sacramento River [*Singer*, 2008a], California and identified patterns in longitudinal grain size that diverge strongly from other published studies: separate fining trends in median grain size (d_{50}) for gravel and fines overlap for ~175 km, thus creating longitudinal patchiness in alternating gravel and fine reaches and consequently, a protracted GST (this study conservatively restricts the GST to 125 km). This work was framed within the broader context of grain size adjustment to naturally low sediment supply (due to basin shape and tectonic setting) that was aggravated in the last 60 years by anthropogenic impacts to the river basin (e.g., dams, aggregate mining, bank protection) that have mostly reduced the gravel supply.

This paper interrogates the full bed material dataset from the Sacramento River alongside high-resolution bathymetry, output from hydraulic modeling, sediment budget calculations, and bed-material flux estimates to assess the variables controlling longitudinal grain size, as well as the sediment transport processes and the evolutionary trajectory of the protracted GST. This work analyzes the first field dataset capable of addressing a question that has been thus far restricted to flumes and models. The results have broad relevance to studies of landscape evolution in response to external forcing, sediment transport dynamics and their impact on river channel adjustment, sedimentary geology, as well as to engineering and aquatic habitat in large, managed rivers worldwide.

METHODS

Extraction of bed material and the field campaign/laboratory analysis to obtain grain size distributions are described elsewhere [*Singer*, 2008a; *Singer*, 2008b]. In summary, point-based surface samples collected from 1-3 locations (depending on river width) within cross sections spanning ~400 river kilometers were selected between river bends to minimize cross-stream topography. They were dried, sieved, weighed, and aggregated to obtain section samples (n=107) that satisfied the criterion whereby the largest particle comprised <5% of the total mass [*Mosley and Tindale*, 1985]. The field campaign was carried out over a two-year period with no intervening high flow events, so the data are assumed to be representative of low flow conditions, where fine sediments may be marginally more prevalent due to decreases in high flows by dams.

Long profiles, local bed slope, and bed curvature were obtained for each sampling location by extracting thalweg elevations from US Army Corps of Engineers (USACE) and California Department of Water Resources (CDWR) ~0.6-m resolution bathymetric surveys. Hydraulic data were extracted from unsteady, 100-year return-interval flood simulations over this bathymetric data conducted by the CDWR and USACE (http://www.compstudy.net/). Grain size characteristics were computed by logarithmic method of moments within GRADISTAT software [*Blott and Pye*, 2001].

To obtain local estimates of transport, I used grain size data and hydraulic model output within the Singer and Dunne [2004] bed material formula, which is a modified form of the Engelund-Hansen formula calibrated to bedload and bed material data from a range of fluvial environments, acknowledging that fractional sediment transport is strongly dependent on local bed material grain size:

$$qs_i = \alpha \frac{\rho_s U^2 (\tau^* - \tau_c^*) \sqrt{\tau_i^*} \sqrt{\left(\frac{\rho_s}{\rho} - 1\right) g d_i^3}}{2ghS} F_i \qquad (1)$$

where qs is unit transport rate for a particular grain size class (subscript i), ρ_s is sediment density, U is velocity, τ^* is Shields stress, $\rho ghS/[(\rho_s - \rho)gd_{50}]$, whose critical value τ^*_C is assumed to be 0.047 (results from (1) at high shear stresses are insensitive to the chosen value of τ^*_C [*Singer and Dunne*, 2006]), ρ is water density, g is gravitational acceleration, d is characteristic grain size for a particular size class, h is flow depth, S is water surface slope, and F is fraction within a grain size class. α, the calibration parameter, is computed as a function of local sorting and hiding [*Singer and Dunne*, 2004]. This method is sensitive to surface grain size similar to Wilcock and Crowe [2003], but is more responsive to relative values of sorting and hiding, rather than to the influence of sand percentage on flux. I calculated fractional sediment flux at all cross sections for full φ sizes ranging from 0.125 mm to 128 mm, computed based on their local availability. I present the results from a 100-year recurrence interval flow simulation, which represents conditions that reset the bed, though the relative results are not markedly different for a 50-year recurrence interval flow.

RESULTS

Figure 1 shows that sorting becomes progressively poorer (increases) and peaks over a broad area that coincides with the GST, as bed slope declines and flow depth rises. Average sorting (σ_φ) increases from 1.4 upstream of the GST to 2.1 within it, and then declines to 0.8 downstream of it (Tab. 1), highlighting the mixing of two distinct sediment populations in the GST [*Singer*, 2008b]. Poor sorting in the GST is also reflected in size distributions that are skewed fineward with low kurtosis, and d_{10}, d_{50}, and

d_{90} finer than in upstream sections (Tab. 1). These indicators are directly related to low pocket angles and thus ease of transport for a wide range of grain sizes [*Buffington et al.*, 1992], which when coupled with biomodality promotes the development of patches and sediment transport as bedload sheets [*Paola and Seal*, 1995; *Whiting et al.*, 1988].

It has been suggested that concomitant declines in both shear stress (τ) and σ_φ lead to an abrupt GST [*Ferguson*, 2003]. The Sacramento data reveal that σ_φ does not decline with τ in the GST, but in fact increases as τ declines between river kilometers (RK) 345 and 280 (Fig. 2). This increase in sorting is spatially consistent with longitudinally patchiness, as fines intermittently depress d_{50} into the sand range. This alternation of gravel and fines is consistent with observations of pulsed sediment transport in 'transitional' reaches [*Iseya and Ikeda*, 1987], and suggests that small areas convey large proportions of the total bed load, which is expected in sediment-poor channels with low mobility [*Lisle et al.*, 2000]. Fig. 2 also shows that while τ is correlated with reach-averaged net sediment flux (i.e., erosion for constant τ and deposition for declining τ), σ_φ does not exhibit such coupling, indicating non-hydraulic factors control grain size in the GST.

Figure 3(A) shows that local bed slope declines monotonically with distance until RK 390, where it flattens upstream of the GST. Throughout the GST, average local slope is less than half the value of upstream sections (Tab. 1) and declines 3-fold within the GST. This is more clearly exhibited as a marked increase (~10^4) in local bed curvature between RK 340 and 240 (Fig. 3B and Tab. 1), which slows the fining rate [*Inoue*, 1992]. The GST can be characterized topographically by three segments: RK 345-280 is concave (up); RK 280-260 is increasingly convex; and RK 260-240 is a zone of maximum curvature. Curvature is echoed (with a small phase shift) by a rise in τ^* beginning near RK 270, and by an abrupt decrease in width (Fig. 3C & D), perhaps associated with a loss of gravel bars. The rapid changes in width and τ^* are spatially correlated with a progressive decline in gravel flux, which is otherwise uncharacteristically high through the GST (Fig. 3E). The stepwise, yet gradual increase in τ^* across the GST is new in that the value is usually assumed to be bimodal in rivers (e.g., ~0.1 for gravel v. ~1-2 for sand beds). Flux rates for fines and gravel are far higher within the GST than outside it, and the ratio of fine to coarse sediment flux is ~10^3 upstream of the GST, but only ~10^1 within it. Critically, fine sediment flux (*qsF*) is very high in coarse sections upstream of the GST, indicating a process of winnowing that is supported by local erosion up to 3.5m observed over the last few decades (Fig. 2). Coarse sediment flux (*qsC*) is highest in fine sections, consistent with the idea that gravel flux is augmented by the presence of fines [*Wilcock and Crowe*, 2003].

DISCUSSION

The results presented here describe a transient fluvial system, wherein a change in boundary condition (sediment supply) leads to internal instability (protracted GST). An overall reduction and a fineward shift in sediment supply over the last ~60 years due to anthropogenic impacts have led to upstream winnowing, which coarsened upstream beds relative to their downstream counterparts (Tab. 1) and created sedimentary congestion (<30% fines, Fig. 4). The fine material evacuated from these beds combines with small and relatively fine bed material loads from tributaries [*Singer and Dunne*, 2004] to create fine deposits downstream, where net aggradation results in a topographic hump (Fig. 3, Tab. 1). This accumulation of fine material disrupts downstream trends in surface grain size, fills in the interstices of gravel (Fig. 4) and accelerates its evacuation [*Iseya and Ikeda*, 1987] through increases in near-bed velocity and drag on coarse particles [*Sambrook Smith and Nicholas*, 2005]. The presumed formerly abrupt GST (i.e., RK 260-220) is punctuated by a short congested (<30% fines) gravel reach (RK 280-260) at its upstream end and by a smooth (>50% fines) reach downstream. It becomes obscured by fine accumulation between RK 345 and 280, which creates a transitional (30-50% fines) reach of gravel and sand sections (Figs. 2 & 4). These are accompanied by order-of-magnitude local bed slope oscillations (Fig. 3A) and suppression of τ^* that slowly increases in the GST (Fig. 3D) in contrast to previous work [*Parker et al.*, 2007]. This transitional reach of the river is the most poorly sorted and therefore the least adjusted in terms of slope to sediment supply [*Paola and Seal*, 1995] (Fig. 2), where fine-grained longitudinal patchiness is aided by relatively high channel width (Fig. 3C) [*Toro-Escobar et al.*, 2000]. Here pulsed sediment transport corresponds to changing availability of bed materials induced by longitudinal sorting [*Iseya and Ikeda*, 1987] and flux occurs as bedload sheets (Fig. 4, based on $d_{90}/d_{10} > 4$ [*Nelson et al.*, 2009]), preferentially depleting this reach of gravel that is not replenished from upstream. Similar processes occur in the former GST (RK 260-220), but the two regions are separated by a congested reach where sediment flux is low (Fig. 3E).

Effectively, these factors have extended the GST upstream to RK 345 (from ~40 to ~125 km). However, this is not expected to last. As long as relatively low gravel supply persists, the fines delivered from upstream will replace the remaining gravels and will smooth the long profile. Ultimately, the fines accumulating in the transitional reach (RK 345-280) will migrate downstream and further encroach on the congested gravel reach (RK 280-260) until the two fine regions are linked and the long profile is smoothed, facilitating transport that re-segregates gravel and fines longitudinally. At this point, the GST will have shifted upstream by tens of kilometers, though its precise delineations and the timing of its coalescence are subject to speculation.

Ferguson [2003] has described the abrupt GST as an emergent phenomenon in fluvial systems that is not dependent on initial or boundary conditions. Although this may be true, changes in boundary conditions apparently lead to transience that obscures the GST and has the potential to shift its location. Indeed, Ferguson [2003] anticipated this by demonstrating the GST forms farther downstream with larger d_{50} of sediment supply and Knighton [1999] presented a downstream shift associated with sediment supply increase. Research on the impact of sediment supply on the interplay between bed state and transport has identified discontinuities in longitudinal grain size and flux rates [*Iseya and Ikeda*, 1987] and the development of bedload sheet (or grain-size segregated) sediment movement associated with patches [*Nelson et al.*, 2009]. However, instead of coarse patch expansion compared with fine, mobile ones in response to supply reduction [*Dietrich et al.*, 1989], the data presented here suggest that as the grain size distribution shifts fineward with supply reduction, fine patches may expand disproportionately with gravel burial and net gravel efflux.

These new observations suggest that the character of the GST may change in a transient way, depending on changes in factors exogenous to the drainage basin, including sediment supply (natural or anthropogenic) and/or climate, which in turn may affect the caliber of sediment supply. This occurs as a loss of GST coherence and its subsequent reforming at a new location, wherein hydraulics and slope also readjust to the imposed supply. Thus, detection of the character and behavior in the GST may be diagnostic of basin-scale perturbations that impact long profile development, basin-scale sediment budgets, depositional environments, aquatic habitat, and flood risk.

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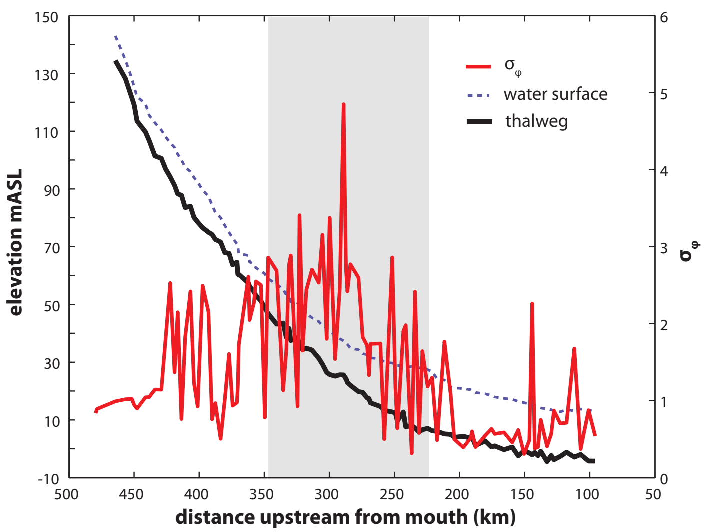
FIGURE CAPTIONS

Figure 1. σ_φ and elevation v. distance. GST is indicated by gray rectangle (for Figs. 1-3).

Figure 2. d_{50}, τ, and σ_φ v. distance. Gaps in τ are due to a flattening or negative value of S. Reach-averaged erosion/deposition from Singer and Dunne [2004]. General trends in τ shown in dash lines. Long-term change at USGS gauges (black dots) obtained from http://waterdata.usgs.gov/nwis/.

Figure 3. Channel bed slope (A), curvature (B), width (C), τ^* (D), d50 and sediment flux (E) v. distance. Smoothed curves obtained by robust LOWESS fits in Matlab (span = 0.25). Gaps in E indicate no flux based on grain size and hydraulics.

Figure 4. d_{90}/d_{10} and % fines v. distance.



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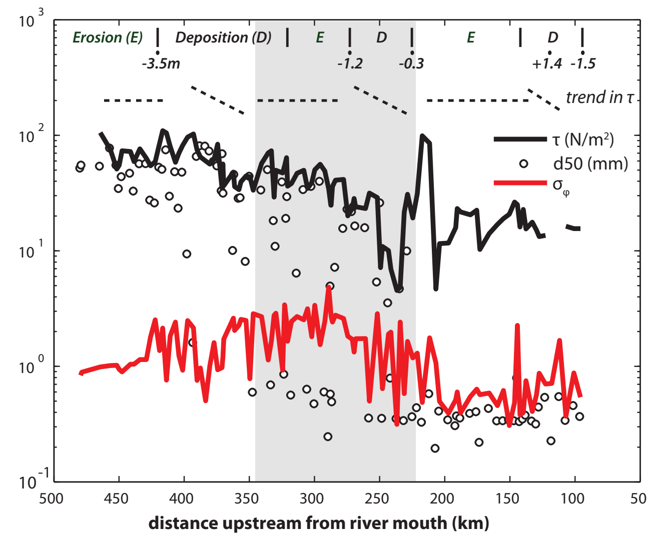

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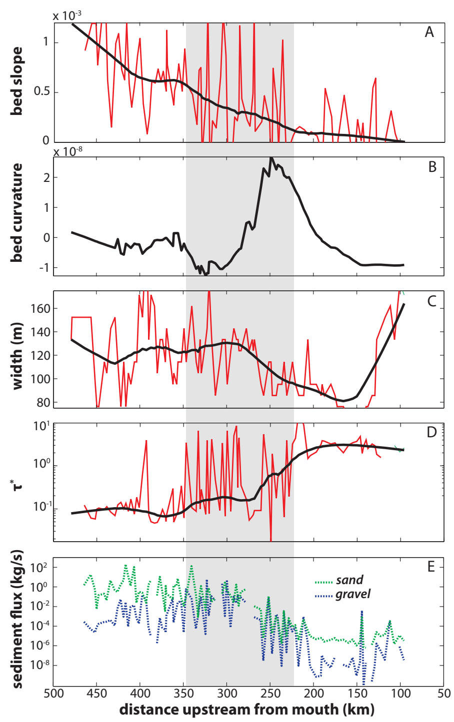

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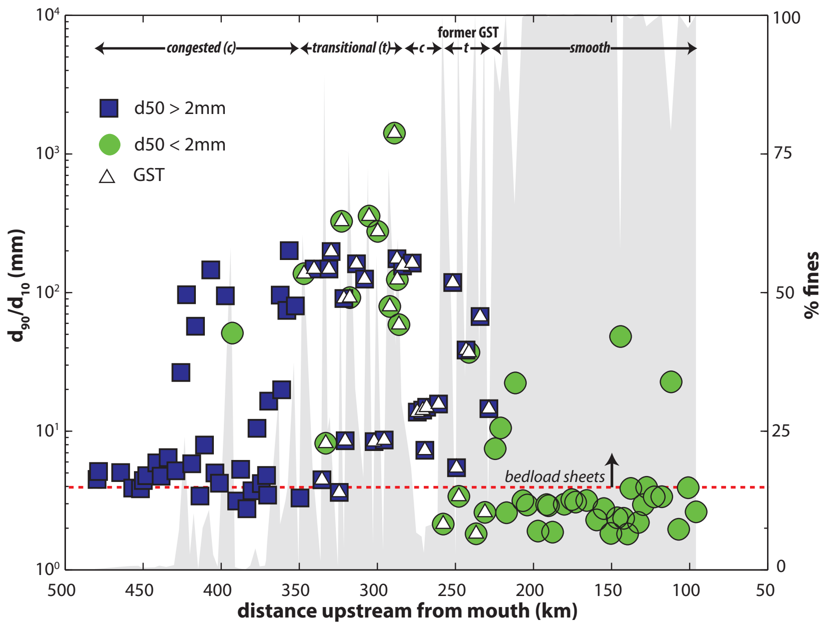

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TABLE 1. GRAIN SIZE, CHANNEL CHARACTERISTICS, HYDRAULICS, AND SEDIMENT FLUX†

Cross Section	d50 (mm)	d90 (mm)	d10 (mm)	σ_φ	Skew	Kurtosis	Fines (%)	Width (m)	Slope	Curvature	τ (N/m^2)	τ*	qsF (kg/m/s)[§]	qsC (kg/m/s)[#]
GST (all) (n=39)	13.35	42.13	2.79	2.09	0.75	7.2	38.1	120.4	3.68E-04	-5.24E-10	28.6	1.33	3.10240	0.32330
Non-GST (all) (68)	24.81	54.79	9.09	1.12	1.31	14.4	47.7	113.5	4.15E-04	-9.95E-10	38.9	0.80	4.80260	0.00570
GST (fine) (15)	0.55	17.93	0.21	2.03	-0.54	8.2	75.6	112.3	5.27E-04	-6.19E-08	30.3	3.50	0.07940	0.86810
Non-GST (fine) (32)	0.42	1.75	0.22	0.78	0.29	13.4	94.6	104.2	5.22E-05	4.45E-09	11.4	1.53	0.00072	0.00140
GST (coarse) (24)	20.51	55.69	4.23	2.13	1.47	6.7	17.2	125.0	2.79E-04	3.39E-08	27.6	0.11	4.79530	0.01820
Non-GST (coarse) (36)	46.49	101.94	16.96	1.41	2.22	15.2	6.0	121.7	7.56E-04	-6.28E-09	64.9	0.12	9.07090	0.00950

[†] values determined from distributions use mean as the measure of average (since they are already nonparameterized); all others are median values reflecting their non-normality

[§] fine (d < 2mm) sediment flux is computed fractionally based on local grain size distribution and hydraulics

[#] coarse (d ≥ 2mm) sediment flux is computed fractionally based on local grain size distribution and hydraulics

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