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Sediment dynamics across gravel-sand transitions: Implications for river stability and floodplain recycling

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ABSTRACT

The gravel-sand transition (GST) is commonly observed along rivers. It is characterized by an abrupt reduction in median grain size, from gravel- to sand-size sediment, and by a shift in sand transport mode from wash load–dominated to suspended bed material load. We documented changes in channel stability, suspended sediment concentration, flux, and grain size across the GST of the Karnali River, Nepal. Upstream of the GST, gravel-bed channels are stable over hundred- to thousand-year time scales. Downstream, floodplain sediment is reworked by lateral bank erosion, particularly during monsoon discharges. Suspended sediment concentration, grain size, and flux reveal counterintuitive increases downstream of the GST. The results demonstrate a dramatic change in channel dynamics across the GST, from relatively fixed, steep gravel-bed rivers with infrequent avulsion to lower-gradient, relatively mobile sand-bed channels. The increase in sediment concentration and near-bed suspended grain size may be caused by enhanced channel mobility, which facilitates exchange between bed and bank material. These results bring new constraints on channel stability at mountain fronts and indicate that temporally and spatially limited sediment flux measurements downstream of GSTs are more indicative of flow stage and floodplain recycling than of continental-scale sediment flux and denudation rate estimates.

INTRODUCTION

Downstream of mountain ranges, riverbed sediment fines as channels flow onto lower-gradient and laterally unconstrained landscapes (Sternberg, 1875). Sediment fining is a key component of sediment transport that underpins the dynamic nature of rivers and is central to fluvial geomorphology and the depositional record it constructs. Downstream fining is attributed to size-selective sediment sorting (e.g., Ashworth and Ferguson, 1989; Paola et al., 1992a; Ferguson et al., 1996) and the mechanical breakdown (abrasion) of particles (e.g., Parker, 1991; Attal and Lavé, 2006; Dingle et al., 2017). Rivers commonly exhibit an abrupt transition in bed grain size, from gravel to sand, over a short downstream distance (e.g., Shaw and Kellerhals, 1982; Ferguson et al., 1996), termed the gravel-sand transition (GST). The development of GSTs has been attributed to a combination of size-selective sorting (e.g., Paola et al., 1992b; Wathen et al., 1995; Ferguson et al., 1996; Seal et al., 1997; Parker and Cui, 1998), abrasion of particles (e.g., Jerolmack and Brzinski, 2010), and abrupt changes in Reynolds number–dependent sediment suspension thresholds (e.g., Venditti and Church, 2014; Lamb and Venditti, 2016). There is no generally accepted or universal theory for why GSTs develop.

Across GSTs, observed changes in channel morphology may help to elucidate sediment transport adjustments and hint at possible causal mechanisms. Upstream of the GST, channels are typically mobile only at high flows (Dong et al., 2019). Downstream, channels are lower-gradient and generally lower-energy environments, but they can be highly mobile when transporting large sediment loads (Montgomery et al., 1999). A reduction in channel gradient is also commonly observed at the GST (Sambrook-Smith and Ferguson, 1995; Ferguson, 2003), which, for stable channel conditions, should reduce sediment transport capacity. Progress in understanding how sediment transport adjusts across GSTs is limited by a paucity of direct observations.

In this paper, we tested for changes in sediment transport and channel mobility across a GST in the Karnali River, Nepal. We documented the sediment and channel dynamics at a range of time scales, including daily (suspended sediment samples), decadal (channel migration rates and patterns from satellite imagery), and centennial to millennial scales (dating of paleochannels). We complemented these observations with calculations of sediment entrainment thresholds and frequency of bed mobility based on hydrological records to constrain time scales of channel mobility.

Karnali River

The Karnali basin has a drainage area of 43,000 km^2 at the Himalayan mountain front. Its climate is dominated by the Indian summer monsoon between May and September, when the majority of annual water and sediment discharge occurs (Sinha and Friend, 1994). At the mountain front, near the town of Chisapani, the river exits a confined bedrock gorge and flows onto the alluvial Ganga Plain, where it bifurcates into two branches (Fig. 1). At moderate flow in August 2017 (~4500 m^3/s), discharge was observed to split between the two branches equally. The GST is ~40 km downstream of the mountain front, where there is a gradient break in the longitudinal river profile (Fig. DR1 in the GSA

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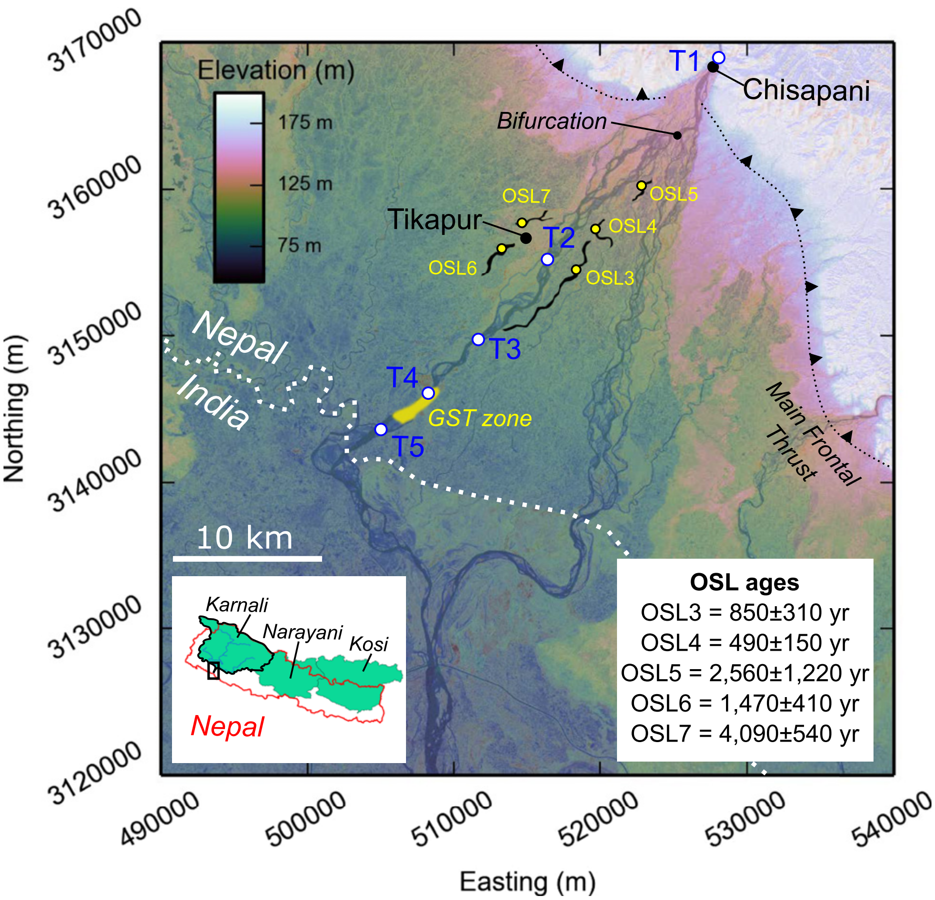

Figure 1. Study area showing suspended sediment sampling locations (T1–T5) and gravel-sand transition (GST) zone on Karnali River, Nepal. Paleochannels (black lines) on fan and optically stimulated luminescence (OSL) locations and dates are labeled (see the Data Repository [see footnote 1] for full methods). Data sources: 30 m Shuttle Radar Topography Mission digital elevation model (coordinates in Universal Transverse Mercator Zone 43N) and *Sentinel*-2 satellite imagery (26 October 2016).

Data Repository[1]). Over a distance of ~5 channel widths, the riverbed composition changes from 85% gravel to >95% sand. The gravel reach gradient (0.001–0.002 m/m) is twice that of the sand reach gradient.

METHODS

Suspended sediment concentration and grain size data were collected at five sampling locations (Fig. 1) at four or five different depths, using a horizontal Van Dorn sampler deployed from an inflatable cataraft in August 2017 (see Figs. DR2.1–DR2.5). Instantaneous sediment flux was calculated using two methods to evaluate uncertainty. We first calculated flux as the product of depth-averaged concentration and acoustic Doppler current profile discharge measurement. We also calculated suspended sediment flux from the Rouse equation (see the Data Repository). We regard the Rouse profile method as most reasonable because it uses the concentration data to estimate a profile that roughly fits the observations at lower depths, but it does not incorporate the local and temporal variability inherent with measurements.

Paleochannels were identified on the Karnali fan (Fig. 1) and dated using optically stimulated luminescence (OSL) to determine when the channel was last active within the main channel network (see the Data Repository). To constrain shorter-term rates of channel mobility, satellite imagery was analyzed for a 10 and 16 km reach upstream and downstream of the GST, respectively. Channel positions were mapped from images between 1984 and 2016 for the gravel-bed reach, and between 1975 and 2016 for the sand-bed reach.

The discharges required to move sediment in the gravel and sand reaches were calculated using a model based on the modified Chezy equation (Parker, 2004) and the Shields number (see the Data Repository). For gravel reaches, we used a slope-dependent critical Shield's number (Lamb et al., 2008), and we used a value of 0.03 for sand reaches. Flood event return periods were calculated using gauged flow data fitted to Gumbel and Log-Pearson type III distributions. This assumes a stable climate over the time intervals considered here (10^4 yr) such that the magnitude of a given return-interval discharge is approximately constant. Holocene climate records suggest that the intensity of the Indian summer monsoon has gradually weakened over the past ~8 k.y., but it has been relatively stable since ~5 k.y. (Gupta et al., 2005; Dixit et al., 2014). The return period of our projected discharges may be underestimated at $>10^3$ yr time scales.

Grain size measurements were taken from two gravel surfaces (Fig. DR4; "gravel bar" and "gravel bed") near the bifurcation using photo counting (Attal and Lavé, 2006; Whittaker et al., 2011; see the Data Repository). Measurements were made of sand samples below the GST from material collected from the channel bed (T5) and an adjacent bank (Table DR3).

RESULTS

OSL dating of paleochannels on the gravel fan suggested that these reaches change location through avulsion on time scales of 10^3–10^4 yr (Fig. 1). This is consistent with satellite imagery showing that the gravel channel belt position was stable between 1984 and 2016 (Fig. DR5.1). In contrast, meander migration rates immediately downstream of the GST are up to ~450 m/yr (Fig. DR5.2).

Sand is transported throughout the year (Fig. 2A). Gravel that makes up the bar surfaces in the gravel reach (D_{50} = 65 mm) is moved when discharge exceeds ~5100 m^3/s. This threshold is exceeded annually, based on discharge records. Coarser gravel (D_{50} = 231 mm) on the bed of the dry bifurcation point requires a discharge of ~31,500 m^3/s if the form drag correction (β) is 0.5, which corresponds to a 1-in-7000 yr discharge (Fig. 2B). Increasing β to 0.6 reduces the threshold to ~23,500 m^3/s, which corresponds to a 1-in-500 yr discharge. Values of β reported for gravel-bed channels typically vary between 0.5 and 0.6 (Venditti and Church, 2014).

Suspended sediment samples were collected during a moderate monsoon flow (4500 m^3/s, return interval ~1 yr; Fig. 2B). In the gravel reach (T1 to T4), suspended sediment grain size (Fig. 3A) showed a slight overall downstream decrease and a less prominent reduction in concentration (Fig. 3B). Both showed minor variations with flow depth. In the sand reach (T5), concentration and D_{50} were higher in the lower 20% of the water column compared to the gravel reach, and the vertical gradients were steeper (Figs. 3A and 3B). Suspended sand flux remained comparable between the bifurcation and upstream of the GST at ~0.3–0.4 Mt/d (T2–T4; Fig. 3C). In the sand reach, the instantaneous sediment flux was an order of magnitude higher at ~3.7–4.5 Mt/d.

[1]GSA Data Repository item 2020126, additional details on methods, sampling locations and results, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.

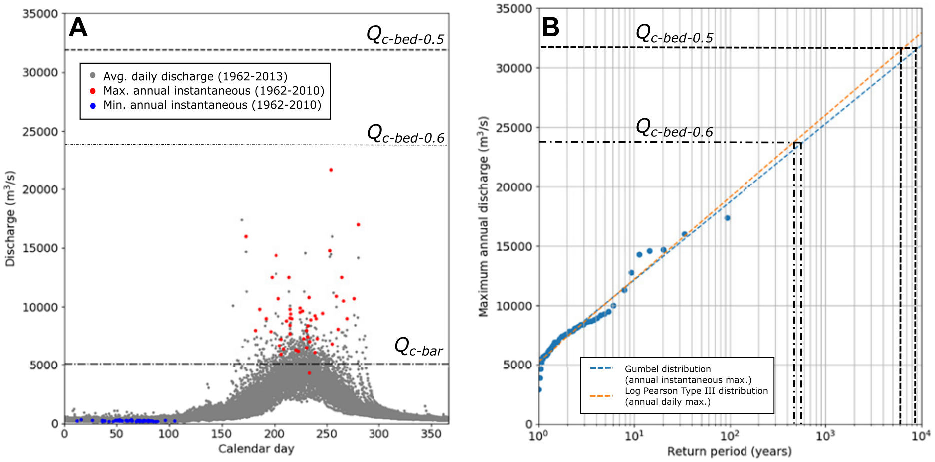

Figure 2. (A) Discharge at Chisapani gauging station (Karnali River, Nepal) from 1962 to 2010 CE. (B) Projected return interval of discharges. Discharges required to mobilize gravel-bar surface ($Q_{c\text{-}bar}$) and median gravel-bed size at bifurcation using β = 0.5($Q_{c\text{-}bed\text{-}0.5}$) and β = 0.6($Q_{c\text{-}bed\text{-}0.6}$), where β is form drag correction used (see the Data Repository [see footnote 1]), are shown. Discharge required to mobilize sand is 3–4 m³/s.

DISCUSSION

Changes in Channel Mobility

Upstream of the GST, there is minimal lateral migration of the channel belt across the floodplain. Major changes in channel configuration in the gravel-bed portion of the river appear to be driven by apex-avulsion (Leddy et al., 1993), where channel thalweg sinuosity drives inner-bend lateral accretion and outer-bend erosion, resulting in cycles of channel plugging and abandoned channel re-occupation. OSL dating and calculations of threshold for gravel-bed entrainment at the bifurcation suggest time scales associated with channel avulsion are ~400–7000 yr. In contrast, downstream of the GST, high rates of channel migration driven by lateral meander migration are enhanced by the presence of a poorly consolidated, low-clay-content floodplain material that is devoid of deep-rooted vegetation. Even under low-flow conditions, both bed and bank material are mobilized, enhancing sand delivery to the bed and lower portion of the water column. Anecdotally, during our 3 hr survey of site T5, we observed the adjacent sand bank retreat by ~3 m. The increase in D_{50} in the near-bed sample at T5 may reflect the fact that material eroded from the bank is coarser than the material carried in suspension through the gravel reach at that time. These coarser sediments may have been transported and deposited under larger flood discharges, in contrast to the conditions under which the channel was sampled. The coarser grain sizes at T5 were absent from samples in T1–T4, suggesting this observation was unlikely to be a simple function of grain size sorting associated with the development of a Rouse-like suspended bed material profile. These combined results suggest that the location of the GST controls channel migration of alluvial rivers downstream of the Himalayan and possibly other mountain fronts.

Temporal Changes in Sediment Transport

The absence of grain size or concentration gradients for profiles collected in the gravel reach suggests that sand is transported there as wash load. The steep concentration and grain size gradients at T5 are consistent with theoretical models indicating this material is sourced from the bed (Rouse, 1936). The significant increase in sediment flux and grain size across the GST (T4 to T5) coincides with observed changes in channel mobility. We infer that the augmented sediment flux in the sand reach is sourced from the banks. The interpretation that sand is no longer transported as wash load at T5 is consistent with wash load deposition patterns modeled by Lamb and Venditti (2016), and direct observations from the Fraser River (Venditti and Church, 2014; Venditti et al., 2019).

Mass continuity dictates that the increase in sediment concentration across the GST cannot be a persistent feature, given the aggrading nature of the Ganga Plain (e.g., Dingle et al., 2016). Our flux estimates were from moderate monsoonal flow conditions. During peak seasonal flow conditions, shorter-lived and more-intense floods occur, during which pulses of sand would be delivered out of the mountains and into the gravel reach. A further increase in suspended sand load within the gravel reach would also be expected due to the breakdown of the bed surface armor layer and associated release of finer matrix material. As flow receded, the gravel bed and banks would no longer be mobile, and sand transport would be reduced through the gravel-bed reach (Fig. 4). Downstream, the sand channel would still be capable of reworking flood-flow deposits (even under lower flows) via lateral channel migration. The increase in sediment grain size, concentration, and instantaneous flux below the GST likely reflects continuous reworking and intermittent

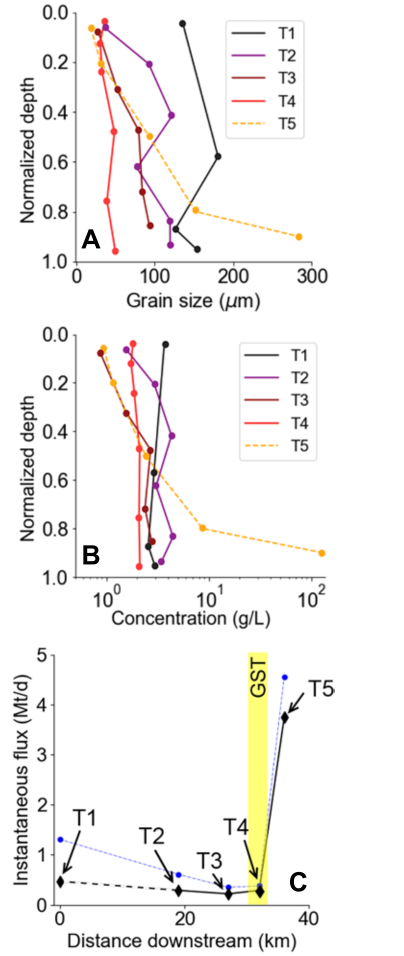

Figure 3. (A) Median grain size at each vertical (Karnali River, Nepal). (B) Suspended sediment concentration at each vertical. (C) Instantaneous sediment flux estimates. Black line and diamonds represent sediment fluxes calculated from depth-averaged Rouse profile concentrations; blue circles and dashed lines represent fluxes calculated from depth-averaged measured concentrations. T1 is upstream of bifurcation, so some sediment is routed through east branch before T2 (dashed line between T1 and T2). Channel depths are normalized; see Figures DR2.1–DR2.5 (see footnote 1) for absolute depths. GST—gravel-sand transition.

cannibalization of bank material deposited by past floods. This sediment is likely only translated a short distance before being deposited on downstream point bars and integrated back into the bank as the channel migrates laterally and the bank accretes vertically.

Implications for Sediment Flux Estimates

In many systems, cohesive bank material and root networks limit lateral migration, but sediment storage and recycling are observed (e.g., Venditti et al., 2015), suggesting that our observations are not unique to the Karnali River. An increase in suspended sediment concentration has been observed across the GST in the Fraser River, British Columbia (Venditti et al.,

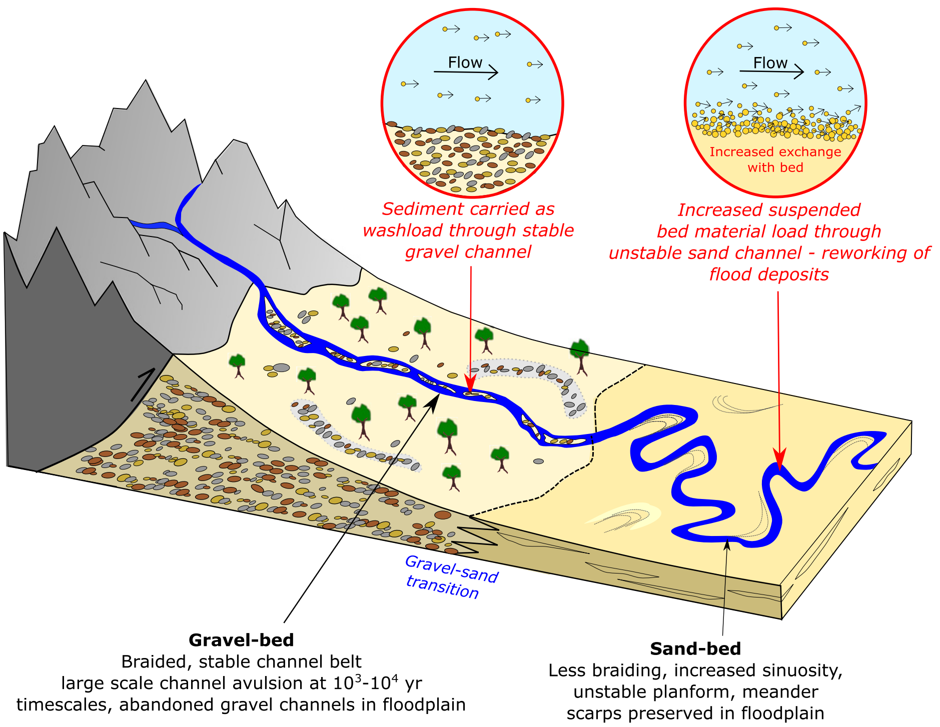

Figure 4. Summary of changes in channel morphology, migration style (black text), and modes of sediment transport (red text) across Karnali River (Nepal) gravel-sand transition under low- to moderate-flow conditions.

2015). Following a peak spring freshet flow in June 2007, observations of suspended sediment across the Fraser GST revealed that the total flux of sand (bed load and suspended load) increased downstream from 0.044 Mt/d to 0.127 Mt/d (see the Data Repository; Table DR4). However, unlike the Karnali River, the Fraser River is laterally constrained; the increase in sediment flux occurs because of changes in sand storage across the GST under different flow stages. During high flows, a thick deposit of sand, up to 10 m thick, is mobilized at the upstream limit of the GST and diffused downstream. The storage at the upstream limit has been observed to fill again as flow wanes (Venditti et al., 2015).

Both lateral channel migration and vertical filling and depletion of sand across the Karnali and Fraser River GSTs are reflected by a counterintuitive downstream increase in sediment flux under moderate- and high-flow conditions, respectively. This highlights potential limitations in the use of temporally limited, local sediment sampling downstream of mountain ranges when calculating continental-scale sediment fluxes and denudation rate estimates. Sediment flux estimates using comparable methods by Lupker et al. (2011) on the Ganga River at Harding Bridge, Bangladesh, were 7.51 Mt/d under peak flow conditions (44,800 m^3/s). Our measurements collected under moderate monsoonal flow conditions (~2000 m^3/s) were >50% of this value, despite the Karnali basin making up <5% of the Ganga catchment area upstream of Harding Bridge. Our results indicate that downstream increases in suspended sediment concentration and grain size arise due to remobilization of bank material through lateral migration, suggesting that sediment flux measurements in such settings are enhanced by this process. To confirm, long-term records capturing sediment flux under a range of flow conditions are required.

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