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# Millennial lag times in the Himalayan sediment routing system

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ABSTRACT

Any understanding of sediment routing from mountain belts to their forelands and offshore sinks remains incomplete without estimates of intermediate storage that decisively buffers sediment yields from erosion rates, attenuates water and sediment fluxes, and protects underlying bedrock from incision. We quantify for the first time the sediment stored in $> 38\,000$ mainly postglacial Himalayan valley fills, based on an empirical volume-area scaling of valley-fill outlines automatically extracted from digital topographic data. The estimated total volume of $690(^{+452}/_{-242})$ km$^3$ is mostly contained in few large valley fills $> 1$ km$^3$, while catastrophic mass wasting adds another $177(\pm 31)$ km$^3$. Sediment storage volumes are highly disparate along the strike of the orogen. Much of the Himalaya's stock of sediment is sequestered in glacially scoured valleys that provide accommodation space for $\sim 44\%$ of the total volume upstream of the rapidly exhuming and incising syntaxes. Conversely, the step-like long-wave topography of the central Himalayas limits glacier extent, and thus any significant glacier-derived storage of sediment away from tectonic basins. We show that exclusive removal of Himalayan valley fills could nourish contemporary sediment flux from the Indus and Brahmaputra basins for $> 1$ kyr, though individual fills may attain residence times of $> 100$ kyr. These millennial lag times in the Himalayan sediment routing system may sufficiently buffer signals of short-term seismic as well as climatic disturbances, thus complicating simple correlation and interpretation of sedimentary archives from the Himalayan orogen, its foreland, and its submarine fan systems.



## 1. Introduction

The Indus and Ganges–Brahmaputra Rivers rank amongst Earth's largest river systems, and drain the Himalayas, one of the planet's premier mountain belts, featuring active tectonic shortening, extreme relief, highly seasonal precipitation, and commensurate erosion rates. Sediments flushed from the orogen are deposited in the foreland basin of the Indo-Gangetic Plain, and, ultimately, in the Indus and Bengal submarine fan systems, which have attained sediment piles $> 9$ and $> 16$ km thick, respectively (Clift et al., 2001; Curray, 1994). The Ganges–Brahmaputra system delivers by far the largest amount of terrestrial sediment to the ocean, at an annual flux $\sim 10^3$ Mt yr$^{-1}$ (e.g. Curray, 1994; Goodbred and Kuehl, 2000; Milliman and Meade, 1983). Besides analytical errors associated with measurement procedures, large uncertainties in these estimates (Table A.1) derive from elusive data on the build-up and removal of intermediate sediment storage. This critical term in the sediment budget is potentially governed by stochastic internal system dynamics that introduce significant variability to short-term measurements of sediment flux, likely to be amplified by the reworking of stored sediments (Jerolmack and Paola, 2010; Simpson and Castelltort, 2012; Van de Wiel and Coulthard, 2010). Particularly intermontane valley fills such as floodplains, fans, and terraces, are important landforms, decoupling hillslopes from river-channel processes and buffering sediment sources from sinks (Castelltort and Van Den Driessche, 2003; Fryirs et al., 2007; Straumann and Korup, 2009); sequestering biogeochemical constituents including nutrients and pathogens alike; containing archives of environmental change; modulating natural hazards by either attenuating or amplifying water-sediment fluxes as well as seismic shear velocities (Wald and Allen, 2007); and ultimately providing the amenity of flat ground for tens of millions of people and their agricultural livelihood in otherwise steep mountainous terrain.

Storage is fundamental to any sediment budget, but remains a black box for many large drainage basins, spawning large uncertainties about reported sediment yields and potentially introducing long-term stability of sediment yields by buffering signals of environmental change (e.g. Allen, 2008; Métivier and Gaudemer, 1999; Milliman and Syvitski, 1992; Phillips, 2003). Distinct research gaps concern the spatial distribution, residence times, and resulting lag times between rates of erosion and sediment yields that only a quantification of sediment storage can elucidate (Castelltort and Van Den Driessche, 2003; Hinderer, 2012). Until recently, systematic analyses and quantification of sediment storage focused on smaller drainage basins or individual landforms (e.g. Schrott et al.,

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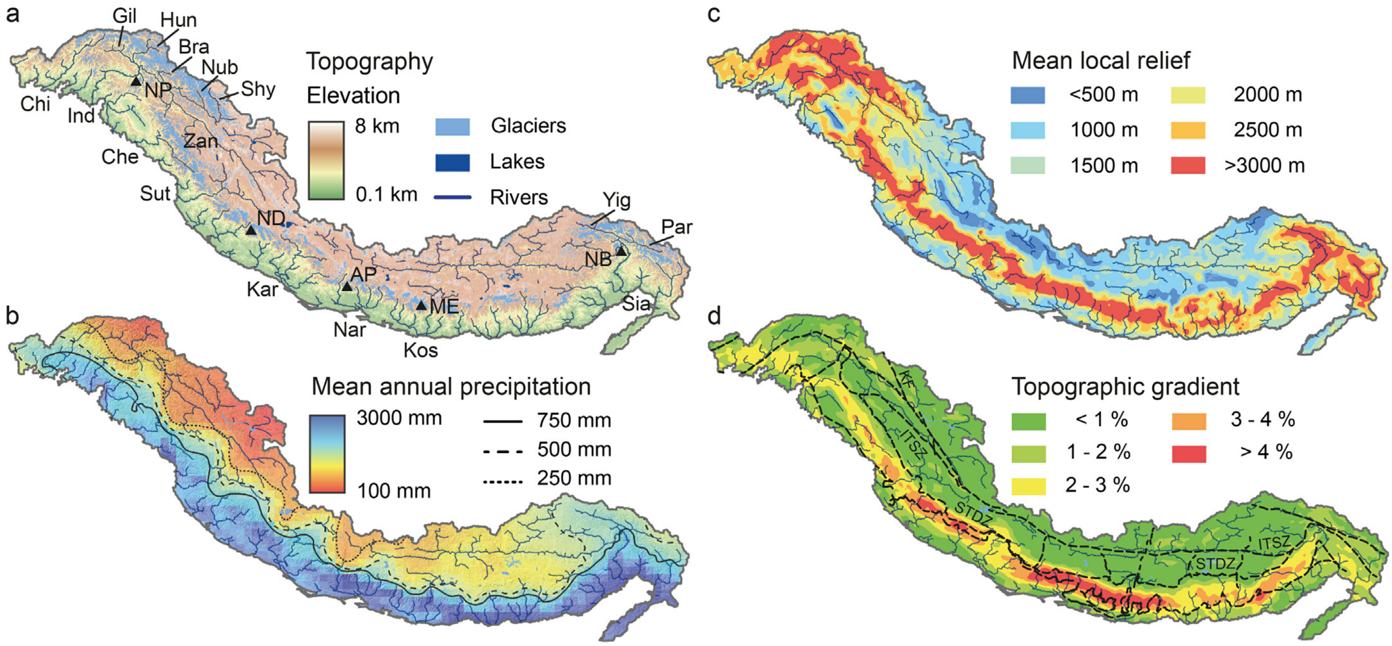


**Fig. 1.** Study area of the Himalayas and adjacent areas. (a) Topography with rivers, lakes, and contemporary glacier cover. Black triangles are major peaks: NP = Nanga Parbat; ND = Nanda Devi; AP = Annapurna; ME = Mount Everest; NB = Namche Barwa. Labels indicate rivers referred to in text and tables: Chi = Chitral; Ind = Indus; Gil = Gilgit; Che = Chenab; Hun = Hunza; Bra = Braldu; Sut = Sutlej; Nub = Nubra; Shy = Shyok; Kar = Karnali; Nar = Narayani; Kos = Kosi; Yig = Yigong Tsangpo; Sia = Siang; Par = Parlung Tsangpo. (b) Mean annual precipitation from APHRODITE dataset (Yatagai et al., 2009) with major contour lines. (c) Mean local relief, expressed as maximum elevation difference in 10-km radius on SRTM90 data. (d) Long-wave topographic gradient (LWT), calculated from mean elevation in a 100-km radius based on SRTM data resampled to 270-m resolution. Black dashed lines are major tectonic lineaments: KF = Karakorum Fault, ITSZ = Indus-Tsangpo Suture Zone, STDZ = Southern Tibetan Detachment Zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2003). Efforts to integrate up to the mountain-belt scale (Hinderer, 2001; Straumann and Korup, 2009; Wasson, 2003), as well as to quantify sediment budgets on million-year timescales (Métivier and Gaudemer, 1999), have been rare. Yet estimates of the sediment storage in the vast floodplains of the Brahmaputra River (Allison et al., 1998; Goodbred and Kuehl, 1998) have underscored the unique opportunity to contributing regional jigsaw pieces to completing our understanding of Earth's largest sediment routing system.

Here we estimate Himalayan sediment storage by extracting and analyzing the size, regional distribution, and minimum life span of intermontane valley fills from digital topography. We evaluate their pattern with respect to the variability of litho-tectonic units, local and long-wave topographic relief as proxies of erosion rates (e.g. Montgomery and Brandon, 2002), precipitation patterns, glacier cover, and river-channel steepness along the entire Himalayan orogen and its adjacent ranges over an area of $\sim 438\,780\ \mathrm{km}^2$ (Figs. 1 and 2a). We automatically extracted the outlines of major valley fills along the Himalayan arc from a digital elevation model (DEM), and used an empirical volume-area scaling relationship with Monte Carlo-based error propagation to conservatively estimate the minimum volume contained in $> 38\,000$ valley fills.

## 2. Study area

Our study area encompasses the entire Himalayan orogen as defined by Yin (2006) together with the southernmost parts of the Karakorum, the Gangdese Shan, and those parts of the Tibetan Plateau that are drained by the Indus and Ganges–Brahmaputra river systems. We simplistically refer to this area ($\sim 995\,000\ \mathrm{km}^2$) as the *Himalayas* (Figs. 1a and 2a). We distinguish between three major hydrological compartments, i.e. the Western, Central, and Eastern Himalayas, which are drained by the Indus, Ganges, and Brahmaputra River systems, respectively. The elevation in the study area rises from $< 500$ m to $> 8000$ m asl within a 250–500 km horizontal distance. This pronounced topographic gradient between the Greater Himalayas and the Trans-Himalaya is steepest in the Central Himalaya, and coincides with a sharp precipitation gradient, although precipitation is by no means uniform along the strike of the orogen (Bookhagen and Burbank 2010, 2006) (Fig. 1b). Mean annual rainfall is dominated by the South Asian summer monsoon (SASM), whereas the influence of the westerlies circulation, mainly bringing winter precipitation, decreases towards the East (Bookhagen and Burbank, 2010). Oscillations in SASM intensity have been reported on various timescales, though the overall regional climatic pattern appears to have remained largely unchanged since the Early Miocene (Clift et al., 2008). Mean local relief, computed as the maximum elevation range in a 10-km radius, exceeds 3000 m in the Central Himalayas, the Karakorum, and the Nyainqentanglha mountains; it is highest at the core of the Himalayan syntaxes (e.g. Korup et al., 2010) (Fig. 1c). The sharp break in topography in the vicinity of the Main Central Thrust (MCT) (e.g. Wobus et al., 2003) is well captured by the long wavelength topographic gradient (LWT) that we calculated from mean elevation in a 100-km radius based on DEM data that we resampled to a 270-m grid-cell resolution (Fig. 1d).

## 3. Methods

### 3.1. Digital topography

We analyzed digital topographic data from the SRTM90 DEM with gaps filled by topographic map data (www.viewfinderpanoramas.org, srtm.csi.cgiar.org). Hydrologic correction was done using a Matlab TopoToolbox carving routine (Schwanghart and Kuhn, 2010), followed by a fill calculation using the ArcMap Spatial Analyst *fill* algorithm; DEM tiles were merged for the entire Indus and Ganges–Brahmaputra drainage networks, excluding areas below a smoothed 500-m contour line in order to restrict our analyses to the mountain range.