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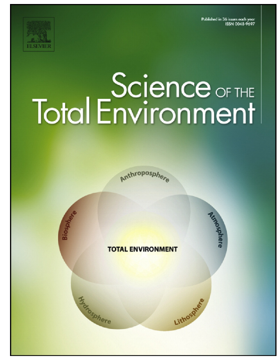

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A first-order geochemical budget for suspended sediment discharge to the Bay of Bengal from the Ganges-Brahmaputra river system

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Highlights:

- Published data are used to estimate sediment-element discharge to the Bay of Bengal.
- Ganges-Brahmaputra river contributes >10% ocean supply of solid-phase Hf and Zr.
- Future anthropogenic changes could significantly alter element discharge to the ocean.
- Such approximations can direct future analysis of globally important element fluxes.
- Ganges-Brahmaputra contributes <1% of global ocean solid-phase As.

Abstract:

The Ganges-Brahmaputra-Meghna (G-B) river system transports >1x10^{9} t/yr of sediment, with an estimated 0.7x10^{9} t/yr reaching the Bay of Bengal (BoB). This discharge represents a major input of sediment and associated elements to the global ocean, but quantification of the sediment-element mass reaching the BoB has yet to be fully explored. Published geochemical and suspended sediment data are used to calculate a first-order budget for the modern sediment supply of geochemical elements to the BoB. River profile bulk sediment-element concentrations are calculated based on suspended sediment and element measurements taken in the Ganges and Brahmaputra rivers. A Monte Carlo analysis is applied to account for variable sediment and geochemical contributions from each river. Results show that on average, the G-B system contributes ~5% of the global riverine discharge of solid-phase elements from sediment to the oceans. G-B sediments transport >10% of the global element supply of Hf and Zr. For others, like As and Cu, contributions from the G-B are <5%. Results also show that sediment reaching the BoB is relatively enriched in Hf, Zr, Th, REEs, Sn, and Bi, and majorly depleted in Na and Sr compared to UCC elemental concentrations. While limited by data availability and necessary simplifying assumptions, this study nevertheless provides a reasonable first-order budget for the modern discharge of solid-phase elements to the BoB. Insights from this work are significant for understanding the role of the G-B river system in global elemental cycling, and for providing a basis of comparison for future sediment-element discharge in light of rapid environmental change taking place in the region.

Keywords: *geochemical flux, suspended sediment, Ganges-Brahmaputra-Meghna river delta, Monte Carlo analysis*

Introduction:

The Ganges-Brahmaputra river system (G-B) in South Asia represents one of the most dynamic river systems on the planet, with approximately $1x10^9$ metric tons of sediment transported to the continental margin each year (Milliman and Farnsworth, 2011). While the G-B sediment load is reasonably well-constrained, sediment-element discharge data from the system is lacking, yet is important to quantify for insight into continental weathering and anthropogenic influence on solid-phase element concentrations (Martin and Meybeck, 1979; Viers et al., 2009). Previous research has illustrated the importance of the G-B in transporting and burying organic carbon through rapid, large-scale sedimentation (e.g. Galy and Eglinton, 2011; Galy et al., 2007;

Galy et al., 2008), as well as the high magnitude of sediment-element fluxes in the Ganges River (Lupker et al., 2011; Singh et al., 2003). However, although detailed examination of suspended sediment profile chemistry and mineralogy has been conducted within the G-B and estuary (e.g., Borromeo et al., 2019; Garzanti et al., 2011; Lupker et al., 2011; Stummeyer et al., 2002), there are no updated estimates of the entire G-B sediment-element load delivered to the Bay of Bengal (BoB). The only first order estimate of joint G-B sediment-element discharge into the BoB was performed by Subramanian et al. (1987) but contained limitations such as only sampling suspended sediment in the upper 1m of the water column.

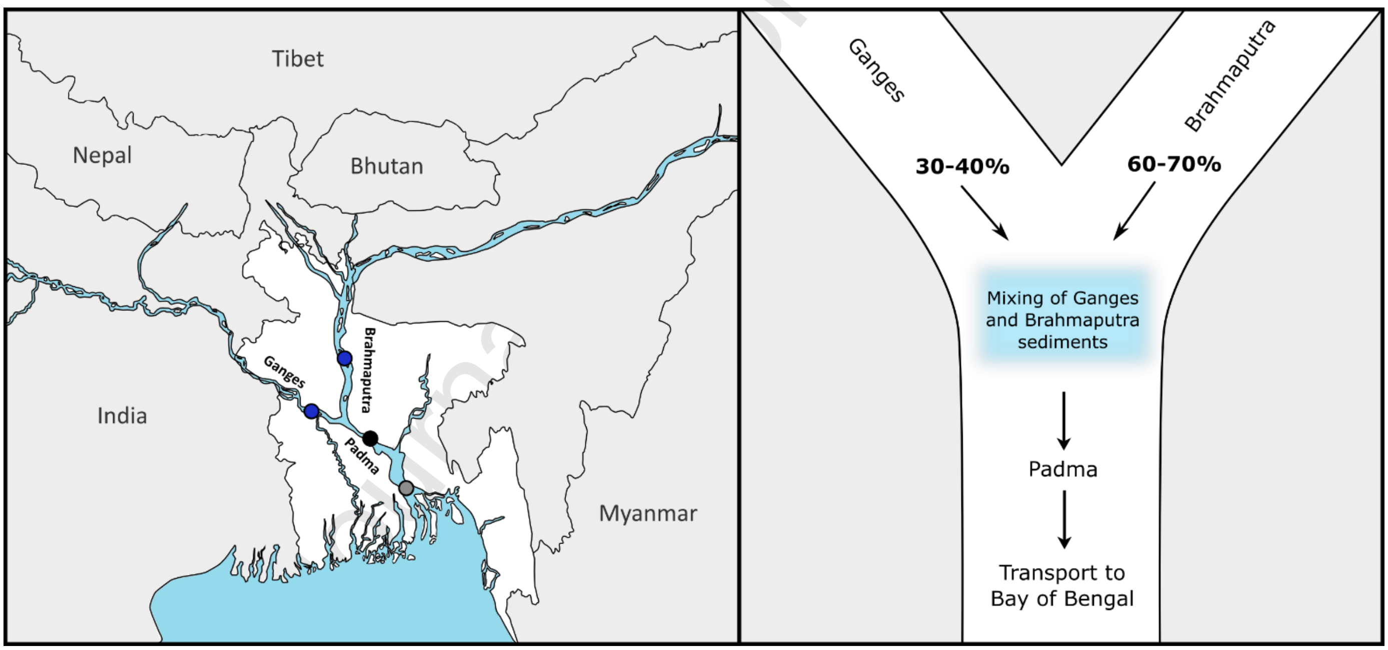

Figure 1: Left. Sampling locations from Garzanti et al. (2011). This study uses data from the sample locations denoted in blue. The sample location denoted in black contains suspended sediment samples in the Padma and is compared to the results of this study. The sample location denoted in gray does not contain suspended sediment concentrations and is excluded from these analyses. **Right.** Conceptual mixing model showing the relative contribution of Ganges and Brahmaputra sediments, mixing in the Padma (lower Meghna), and element and sediment discharge to the Bay of Bengal.

River sediment transport dynamics are inherently complex, particularly in tidally-influenced coastal areas like the lower G-B delta. Because of this complexity, first-order sediment-element discharge estimates for the G-B are therefore useful for estimating the global contribution of solid-phase elements reaching the oceans which may otherwise be difficult to quantify. River systems with large suspended sediment transport are also suggested to have a proportionally high impact on the supply of some dissolved metals to the oceans through ion exchange and desorption from fine suspended sediment particles when mixing with seawater (Samanta and Dalai, 2018). The high sediment discharge of the G-B system provides solid-phase elements that may be partially mobilized into the dissolved load when exposed to BoB seawater.

Compiling modern sediment-element discharges within the G-B can also be used as a basis of comparison to future discharges to deduce environmental change in the system, such as the potential impact of regional damming projects (Higgins et al., 2018) and climate change on sediment transport in the region (Darby et al., 2015). Furthermore, understanding what elements in the G-B annual sediment discharge are elevated or depleted can give insights into regional sediment characteristics that affect sediment flux and composition, such as sediment source and weathering. Toward these goals, this paper uses published data from several recent studies to generate a first-order estimate of yearly discharge of elements in the suspended sediment load to the BoB by the G-B. We show that relatively straightforward calculations can provide an estimation of G-B sediment-element discharge within an order of magnitude and supplement world river chemical flux databases such as Viers et al. (2009).

Methods:

Data

This work utilizes a robust dataset from Garzanti et al. (2011) that includes grain size, suspended sediment concentration, mineralogy, and element concentrations for suspended load samples collected at various depths from locations in the Ganges, Brahmaputra and Padma rivers during the monsoon season, when about 95% of sediment is discharged from the G-B river system (**Fig. 1**; e.g., Galy et al., 2007; 2008; Lupker et al., 2011). The vertical profiles of suspended sediment load (SSL) and sediment-elemental concentrations in both the Ganges and Brahmaputra rivers were utilized in our analysis. Specifically, suspended sediment samples at the depths of 0, 3, 8, 9.8, 10.3 and 10.8 meters from a vertical profile at the Ganges River on August 17, 2007 were utilized in this analysis, along with suspended sediment samples taken in a vertical profile in the Brahmaputra River on July 12, 2004 at depths of 0, 1.5, 3, 5, and 11 meters (Garzanti et al., 2011). Garzanti et al. (2011) took all samples from a boat, with representative profiles where water velocity was greatest. Vertical profile samples from the Padma River (black dot; **Fig. 1**) were also used for comparison with our model results, with suspended sediment samples taken in the monsoon season (no specific date given) at depths of 0, 2.3, 5, 7.5, and 9.5 meters (Garzanti et al., 2011). All suspended sediment element concentrations from Garzanti et al. (2011) were determined via ICP-AES and ICP-MS following lithium metaborate fusion. Only elements where all concentrations were above detection limit were used in our analysis. A full description of data collection and analysis can be found in Garzanti et al. (2011), and complete data used for this analysis can be found in Supplementary Materials (**Table S1**).

Sediment-element load calculations

The first-order nature of this analysis requires several key assumptions. First, we assume that during monsoon flow (when the majority of sediment is delivered) the measured SSL and elemental vertical profiles are representative for flow with depth along each river. We do not account for bedload transport, weathering, and desorption in this system. Although bedload transport is difficult to quantify, Lupker et al. (2011) estimated it to be <2% of the suspended load in the Ganges and in general it is estimated to be only around 10% of the sediment load in river systems (e.g., Borromeo et al., 2019; Higgins et al., 2018; Syvitski et al., 2003).

While weathering is an active process occurring in the river system, particularly from the Himalayan front through the entire Ganges floodplain for mobile elements such as Na and Ca (Bickle et al., 2018; Lupker et al., 2012), depletion of most elements in suspended sediment from weathering is likely limited during the relatively short distance (~400-450km) from the sampling locations to the BoB **(Fig. 1)**. This is supported by sediment chemical data from Singh et al. (2003), where they saw relatively minimal variation in nine metals analyzed in the <20 μm riverbed sediment fraction along a 1,700 km flow-path of the Ganges (far longer than the distance from the sample sites used in this study to the BoB), and attributed the differences in concentrations largely to varying tributary sources along the river flow-path. The Singh et al. (2003) data therefore also supports that desorption of most elements (particularly metals) from suspended sediment should be relatively minimal from the sampling locations of Garzanti et al. (2011) to the BoB. Additionally, Ayers et al. (2020) suggests that the Ganges tidal delta plain is transport limited, where chemical weathering is minimal on already highly weathered sediments. However, it is acknowledged that Ba may desorb along the flow-path before the salinity front as well as in more saline waters near the coast of the BoB (Carroll et al., 1993). Some metals such as Cr, Zn, Co, Cu or Ni may also desorb from suspended sediment close to the BoB from competitive salt ion adsorption (e.g., Machado et al., 2016 and the sources cited therein; Samanta and Dalai, 2018), although this is likely not occurring in the monsoon season until sediment reaches the BoB because of a suppressed salinity front from heavy river discharge.

Lastly, we assume that sediment does not experience intermittent storage, but is instead flushed out of the system from the river mouth into the subaerial intertidal lower delta, subaqueous clinoform, and The Swatch of No Ground canyon head of the BoB at a rate of $0.7x10^9$ t/yr (Rogers et al., 2015 and the sources cited therein). For simplicity, we consider the subaerial intertidal lower delta as part of the BoB system. These assumptions allow us to perform a simplistic estimation of yearly sediment discharge without handling the complex fluvial, tidal, and sediment dynamics in this system. Though the approach is straightforward, this first-order estimate of solid-phase element transport advances the current state of knowledge on geochemical contributions of the G-B to the global oceans.

$$C_i = \frac{C_{sed}}{C_{sed-tot}} * C_x \quad (1)$$

$$C_{x-tot} = \sum_{i=0}^{z} C_i \quad (2)$$

$$C_{x-GB} = wG * C_{x-tot-G} + (1 - wG) C_{x-tot-B} \quad (3)$$

$$M_{tot} = C_{x-GB} * M_{GB} \quad (4)$$

With the selected data from Garzanti et al. (2011) (**Table S1**), we calculate a weighted average of elemental concentration in the water column of each river. We use the fraction of total suspended sediment concentration ($C_{sed}/C_{sed-tot}$) at each depth (i) to weight the corresponding measured element (x) concentrations (C_x), resulting in an element concentration at each measured depth in the water column (C_i) (**Eq. 1**). We then integrate over the total depth of the water column (z; **Eq. 2**) to calculate the total concentration for each element (C_{x-tot}) in each river's suspended sediment load. These weighted and vertically integrated elemental concentrations are then combined (C_{x-GB}) to represent mixing at the confluence of the Ganges and Brahmaputra rivers with the Padma river, which then transports sediment into the BoB. Because the relative contributions of both SSL and element fluxes from the Ganges and Brahmaputra into the Padma are not accurately known, we performed a Monte Carlo analysis to combine the inputs from the two rivers during mixing (C_{x-GB}). Current estimates suggest that the Ganges contributes approximately 30-40% of sediment to the Padma and ultimately the Bay of Bengal, with the Brahmaputra contributing the remaining 60-70% (e.g., Borromeo et al., 2019; Garzanti et al., 2019; Lupker et al., 2013). Sediment inputs from the Meghna at the confluence are estimated to be <1% of the estimated combined sediment flux (e.g., Rahman et al., 2018 and the sources cited therein) and are therefore considered to be negligible in this analysis. A mass fraction from the Ganges (wG) is randomly selected from a normal distribution with a mean of 0.35 and standard deviation of 0.1 within the Monte Carlo analysis. During each model run, elemental concentrations and suspended sediment loads from each river ($C_{x-tot-G}$ and $C_{x-tot-B}$) are mixed according to this simulated mixing percentage (**Eq. 3**). The Monte Carlo is repeated 10,000 times to account for the range of possible elemental concentrations in the Padma after the Ganges and Brahmaputra have mixed. Median element concentrations of suspended sediment from the Monte Carlo simulation are listed in **Table S2**. Lastly, we convert the estimated mixed concentration ranges (C_{x-GB}) to mass (M_{tot}) by multiplying the median mixed concentration of each element by the total sediment load annually transported by the G-B river mouth to the BoB (M_{GB}= 0.7x10^9 t/yr; Rogers et al., 2015) (**Eq. 4; Table 1**).

We chose to use the Monte Carlo analysis to estimate ranges of bulk sediment-element concentrations entering the BoB (**Fig. S1**) due to limitations in the Padma dataset (Garzanti et al., 2011), which is likely biased towards smaller suspended sediment grain sizes since the data profile does not capture information deeper than 9.5 m. The lack of a steep gradient in suspended sediment load, like that observed for the vertical profiles from the Ganges and Brahmaputra sampling sites, suggests that the Padma dataset is missing the higher concentrations of deeper, typically coarser, suspended sediment. Also, the data from the Padma captures information from a single point in time, while the Monte Carlo analysis allows us to capture more variability in element concentrations and relative contributions from the Ganga and Brahmaputra. While Garzanti et al. (2019) include suspended sediment bulk chemistry data along a vertical profile in the Meghna estuary below the Ganges-Brahmaputra confluence, there are no suspended sediment concentrations for us to compare using our weighted average approach. Nevertheless, our analysis provides a range of average bulk sediment-element concentrations theoretically entering the BoB at the mouth of the river system based on the mixing of two vertical profiles from each of the rivers. These ranges can then be compared to Garzanti et al. (2011) data from the Padma.

Estimates of suspended sediment-element world riverine fluxes to oceans from Viers et al. (2009) were used along with the median fluxes into the BoB calculated by the Monte Carlo to estimate the percent of global riverine suspended sediment-element supply that can be attributed to the G-B river system (**Fig. 2; Table 1**). Expected geochemical inputs from the G-B system were estimated based on global annual suspended sediment discharges, which range from 15-20x10^9 t/yr (Walling, 2006 and the references cited therein). Ultimately, 15x10^9 t/yr was chosen to be consistent with Viers et al. (2009). Based on 15x10^9 t/yr of global sediment discharge and assuming 0.7x10^9 t/yr of G-B sediment transport to the BoB, the G-B system exports ~4.7% of the global suspended sediment. A simplistic basis for comparison using these estimates is to assume G-B solid-phase element concentrations are similar to global suspended sediment-element average concentrations. The G-B element discharge would then reflect 4.7% of the total riverine inputs to oceans for each element. Therefore, sediment-element discharges greater than 4.7% are relatively enriched, and those less than 4.7% are relatively depleted compared to the global average suspended sediment.

Results and Discussion

Calculated sediment-element discharges into the BoB range from 100's of metric tons per year (Bi, Sb) to 100's of millions of metric tons per year in the case of Si (**Table 1**). Sensitivity to the fraction of Ganges or Brahmaputra River contribution appears minimal based on low standard deviations/variance of both Monte Carlo median sediment-element concentrations **(Fig. S1)** and G-B sediment-element fluxes **(Table 1)**. Thus, the composition of the sediment profiles between the Ganges and Brahmaputra Rivers are at least similar enough to prevent drastic changes in joint-load composition, provided that the current % river contribution constraints are reasonably accurate. Estimates of contributions range from <1% of global sediment-element discharge (As) to more than 11% (Hf). These first-order estimates of suspended sediment-element loads into the BoB illustrate the relative worldwide influence of elements discharged into the oceans by the G-B. This work provides insights into what elements are enriched in G-B sourced sediment relative to other riverine systems and can further understanding of the G-B's role in global geochemical cycling. Elements of particularly high contribution to the world oceans include: Zr, Hf, Ce, Lu, Na, Rb, Th, Yb, Y, Pr, Ge, Er, and Dy (**Fig. 2**). Additionally, elements such as Al, Ca, and Fe that have large absolute contributions to the ocean are still important to quantify despite their relatively low percent contribution from the G-B. Most elements estimated here have world ocean contributions of >3% (with the exception of As, Cu, Mn, Ni, P, Pb, Sb, and Zn), making the G-B system an important component of the Asian continental sediment-element supply to the ocean.

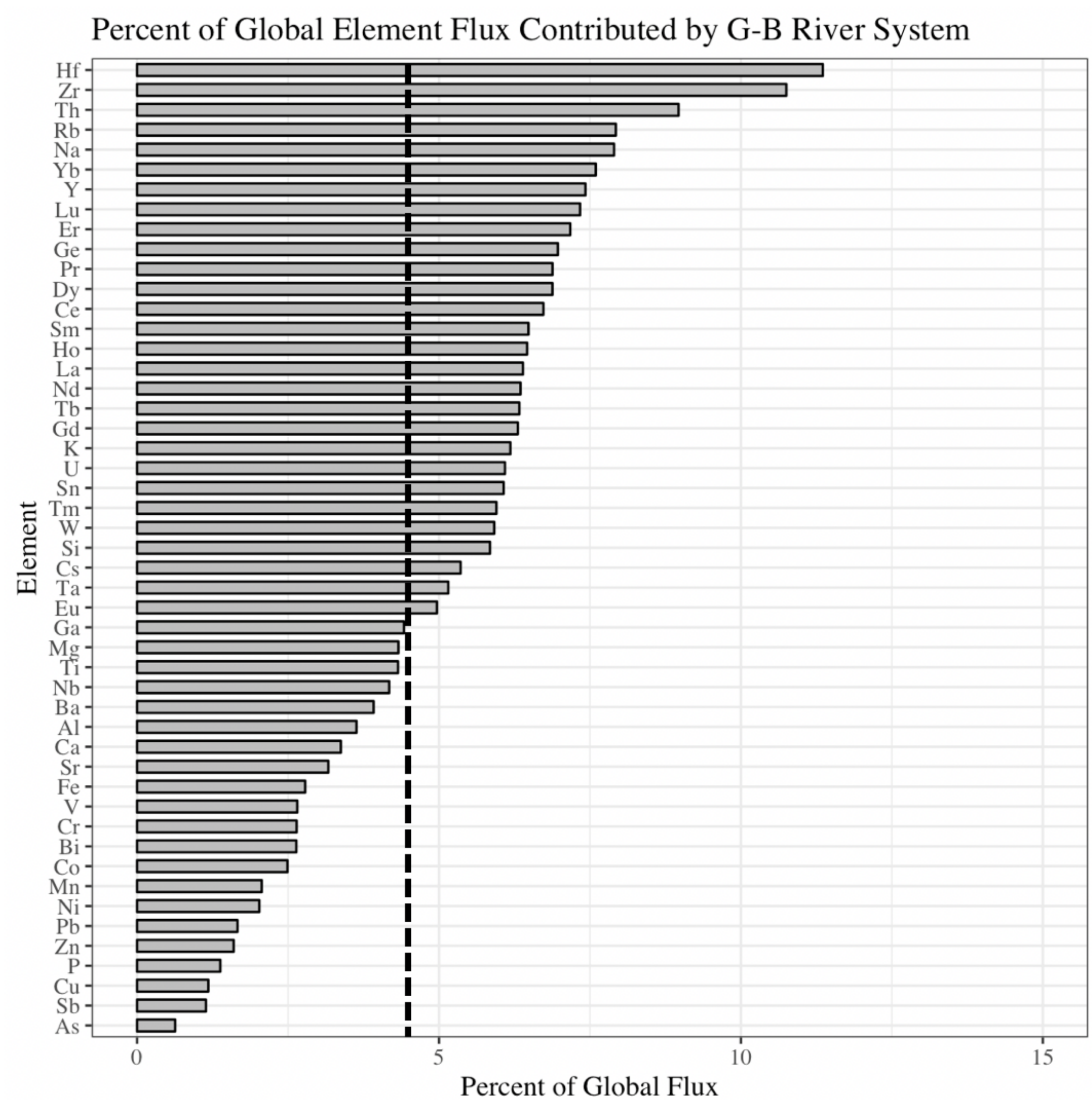

Figure 2: Estimated percent contribution of annual sediment-element riverine fluxes to world oceans by the G-B river system based on median element fluxes into the BoB calculated by Monte Carlo analysis and global suspended sediment-element fluxes from Viers et al. (2009). Dashed line at 4.7% represents expected element flux based on the G-B river sediment contribution (700 Mt/yr) (Rogers et al., 2015) to recent estimates of the global sediment budget (~15 Gt/yr) (Viers et al., 2009; Walling, 2006).

The rare earth elements (REE) are particularly enriched in the G-B sediment load **(Fig. 2)**. This is also seen when comparing concentrations in the suspended sediment to UCC, with all the REEs enriched compared to UCC **(Fig. 3)**. Garzanti et al. (2010) and Garzanti et al. (2011) also saw relative enrichment in REEs compared to UCC in their different measurements of suspended load and bedload. This could be indicative of dense minerals rich in REEs incorporated in the suspended load of the G-B, either through a high proportion of sand-sized sediments transported in the deep suspended load or enrichment in the fine near-surface suspended load (Borromeo et al., 2019; Lupker et al., 2013; Garzanti et al., 2011; Lupker et al., 2011; Garzanti et al., 2010; Galy et al., 2007). The enrichment of REEs compared to UCC and the expected sediment-element flux is also indicative of the Himalayan source of the sediment. Thick crust in the Himalayas sourcing accessory minerals such as monazite, zircon and apatite rich in REEs from granites and gneisses (Le Fort et al., 1987) would explain the high fluxes and enrichment of Zr and REEs compared to UCC. Additionally, although Na from the G-B contributes approximately 8% of global sediment-element fluxes into world oceans, it is relatively depleted compared to UCC (**Figs. 2 & 3**). This reflects that Na is often depleted in riverine suspended sediment relative to UCC, such as through weathering in the Ganges floodplain (Bickle et al., 2018; Lupker et al., 2012), but in the G-B it is less depleted relative to the world average suspended sediment concentration (Viers et al., 2009). Interestingly, arsenic sediment-element discharge from the G-B system contributes <1% of world riverine sediment-element discharge to oceans and is close to UCC values (**Figs. 2 & 3**), despite toxic levels of As in groundwater drinking wells in this region (e.g., Ayers et al., 2016). This further supports the idea that the sediments delivered by the G-B system are not anomalously high in As, and it is rather the geochemical conditions in the subsurface that drive high dissolved As release from sediment to groundwater in the region (e.g., Anawar et al., 2003; McArthur et al., 2001).

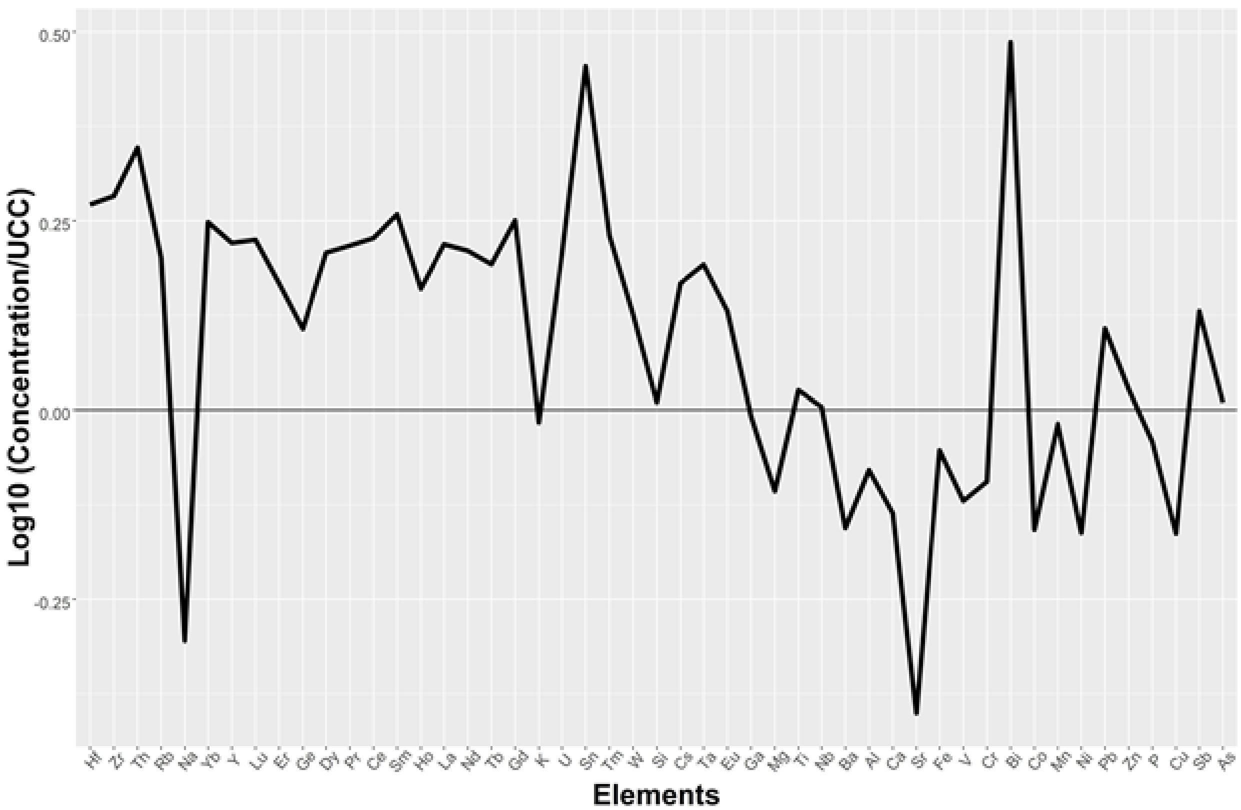

Figure 3: Comparison of median Monte Carlo calculated suspended sediment-element concentrations delivered to the Bay of Bengal (BoB) normalized to UCC values (Rudnick and Gao, 2003). Elements are ordered in decreasing global sediment-element ocean flux contribution from left-right. All elements plotting above 0 are enriched relative to UCC, all elements plotting below 0 are depleted relative to UCC and tend to be in the dissolved load. Similar to figures in Garzanti et al. (2010) and Garzanti et al. (2011), but includes estimated concentration of suspended sediment in the entire "mixed" river profile from a Monte Carlo output.

Any changes in the near-term to these sediment-element discharges could have far-reaching implications in terms of riverine inputs into world oceans. Therefore, quantifying chemical transport in the G-B system is essential for understanding the impact of climate change and anthropogenic influence of waterways on sediment-element discharge via means such as damming and canal development. For example, the proposed National River Linking Project (NRLP) in India is estimated to reduce the annual suspended sediment load in the Ganges and Brahmaputra by 39-75% and 9-25%, respectively, if completed (Higgins et al., 2018). However, with projected climate change scenarios it is also likely that, if the G-B flow-path is not severely altered, sediment discharge may increase by 34-37% in the Ganges and 52-60% in the Brahmaputra by the end of the 21st century (Darby et al., 2015). Thus, future alterations to the G-B river system may have large impacts on global riverine suspended sediment-element contribution to the world's oceans. Future G-B regional sediment-element discharge could then be compared to modern estimates like the one provided here to determine how element cycling has changed due to environmental alteration.

Estuarine environments with high concentrations of seawater cations like Na leads to desorption of several trace metals such as Zn, Cr, Ni, Co and Cu from the suspended sediment load to the dissolved load (e.g., Machado et al., 2016 and the sources cited therein; Samanta and Dalai, 2018). This could have implications for a high sediment discharge area like the mouth of the G-B river system, where the higher levels of salinity in the dry season can cause elevated levels of trace metals in sediment to be released into the ocean through the dissolved phase.

Although the first-order approach of our elemental budget is relatively simple, it incorporates several of the main components of hydrologic sediment transport. Because suspended sediment concentration tends to increase with depth in river profiles (e.g., Galy et al., 2007; Galy et al., 2008), it is imperative to use a weighted average of sediment-element concentration based on the amount of sediment at each depth interval. Thus, the depths with the greater amounts of suspended sediment were weighted more heavily when calculating average element concentration in each suspended sediment profile. This weighted average approach, albeit simple, inherently takes into account grain size settling, as coarser particles are more highly concentrated towards the bottom of a river profile due to their faster settling rates (e.g., Galy et al., 2007; Lupker et al., 2011). This point is further proven by Bouchez et al. (2011), who illustrated how important integrated depth profiles are in the Amazon River due to sediment-element composition changing markedly for many elements throughout the water column. Pertaining to the dataset used in this study, figures 4, 5 and 9 from Garzanti et al. (2011) clearly show the change in concentrations of suspended sediment element concentrations with depth, and Figure 9 specifically illustrates the increase of suspended sediment with depth in the Ganges and Bramaputra river profiles. We also acknowledge that bedload element concentrations can be quite different from suspended sediment-element concentrations based on mineral density and grain size settling (e.g., Garzanti et al. 2010; Lupker et al., 2011; Garzanti et al. 2011). Although we did not include bedload transport when determining average element concentrations in the sediment load, bedload is likely incorporated into the bottommost river sediment samples through particle resuspension and selective entrainment (Garzanti et al., 2010 and the references cited therein).

Model validation

Estimates through our straightforward weighted-averaging method in the Ganges (assuming 0.39×10^9 t/yr sediment load in the Ganges as used by Lupker et al. (2011)) were within 1.3-12.5% of calculated sediment-element fluxes for elemental Al, Si, and Fe by Lupker et al. (2011), who considered bedload, multiple vertical profiles, and other, more sophisticated fluid-dynamics (**Table S3**). Furthermore, comparison of our modeled “mixed” sediment-element concentrations showed good agreement with weighted averages deduced by the same methodology in the Padma River after the G-B confluence (slightly upstream of the Meghna confluence), where all but one element flux (Bi) were within an order of magnitude and the average % difference in element concentrations was ~18.6% (**Table S2**). Differences between our model results and the Padma River observations are likely attributable, in part, to slight sampling bias. There were no Padma samples within 1.5m of bedload, where the suspended sediment concentration may have increased drastically, and the sampling location may not have encapsulated full mixing of the G-B contributions with sampling at only one point in time. When comparing our sediment-element discharges to those estimated in Subramanian et al. (1987) though, our estimates are 1-2 orders of magnitude lower. However, this is likely attributed to large differences in sampling techniques and analytical methodology. In particular, the suspended sediment-element concentrations used in Subramanian et al. (1987) were measured by X-ray fluorescence (XRF) and yielded much higher concentrations than the likely more reliable inductively coupled plasma (ICP) data from Garzanti et al. (2011). Additionally, Subramanian et al. (1987) made their sediment-element G-B discharge estimates from suspended sediment samples collected only in the upper 1m or so of the river profile, and used a sediment load of $1.17x10^9$ t/yr instead of the more-constrained $0.7x10^9$ t/yr we used in this study. Thus, we believe our calculated element suspended sediment concentrations are reasonable to a first-order.

Conclusions

The Ganges-Brahmaputra river delta contributes >10% of global ocean estimates of riverine sediment-derived Hf and Zr, but <1% of As. The sediment flux reaching the Bay of Bengal is relatively enriched in Hf, Zr, Th, REEs, Sn, and Bi and majorly depleted in Na and Sr compared to UCC elemental concentrations, largely reflecting the nature of Himalayan source material containing incompatible elements in accessory minerals resistant to weathering. Future anthropogenic changes such as large-scale damming projects and climate change could significantly alter the delivery of sediment into the Bay of Bengal and therefore alter sediment-element mass transport into the ocean.

This study shows how existing suspended sediment discharge and geochemical data from the Ganges and Brahmaputra rivers can be incorporated into straightforward calculations to approximate the solid-phase element mass transported to the Bay of Bengal. Such first order approximations can help direct more sophisticated analysis of globally important element mass transfers. However, more work is required to better constrain these estimates of sediment-element discharge from the G-B river system to the BoB. Future research should investigate the contribution of bedload to sediment load transport, measure continuous suspended sediment and bedload samples throughout the year at more depth intervals in the Meghna River after the Padma River and G-B confluence, and aim to better quantify the amount of sediment annually released by the river system into the BoB.

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Credit Author Statement:

MD developed the research question. All authors were involved in project design and implementation. KBB was responsible for most data compilation and organization. All authors contributed to data analysis. All authors were involved in data interpretation and writing/revising the paper.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

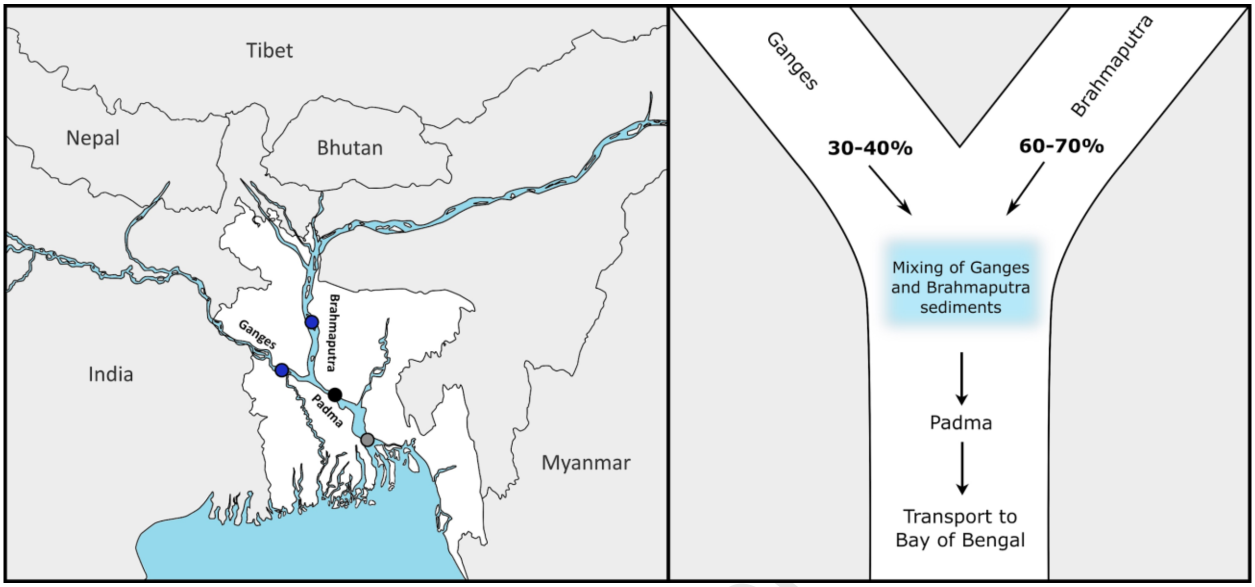
Table 1: Data used for calculations of percent of the global riverine suspended sediment-element ocean flux contributed from the G-B river system. Includes values of annual global flux estimates from Viers et al. (2009), median annual fluxes from this analysis, percent of global flux for each element, and the Monte Carlo output standard deviation of suspended sediment element fluxes in metric tons.

Element	Annual Global Flux (Viers et al. 2009) (metric tons)	G-B Median Annual Flux (metric tons)	Percent of Global Flux from G-B	Monte Carlo Element Flux S.D. (metric tons)
Al	1.31E+09	4.75E+07	3.63	1.05E+06
As	5.44E+05	3.43E+03	0.63	6.61E+01
Ba	7.84E+06	3.07E+05	3.92	6.95E+03
Bi	1.30E+04	3.43E+02	2.64	8.35E+00
Ca	3.89E+08	1.31E+07	3.38	8.61E+05
Ce	1.11E+06	7.44E+04	6.73	4.39E+03
Co	3.38E+05	8.42E+03	2.49	2.78E+02
Cr	1.96E+06	5.18E+04	2.64	1.16E+03
Cs	9.40E+04	5.04E+03	5.36	9.76E+01
Cu	1.14E+06	1.35E+04	1.18	6.91E+02
Dy	6.40E+04	4.40E+03	6.88	2.39E+02
Er	3.30E+04	2.37E+03	7.17	1.31E+02
Eu	1.90E+04	9.44E+02	4.97	1.82E+01
Fe	8.72E+08	2.43E+07	2.78	2.99E+05

Ga	2.72E+05	1.20E+04	4.42	2.76E+02
Gd	7.90E+04	4.98E+03	6.31	2.79E+02
Ge	1.80E+04	1.25E+03	6.97	7.06E+00
Hf	6.10E+04	6.93E+03	11.36	6.08E+02
Ho	1.30E+04	8.40E+02	6.46	4.36E+01
K	2.54E+08	1.57E+07	6.18	3.19E+05
La	5.62E+05	3.59E+04	6.39	2.21E+03
Lu	5.00E+03	3.67E+02	7.34	2.14E+01
Mg	1.89E+08	8.18E+06	4.33	1.23E+05
Mn	2.52E+07	5.20E+05	2.06	6.25E+03
Na	1.07E+08	8.41E+06	7.90	3.05E+05
Nb	2.03E+05	8.48E+03	4.18	1.41E+02
Nd	4.83E+05	3.07E+04	6.35	1.80E+03
Ni	1.12E+06	2.26E+04	2.03	8.93E+02
P	3.02E+07	4.16E+05	1.38	2.58E+03
Pb	9.16E+05	1.52E+04	1.66	2.24E+02
Pr	1.19E+05	8.19E+03	6.88	5.28E+02
Rb	1.18E+06	9.34E+04	7.93	1.83E+03

Sb	3.30E+04	3.77E+02	1.14	3.28E+01
Si	3.82E+09	2.23E+08	5.84	2.70E+05
Sm	9.20E+04	5.96E+03	6.48	3.43E+02
Sn	6.90E+04	4.19E+03	6.07	2.80E+02
Sr	2.81E+06	8.90E+04	3.17	3.21E+03
Ta	1.90E+04	9.79E+02	5.15	3.86E+01
Tb	1.20E+04	7.60E+02	6.33	4.06E+01
Th	1.82E+05	1.63E+04	8.97	1.15E+03
Ti	6.60E+07	2.85E+06	4.32	3.64E+04
Tm	6.00E+03	3.57E+02	5.95	1.86E+01
U	5.00E+04	3.05E+03	6.09	1.95E+02
V	1.94E+06	5.15E+04	2.65	1.15E+03
W	3.00E+04	1.77E+03	5.92	4.83E+01
Y	3.29E+05	2.44E+04	7.43	1.29E+03
Yb	3.20E+04	2.43E+03	7.60	1.39E+02
Zn	3.12E+06	5.00E+04	1.60	8.77E+02
Zr	2.41E+06	2.59E+05	10.75	2.20E+04

Graphical abstract



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