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Sediment delivery to sustain the Ganges-Brahmaputra delta under climate change and anthropogenic impacts

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► To cite this version:

Jessica Raff, Steven Goodbred, Jennifer Pickering, Ryan Sincavage, John Ayers, et al.. Sediment delivery to sustain the Ganges-Brahmaputra delta under climate change and anthropogenic impacts. Nature Communications, 2023, 14 (1), pp.2429. 10.1038/s41467-023-38057-9 . hal-04084194

HAL Id: hal-04084194

<https://hal.science/hal-04084194>

Submitted on 27 Apr 2023

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1 TITLE

2 Sediment delivery to sustain the Ganges-Brahmaputra delta
3 under climate change and anthropogenic impacts
4

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42
43

44 **ABSTRACT**

45 The principal nature-based solution for offsetting relative sea-level rise in the Ganges-
46 Brahmaputra (G-B) delta is the unabated delivery, dispersal, and deposition of the rivers' ~1
47 billion tons of sediment. Recent hydrological transport modeling suggests that strengthening
48 monsoon precipitation in the 21st century could increase this sediment delivery 34-60%; yet
49 other studies demonstrate that sediment could decline 15-80% if planned dams and river
50 diversions are fully implemented. We validate these modeled ranges by developing a
51 comprehensive field-based sediment budget that quantifies the supply of Ganges and
52 Brahmaputra river sediment under varying Holocene climate conditions. Our data reveal
53 natural responses in sediment supply comparable to previously modeled results and suggest
54 that increased sediment delivery may be capable of offsetting accelerated sea-level rise. This
55 prospect for a naturally sustained G-B delta presents possibilities beyond the dystopian future
56 often posed for this system, but the implementation of currently proposed dams and diversions
57 would preclude such opportunities.

58

59 **INTRODUCTION**

60 Only in the past few years have global assessments of river-delta response to accelerated
61 sea-level rise and declining sediment supply utilized datasets more complete^{5,6} than the single
62 mean values often used in earlier studies⁷⁻⁹. Most earlier assessments yield grave predictions
63 for the response of deltas to climate change and human-related impacts, and while those
64 concerns are not unfounded, they generally oversimplify complex system behaviors and can
65 thus mask potentially more positive delta scenarios⁶. One risk of such negative but simplified
66 assessments is to foster dystopian narratives that uphold engineering structures as the key
67 defense against climate change, thereby undermining local to regional efforts to maintain
68 sediment supply and preserve land in these low-lying landscapes^{7,10}.

69 A robust supply of clastic sediment is the principal nature-based resource for offsetting
70 relative sea-level rise in river deltas, yet better constraints and data availability on the delivery
71 and dispersal of sediment are needed¹¹ to ensure that future delta scenarios accurately account
72 for both dynamic natural-system behavior¹² and the continuing impacts of development and
73 land-use change. Furthermore, it is increasingly important that coupled human-natural
74 approaches be used to predict delta fate, because as many as 630 million people currently live
75 in regions that may be uninhabitable by 2100 due to relative sea-level rise (RSLR), flooding, and
76 inundation¹³. Recent global delta studies using highly resolved, spatially and temporally varying
77 data inputs indeed suggest that more deltas than generally recognized have been gaining land
78 and that deltas overall may be collectively more robust than previously thought^{6,14-16}.

79 These recognitions are important because the fate of river deltas and their growing
80 populations are closely tied to riverine sediment supply¹⁴, which has a direct effect on land
81 reclamation efforts, household migration decisions, and the ability to occupy marginal
82 (vulnerable) lands¹⁷⁻¹⁹. For instance the relocation of >20,000 Rohingya refugees to a newly
83 emergent tidal island in the Ganges-Brahmaputra river-mouth estuary is a vivid example
84 involving each of these issues^{20,21}. In fact, the Bangladesh Delta Plan 2100 proposes numerous
85 coastal barriers (i.e., cross-dams) to trap sediment in the same region and accelerate the
86 growth of new land for potential reclamation and human occupation. The social, engineering,
87 and political challenges of relocating displaced communities to emergent lands

88 notwithstanding, a pre-requisite for coastal land reclamation remains the uninhibited delivery
89 of Ganges-Brahmaputra (G-B) river sediment and its effective dispersal across the coastal zone.

90 Among the world's river deltas, the G-B system presents an important example of deltaic
91 response to climate change and sea-level rise due to its naturally large sediment supply,
92 (currently) limited upstream damming, and an immense basin population of ~500 million
93 people³⁵. The basin's hydrology, climate, and sediment transport are controlled by the
94 seasonal South Asian monsoon, the strength of which varies considerably over decadal to
95 millennial timescales³⁶⁻³⁸. Indeed, both modeling and proxy records document large
96 fluctuations throughout the Holocene, with high precipitation in the early Holocene followed by
97 a general reduction after ~8 ka and a smaller increase in the last millennium or two³⁹⁻⁴⁵. For
98 the coming century, the most recent IPCC AR5 and AR6 reports continue to predict increased
99 and more variable monsoon precipitation by 2100 under nearly all representative GHG
100 concentration pathways (RCPs)^{46,47}. Such increases may be comparable to periods of stronger
101 monsoon earlier in the Holocene, and thus provide a possible analog for future responses. In
102 addition to the strengthening of monsoon precipitation, regional warming may also enhance
103 the melting of Himalayan glaciers and further increase discharge and sediment loads for at least
104 the coming decades or century^{3,48}.

105 Observation-based estimates for the supply of sediment currently delivered to the G-B delta
106 range from <500 to >1,100 Mt/yr (Mt = 10⁶ metric tonnes), representing considerable
107 uncertainty and a critical knowledge gap for projecting delta response to sea-level rise^{11,28-30}.
108 Looking forward, recent modeling studies by Darby et al. (2015)¹, Dunn et al. (2018)² and
109 Higgins et al. (2018)³ each consider future changes in G-B sediment supply and their potential
110 consequences for the delta. Their findings suggest historically unprecedented levels of change
111 in sediment supply from the Ganges and Brahmaputra rivers are possible over the next 50-100
112 years, either through reductions from damming and diversions (e.g., Higgins et al. 2018)³,
113 increases from strengthened monsoon precipitation and river discharge (e.g., Darby et al.,
114 2015; Fischer et al., 2017)^{1, 11}, or a combination of these factors (Dunn et al. 2018; Tessler et al.,
115 2018)². The modeled changes, although large ($\pm 50-90\%$), are comparable to other Asian river
116 systems that have undergone large changes in sediment load over the past century^{4,26,27}.

117 Toward a validation of such model projections of future sediment delivery to the G-B, we
118 present a highly resolved, mass-balanced sediment budget that: (a) utilizes over 6,000 new
119 field-based measurements from 500 locations (Figure 1) to provide (b) ground-truthing for
120 modeling studies and (c) a holistic view of river system connectivity from the Himalayan source
121 terrains to deltaic continental margin ^{22,23}. The budget is primarily derived from unpublished
122 borehole data, sediment volume, mass, grain size, and provenance, all supplemented by a
123 compilation of data from over 15 other studies (Tables 1, 2, S1). In addition to greatly improved
124 spatiotemporal resolution, this new work is distinct from previous G-B mass budgets ^{24,25} that
125 lacked any information on the river source (i.e., provenance) or grain-size distribution of stored
126 sediments. Both data types introduced here yield valuable results on total bedload contribution
127 to the delta and the varying and asymmetric delivery of sediment from the two main rivers in
128 response to climate change. To our knowledge, no mass balance of comparable detail and
129 longevity exists for a major river delta, thus providing an unparalleled perspective on natural-
130 system response to climate change and an opportunity to ground-truth modeled responses
131 under future climate scenarios.

132 Here we carefully quantify past changes and compare them with the sediment demands
133 that will be required for the G-B delta to offset projected increases in sea-level rise in the
134 coming century. Our work explores the validity of these sediment-delivery projections through
135 comparison with sediment-load responses to Holocene climate change and monsoon strength.
136 From field data we reconstruct the mass and grain-size distribution (caliber) of sediment
137 sequestered in the delta through the Holocene and how that mass was distributed and stored
138 to build the delta system.

139

140 **RESULTS AND DISCUSSION**

141 **Total Delta Sediment Composition**

142 Reconstructed sediment storage rates from the stratigraphic record represent minimum
143 total riverine sediment loads (bedload and suspended load) delivered to the G-B delta. Unless
144 otherwise noted, sediment delivery will be used to refer to sediment loads reconstructed from
145 stored Holocene sediments. The total mass of sediment stored in the G-B basin over the

146 Holocene (12—0 ka) is $>1.2 \times 10^7$ Mt (Table 1), which averages to a minimum mean delivery
147 rate of ~ 1000 Mt/yr and is comparable to the oft-cited modern load of ~ 1100 Mt/yr. The grain
148 size of sediment stored in the delta is approximately equally apportioned across muds (<62.5
149 μm – 30%), very fine to fine sand (62.5–250 μm – 39%), and medium to coarse sand (250–1000
150 μm – 31%) (Table 1). For this study, we conservatively classify sediments <250 μm (muds to fine
151 sand) as suspended load and larger particles 250–1000 μm as bedload^{31,49}. These delineations
152 result in Holocene delta deposits comprising $\sim 70\%$ suspended load and 30% bedload
153 sediments, considerably exceeding not only the 10% bedload transport rate often presented in
154 the literature but even high estimates typically placed at 20%^{31–33,50}. The significance is that
155 much of the long-term construction of the delta has been through the aggradation of bedload
156 sand, which is highly susceptible to upstream trapping in reservoirs and thus an important
157 consideration for future management of the delta⁴. Moreover, the bedload plays a
158 disproportionate role in the growth of bars and other locally elevated river topography upon
159 which many village communities are sited.

160

161 **Variable Holocene Sediment Storage**

162 Despite similarity between the average modern and Holocene rates for sediment reaching
163 the delta, sediment delivery over millennial timescales varies by $>200\%$ from lowest delivery
164 rates of 850 Mt/yr through the mid-late Holocene (6–0 ka) up to maximum delivery rates in the
165 early Holocene of 1200 Mt/yr (8–6 ka) to 2000 Mt/yr (10–8 ka) (Table 1; Figure 2). Fluvial
166 sediment began aggrading in the delta beginning ~ 12 ka at a rate of ~ 820 Mt/yr (12–10 ka) but
167 delivery increased to at least 2000 Mt/yr (double the modern load) during the period of
168 strongest monsoon from 10–8 ka. These results confirm previous findings that the Ganges and
169 Brahmaputra rivers carried a sediment load at least twice as large as the modern for over two
170 millennia. This large supply supported aggradation on the delta sufficient to offset very high
171 rates of sea-level rise that averaged >1 cm/yr over this period. These high early Holocene rates
172 of sediment delivery and sea-level rise are comparable to those anticipated for the next century
173 based on the Darby et al.¹ modeling for sediment supply and IPCC projections for sea-level rise
174⁵¹. These similarities between our paleo-reconstructions and the modeled futures of other

175 studies highlight a potential scenario of sediment supply whereby the delta may be able to
176 maintain itself against increases in sea-level rise over the next century.

177 Emphasizing that our budget reconstructions represent minimum supply rates, the portions
178 of the sediment load lost through transport to the Swatch of No Ground canyon and G-B fan are
179 not included in the Holocene sediment delivery rates. Such sediment bypass would have been
180 greatest from 12–8 ka when the river channels were constrained to their lowstand valleys and
181 discharged directly to the canyon head. Simple reconstructions of mud deposition in the Swatch
182 of No Ground and active channel of the G-B Fan ^{52–54} suggest that as much as another ~200
183 Mt/yr of sediment may have been delivered by the rivers in the early Holocene. After 8 ka,
184 though, most sediment delivered to the margin was efficiently trapped in the delta and
185 accounted for in our sediment budget, as reflected in part by the abrupt drop in sedimentation
186 on the G-B Fan after 9 ka despite continued high river discharge ^{52–54}. Interestingly, it is during
187 this period of effective sediment trapping that the sediment budget reveals an average long-
188 term sediment load of ~850 Mt/yr, which is slightly above half of the modern supply and
189 indicates that the G-B rivers responded as acutely to monsoon weakening as they did for
190 strengthening in the early Holocene.

191 In addition to variation in total mass delivered, the sediment loads between 12–10 ka and
192 10–8 ka are considerably coarser than the Holocene average and comprise ~40% medium to
193 coarse sand presumably transported as bedload (Table 1). In contrast, the proportion of
194 bedload transported to the delta decreases to ~20–25% after 8 ka. In all, this fraction of bedload
195 comprising delta stratigraphy is more than double the estimated modern value of 10% or less of
196 the measured total load ^{31–33,50}. However, we do not anticipate that future sediment supply
197 would be as coarse as these deposits, even under a strengthened monsoon. Nevertheless, the
198 importance of sand delivery by these large braided rivers for future delta stability should not be
199 undervalued, particularly in context of the massive mining of river sands occurring in the G-B
200 and other rivers worldwide ^{55,56}.

201

202

203

204 **Ganges and Brahmaputra Sediment Provenance**

205 Using bulk Sr concentration of stored sediments, which has been shown to be a reliable
206 indicator of river source in this system^{57–59} (Figure S3), we have quantified the fraction of
207 sediments delivered to the delta by the Ganges, Brahmaputra, and smaller local rivers. Results
208 for the Holocene show that nearly 54% of sediments were sourced by the Brahmaputra, ~30%
209 by the Ganges, and the remaining ~14% by local rivers including the Tista river in northwest
210 Bangladesh and others draining the Indo-Burman fold belt and Shillong Massif to the east (see
211 Methods for further details). Both major rivers demonstrate considerable variability in
212 sediment delivery throughout the Holocene, but responses are more pronounced for the
213 Brahmaputra catchment (Table 2, Figure 2). Since 10 ka, the long-term averages for Ganges
214 sediment load ranges 308 to 426 Mt/yr, which is comparable to the variance in modern load
215 estimates of 300–450 Mt/yr^{30,60,61}. This suggests that Ganges discharge has been relatively
216 stable even with considerable regional climate variability, a finding that is consistent with the
217 similarly modest response projected by Darby et al. (2015) under future climate scenarios. Note
218 that the low Ganges value of 116 Mt/yr stored from 12–10 ka (Table 2) is likely an
219 underestimate due to sediment bypassing, as sedimentation on the G-B fan remained high at
220 this time^{52,54}.

221 In contrast, sediment load for the Brahmaputra has been highly variable over the Holocene,
222 with a 4-fold range from a high of ~1100 Mt/yr at 10–8 ka to a low of ~370 Mt/yr from 6–0 ka.
223 Relative to the Brahmaputra's modern load of 500–650 Mt/yr, these values represent a long-
224 term doubling and halving over the Holocene, respectively, reflecting acute response to
225 monsoon strength and related sediment production and transport processes. As for the
226 Ganges, the magnitude of response for our Brahmaputra reconstructions is similar to the
227 projections made by Darby et al. (2015), lending confidence to their results of increased, but
228 differential, future sediment transport for each river. In particular, the differing response of
229 Ganges and Brahmaputra sediment load to climate change will remain highly relevant to
230 managing the G-B delta, given that the largest sediment-source areas for the two rivers lie in
231 India and China, respectively.

232

233 **Response to monsoon variability**

234 The modeling of river discharge under future climate change suggests that increases in G-B
235 sediment load of 34-60%¹ are possible, which would be a substantial increase in sediment
236 delivered to the G-B delta and thus a potentially important buffer against accelerated rates of
237 sea-level rise. These modeled values are supported by our findings from the early Holocene
238 period (12–8 ka) of strengthened monsoon, when fluvial sediment loads were enhanced for
239 both river systems compared to periods of weaker monsoon from 8–0 ka. Between periods of
240 stronger and weaker monsoon conditions, Brahmaputra discharge varied from 370-1100
241 Gt/yr/377-1119 Mt/yr (i.e., a ± 2 -fold difference from modern), whereas the Ganges varied only
242 308-426 Mt/yr (i.e., a range comparable to modern estimates). Note we do not include here the
243 low Ganges value of 116 Mt/yr for the 12-10 ka period due to presumed sediment bypassing at
244 this low sea-level stage.

245 Our sediment budget reconstructions are also consistent with the results of Darby et al.¹
246 further suggesting that the Brahmaputra river catchment is considerably more sensitive to
247 changes in climate, and that during wetter periods it is the more dominant source of sediment
248 to the delta. Importantly, there is no overlap in methods between our paleo-reconstructions
249 and the forward-looking projections of Darby et al. (2015)¹, suggesting that the comparable
250 results provide a reasonable reflection of G-B system dynamics. Among the reasons for such an
251 acute response from the Brahmaputra relative to the Ganges is the catchment's proportionally
252 smaller lowland area¹ that limits its capacity for sediment storage. This reduced buffering
253 capacity means that variations in sediment yield from the Brahmaputra catchment reach the
254 delta more quickly and with less attenuation than those from the Ganges catchment²².
255 Another factor contributing to acute response of the Brahmaputra sediment supply to climate
256 is the catchment's large area of relatively arid and sparsely vegetated highlands in Tibet, where
257 modest changes in the water budget can drive much higher or lower erosion rates⁶².
258 Moreover, recent (2003–2008) loss of glacial elevation in the Himalayan catchments⁶³
259 introduces glacial melt as another source of increased discharge and sediment delivery,
260 although persistence of this contribution may wane beyond 2100 as ice extent contracts³.

261 In contrast to the Brahmaputra, the Ganges catchment lies at the center of the South Asian
262 monsoon system with robust precipitation and vegetation across the Himalayan front range,
263 which is where most sediment and water discharge are generated. The Ganges also hosts a vast
264 foreland filled by alluvial mega-fans that are capable of storing sediment; however, their ability
265 to buffer short-term changes in sediment supply is limited because many fan channels in the
266 Ganges basin are incised and decoupled from the adjacent plains, or are otherwise heavily
267 embanked like the Kosi River fan, causing greater downstream bypass of sediment^{50,64}. Indeed,
268 during the early Holocene when the monsoon was strong, the Ganges system incised and
269 remobilized megafan sediments that had aggraded in the early post-glacial period^{64–66}. These
270 phenomena in the Ganges catchment support results from models indicating that variable
271 water supply (e.g. due to fluctuations in monsoon strength) can cause periods of aggradation
272 when water flux decreases and periods of incision when water flux increases⁶⁷. Overall, the
273 Ganges fan systems serve to buffer variance in sediment supply as compared with the
274 Brahmaputra that has proportionally less lowland storage area, which is well reflected in both
275 our Holocene reconstructions and the Darby et al.¹ scenarios for the next century.

276 Given interest in the potential increase in sediment load under future climate scenarios, it is
277 important to also consider the timescales at which sediment stored in the upper catchment
278 may be remobilized from hillslope, valley, and floodplain settings and delivered to the delta.
279 Our paleo-reconstructions do not provide great precision on those timescales, but evidence
280 from both the G-B and the Indus delta systems show that changes in the supply of riverine
281 sediment load respond to monsoon precipitation at timescales less than the sub-millennial
282 resolution of radiocarbon-dated stratigraphic sections^{25,68}. Such short response times would
283 indeed be consistent with hydrologically driven changes in transport and an abundance of
284 available sediment (i.e., a transport limited system)⁶⁷. Indeed ~95% of the G-B sediment load is
285 delivered during the summer monsoon and resulting period of high river discharge (May–
286 October). In this context, more precipitation over the catchment readily remobilizes abundant
287 sediment stored as hillslope regolith and alluvial deposits in the upper catchment. Modern
288 examples also appear to confirm rapid sediment transfer from upland source areas to the
289 Bengal margin, perhaps best exemplified by the decadal-scale transport and delivery of

290 Brahmaputra bedload introduced by 100s of landslides generated in the major 1950 Assam
291 earthquake (M 8.6) ^{69,70}. Similarly, HydroTrend, the climate-driven hydrological water balance
292 and transport model used by Darby et al. (2015) to consider future basin response to increased
293 precipitation, does not suggest any significant lag time for the delivery of G-B sediment to the
294 delta ¹.

295

296 **Can increased supply support sediment needs?**

297 To better understand the implications of varying sediment load and rates of sea-level rise
298 on delta sustainability, we have produced mass balance estimates under a variety of past,
299 present, and future scenarios (Figures 3 and 4). The $\Delta Mass$ rates (Mt/yr) represent the annual
300 excess (>0) or deficit (<0) supply of sediment for each scenario, and the $f_{(supply)}$ is the fractional
301 excess or deficit of delivered sediment specifically for the medium-demand scenario. Results
302 show an excess of sediment delivery under most natural conditions during the Holocene and
303 modern, even during periods of rapid sea-level rise comparable to the rates anticipated for the
304 coming century (5 to 12.5 mm/yr). The modern mass delivery also readily meets demand using
305 the most often reported sediment load value of 1100 Mt/yr, but the delta would be facing a
306 measurable deficit if the occasionally cited value of 700 Mt/yr were correct ^{28-30,60}. Given the
307 G-B delta's persistent growth in land area over the last few decades and centuries ⁷¹⁻⁷³, the
308 higher value of 1100 Mt/yr appears to be more accurate. For the future, unabated sediment
309 delivery in the 2050 and 2100 climate-only scenarios yield a $f_{(supply)}$ ranging from a slight to
310 moderate deficits of 7-20%, meaning that erosion rates and land loss may be correspondingly
311 slow and provide valuable time for mitigation strategies to be implemented. These mass
312 balance results (Figure 3) are consistent with persistent growth of the delta from Holocene to
313 modern and are not simply optimistic calculations. Rather, these reconstructions and future
314 scenarios emphasize natural resilience of the G-B delta linked to the region's robust monsoon
315 precipitation and high sediment yield from the tectonically active Himalayan Mountains.

316 Evidence of a robust and resilient G-B delta has received less attention than scenarios
317 considering a heavily engineered future, where major sediment reductions and high rates of
318 land loss are likely – yet both outcomes are plausible, and the eventual pathway is more

319 contingent on the decisions of policy makers than on climate change. Indeed, our mass balance
320 estimates (Figure 3) show massive sediment deficits of more than 100% to over 2000% under
321 all future scenarios that consider widespread dam construction and water diversions. These
322 futures are the ones that will more aptly compare the G-B delta with the catastrophic land loss
323 already occurring in the Mississippi, Nile, Indus, Mekong, and other deltas fed by heavily
324 dammed rivers^{9,74,75}. Thus, the G-B delta is not doomed to drown under climate change – it is
325 doomed to drown under scenarios of anthropogenic reductions in the delivery and dispersal of
326 sediment to the delta⁷⁶.

327 Many damming and diversion plans for the G-B rivers have been developed but not yet
328 widely implemented³, thus presenting a window of opportunity to better steward the G-B delta
329 future. A major risk of not acknowledging the G-B delta's intrinsically robust sediment supply
330 and potential resilience against rising sea level is that environmental managers will otherwise
331 plan for the dystopian future of a drowning landscape and the development of policies that
332 steer toward this anticipated outcome of ruin^{10,77}.

333 Although the potential for considerably enhanced sediment delivery to the G-B delta exists,
334 it alone would still be insufficient to sustain the system. Rather, delivered sediment must also
335 be allowed to freely disperse to regions of the delta where it is needed to offset subsidence and
336 rising sea level. Within the G-B delta itself, widespread embankments in the tidally influenced
337 coastal zone already limit such sediment delivery to poldered islands⁷⁸ and have exacerbated
338 local sea-level rise⁷⁹. Potentially sustainable efforts to manage sediment accretion in these
339 embanked polders are underway but still face implementation challenges^{14,80,81}.

340 In contrast, in natural areas of the delta such as the Sundarbans mangrove forest, a
341 protected UNESCO World Heritage site, and the Meghna (G-B) River mouth estuary, unhindered
342 sedimentation is rapid and is readily keeping pace with effective sea-level rise (0.5-1.5 cm/yr)
343^{76,82,83}. In fact, in the rivermouth estuary, low barriers (i.e., cross dams) built across shallow
344 waterways have been effective at trapping sediment and rapidly converting open water to
345 emergent intertidal and supratidal lands. Such land reclamation projects are a key part of
346 Bangladesh's plans for mitigating the effects of sea-level rise, but the success will require the
347 continued uninhibited delivery and dispersal of sediment. Even under scenarios of enhanced

348 sediment delivery, maintaining these natural morphodynamic processes will remain an
349 essential ingredient for long-term sustainability of the delta, which cannot be fully managed or
350 hardened given its size, complexity, and large mass and energy inputs ^{12,84}.

351

352 **Anthropogenic threats to future sediment delivery**

353 Despite projected increases under a strengthened monsoon, anthropogenic factors may yet
354 dominate the system-scale responses and drive sediment loads to be considerably lower.

355 Specifically, plans across South Asia for hydropower development and interbasinal watershed
356 management portend major reservoir construction and water diversions in the coming century
357 ^{3,85}. Modeling of the impact of these activities on the river basins suggests moderate (30%) to
358 extreme (88%) decreases in sediment discharge under a range of plausible river-management
359 scenarios ^{2,3} (Figure 3). Existing studies focus on the impact of India's National River Linking
360 Project (NRLP) and hydropower projects in Nepal, both of which disproportionately affect the
361 Ganges river system ^{2,3}. No study has yet assessed the potential impact of China damming the
362 Yarlung Tsangpo ⁸⁵, which is the primary water and sediment source for the Brahmaputra.

363 Uncertainty in the G-B delta sediment budget hinders the ability to create sustainable
364 development plans ¹¹ and makes it possible for upstream decision-makers to justify continued
365 dam construction and water diversions ⁸⁶⁻⁸⁹ at the expense of downstream sediment supply to
366 the delta ^{86,90}. Reduced sediment supply will threaten delta stability, particularly if loads
367 decrease below those needed to maintain the delta surface above sea level ^{80,82}. In other mega-
368 deltas like the Mekong and Mississippi, reduced sediment loads from damming and sand
369 extraction have already led to increased saltwater intrusion, decreased soil fertility, loss of land
370 area with rising sea level, and elevation deficits that increase susceptibility to flooding and storm
371 surges ^{9,74,75}.

372 Amidst typically negative risk assessments of the G-B delta, it is rarely acknowledged that
373 the system has persistently gained several km²/yr of land-surface area for at least the last
374 several centuries, a pattern that continues today without any sign of waning ^{76,84}. With the next
375 century of climate change, models indicate that the delivery of sediment to the delta will not
376 only persist but likely increase considerably, with the potential to offset accelerating rates of

377 sea-level rise ^{1,11}. Such projections are consistent with the Holocene sediment reconstructions
378 presented here (Figures 2 and 3), and these results collectively suggest that the G-B delta may
379 be among the world's most naturally resilient large coastal systems.

380 The magnitudes of sediment delivery suggested by our field-based reconstructions and the
381 modeled natural scenarios are very similar, suggesting that the results are reasonably robust;
382 however, even if future increases in sediment load are less than suggested here, a key point is
383 that any increase in sediment supply will help mitigate the impacts of sea-level rise and delay
384 delta drowning. With global warming and sea-level rise baked into the climate system for
385 centuries, any factors such as increased sediment delivery that can delay or reduce impacts
386 may be critically important for effective and manageable human responses.

387

388 **Importance of perception to delta futures**

389 Increased sediment delivery under a strengthened monsoon supports the possibility for a
390 more favorable G-B delta outcome under a majority of future climate scenarios. These natural-
391 system responses to climate variability support conclusions from future model scenarios for the
392 coming century ^{1,91} and modern field-based studies ^{76,82} that the G-B delta is not inherently
393 doomed to drown. Instead, proper management of sediment resources, particularly within at-
394 risk coastal regions ^{78,80}, may provide security for coastal populations and livelihoods often
395 presented as unviable under future climate scenarios^{10,77,92,93}. However, the persistence of a
396 doomed-to-drown narrative for Bangladesh may perpetuate dystopian views in which particular
397 regions of the delta or livelihoods are considered unsustainable and thus become subject to
398 maladaptive policies ⁷⁷. Such perceived threats shift the focus of mitigation projects toward the
399 strengthening or expanding of hard infrastructure, approaches that have already disrupted
400 sedimentation processes and undermine the delta's natural resilience to sea-level rise ¹². The
401 resulting impacts may exacerbate the displacement of households and increase migration away
402 from these supposedly unsustainable coastal locations ¹⁰. Although hard-engineering responses
403 may continue to be part of a sensible coastal management plan, adopting them under threat of
404 a dystopian future may steer policies away from more nature-based solutions and other

405 sustainable development policies that would bolster long-term stability of the coastal zone
406 through the effective management of sediment delivery and dispersal.

407 Upstream of the delta, though, a key concern is how the supply of sediment reaching the
408 delta will be impacted by anthropogenic activities in the catchment basin. In other words, any
409 natural increase in sediment delivery resulting from increased monsoon precipitation ^{1,91} will
410 compete with anthropogenic decreases caused by the construction of proposed dams and
411 water diversions upstream of the delta^{2,3,80}. In all, the work presented here and by others ^{6,76}
412 offers the possibility for a more optimistic future that is often absent in the literature and
413 media coverage of the G-B delta. The emerging narrative on fate of the delta shifts somewhat
414 away from climate change and more toward the sustainable management of water and
415 sediment resources, both in the upstream catchment and across the delta itself. The caveat is
416 that the G-B delta may be more resilient to climate change only in the absence of major dam
417 construction and water diversions upstream of the delta and major disruptions to the effective
418 delivery and dispersal of sediment across the delta and coastal zone.

419

420 **METHODS**

421 **Data source**

422 The sediment budget is produced from a largely unpublished dataset of sediment grain-size
423 and geochemistry measured on 6,100 sediment samples from 455 boreholes collected by the
424 authors and colleagues between 2011-2021. The boreholes have a maximum depth of 95 m and
425 were collected in 23 transects across the delta. The stratigraphy for about half of these cores
426 (~200) has been published in five previous papers ⁹⁴⁻⁹⁸, the radiocarbon ages are published in
427 Grall et al. (2020), and local grain-size and mass-balance for one sub-basin of the delta
428 published in Sincavage et al. (2019). These data are supplemented by widespread core and
429 seismic data previously published by Ahmed et al. (2010), Bangladesh Agriculture Development
430 Corporation (1992), Shamsudduha et al. (2008), Pate et al. (2009), Department of Public Health
431 Engineering and Japanese International Cooperation Agency (JICA) (2006), JICA (1976), Ghosal
432 et al. (2015), Hait et al. (1996), Hoque et al. (2012), Hoque et al. (2014), Khan & Islam (2008),
433 Michels et al. (1998), Palamenghi et al. (2011), and Sarkar et al. (2009) ⁹⁹⁻¹¹³. These

434 supplemental data extend across the entire Bengal Basin, including the continental shelf and
435 West Bengal, India where we do not have samples. The complete compilation of data from
436 these sources adds 3,720 sites to the more detailed results from our 455 cores.

437

438 **Field and laboratory methods**

439 Sediment samples for the cores in this study were collected at 1.5-m depth intervals and
440 photographed, described, and packaged in the field ^{95–97}. In the lab, every third sample with
441 depth as well as samples at sedimentologic contacts were analyzed for grain-size distribution
442 using a Malvern Mastersizer 2000E particle size analyzer at $\frac{1}{4}$ ϕ intervals from clays (0.49 μm)
443 to coarse sands (1000 μm). Samples were also analyzed for bulk geochemistry by X-ray
444 fluorescence using a portable Thermoscientific Niton XL3 Analyzer (pXRF), which returns
445 information on composition of both major and trace elements in the sediments. Strontium
446 concentrations from the XRF results are used to document sediment provenance following
447 published methods ¹¹⁴, effectively distinguishing sediment deposited by the Ganges,
448 Brahmaputra, mixed Ganges-Brahmaputra, or other local river sources ^{57–59} (Figure S3).
449 Sediments having higher bulk Sr values >130 ppm are derived from the Brahmaputra basin,
450 which drains mafic batholiths along the Tsangpo suture zone, compared with lower bulk Sr
451 values < 110 ppm for the Ganges (in central and western G-B) or local sediment sources in the
452 north (Tista River), northeast (Shillong Massif), and east (Indo-Burman Fold Belt). Of the 6100
453 samples analyzed to date for grain size and geochemistry, over 4,000 are Holocene-aged and
454 included in this study.

455

456 **Mapping**

457 Mapping of Holocene G-B delta deposits was performed using ArcGIS. The Holocene-
458 Pleistocene boundary depth was identified using sediment grain size, color as a proxy for
459 oxidation state, and radiocarbon data from the aggregated dataset ^{94–96,105,115–117} and
460 supplemented with depth data from cores, wells, and seismic data in reports and previously
461 published studies ^{99–112}. Simple co-kriging was used to create an interpolated prediction surface
462 of the depth to the Pleistocene boundary from both the hand drawn contours and depth

463 information from >950 core sites and hundreds of kilometers of seismic lines from many studies
464 ^{99–112}. To synthesize the data from these 6000+ samples and to control for variance related to
465 regional tectonics and structure, antecedent Pleistocene topography, and the backwater and
466 coastal transition, we partitioned the delta into 9 physiographic and depositional regions based
467 on similarities in processes and inputs (see Fig. S2). Several of these regions are parsed further
468 into sub-regions, largely based on the core-data distribution, to increase the sediment budget
469 resolution and to account for downstream fining and fluvial depositional processes. The main
470 provinces include the Jamuna valley, Ganges valley, Sylhet basin, Meghna valley, Fold Belt,
471 Madhupur Terrace, West Bengal, Interfluve, and Offshore. We then regroup these sub-regions
472 into valleys (Jamuna valley, Ganges valley, Meghna valley), interfluves (Madhupur Terrace,
473 Paleo-interfluve, Fold Belt, West Bengal), and basins (Offshore, Sylhet Basin). To better
474 understand the subsurface stratigraphy, we calculated the grain-size distribution of all samples
475 by 5-m depth bins within spatiotemporal units and then multiplied by the total sediment mass
476 in that unit to yield the sediment-mass grain-size distribution by depth for each region (n=251;
477 see supplemental materials).

478 Due to spatially varying subsidence rates and temporally changing eustatic sea-level rise
479 that control accommodation in the delta, simple depth conversions do not correlate well with
480 age of the deposits. In other words, establishing well-defined time horizons from radiocarbon
481 ages is complicated by instantaneous variations in delta surface topography. However,
482 averaged over longer periods typical of channel avulsion and migration (i.e. 1000-2000 years),
483 ^{96,118,119} a stable or growing delta system must infill accommodation generated. Therefore, the
484 potential mass of stored sediment at any given interval will be a function of the volume created
485 by subsidence and sea-level rise. Thus, the Holocene unit has been partitioned into Time-
486 Equivalent depositional units (TEQ) based on regional subsidence patterns derived from a large
487 radiocarbon database (n>200) in Grall et al. (2018) ¹¹⁵ and combined with eustatic sea-level
488 reconstructions from Lambeck et al. (2014) ¹²⁰. These relative sea-level rise controls were used
489 to map the base-level and delta surface at 6 ka, 8 ka, 10 ka, and 12 ka. The resulting surfaces
490 were spliced in GIS to form TEQ units that correspond to accommodation generated during the
491 periods 6—0 ka, 6—8 ka, 8—10 ka, 10—12 ka. To calculate the delta surface over which

492 sediments were deposited and the volume of material stored during each TEQ, we subtracted
493 the interpolated Holocene surface from the effective subsidence (land subsidence and sea-level
494 rise) over those years in ArcGIS (Fig. S1, Table S1). The volume of each TEQ was multiplied by a
495 mean bulk density based on field measurements to derive the mass of sediment stored on the
496 delta during each TEQ. The bulk densities used range from 1.3 g/cm³ in the shallow units to 1.8
497 g/cm³ in the deepest units, and a lower value of 1.1 g/cm³ for muddy coastal and shelf units. To
498 calculate the grain-size distribution of each sediment package, we isolated the samples from
499 each core contained within the TEQ, calculated the average grain-size distribution, and
500 interpolated the grain-size distribution to the total mass of the material in each TEQ.

501

502 **Offshore and West Bengal delta regions**

503 For the offshore and West Bengal physiographic regions where we have not collected cores,
504 we base the budget calculations on published studies. For the offshore, growth of the
505 subaqueous delta began after ~8 ka and the stored sediment mass determined from seismic
506 and core data^{52,121}. Our budget calculations proportionally distribute 75% of this offshore
507 delta sediment to the 6–0 ka interval and 25% to the 8–6 ka interval. The source of offshore
508 sediment was partitioned between Brahmaputra (~60%) and Ganges (~40%) based on Sr
509 measurements of shelf sediment by Garzanti et al. (2019)¹²² and Lupker et al. (2013)¹²³. The
510 grain-size distribution of sediments stored in West Bengal is taken from previously published
511 data in Stanley & Hait (2000)¹²⁴, who measured the mud:sand ratio to be ~70:30 in a series of
512 Holocene-scale cores (<50 m). The average Holocene thickness of sediments in their cores was
513 25 m with a maximum thickness of ~45 m. Although kriging analyses show the maximum
514 predicted thickness of Holocene sediments in West Bengal to be ~70 m, >90% of the total
515 sediment package is stored in the upper 45 m, so the data from Stanley & Hait (2000) can be
516 used. For comparison, our data from the G-B interfluvium east of the Ganges valley and just
517 opposite the West Bengal region is a comparable ~63% mud and ~37% sand. Since this grain-
518 size distribution aligns well with measurements from West Bengal¹²⁴, we apply the same
519 distribution for sediment stored in that region.

520

521 **Sediment surplus and deficit calculations**

522 A simple mass-balance model compares the mass aggradation needed to offset relative sea-
523 level rise (RSLR) for the G-B delta with reconstructed sediment delivery rates (Figure 3). The
524 upper delta extends from the delta apex to the slope break at the fluvial- to tide-influenced
525 transition (Fig. S2), the lower delta from the tidal transition at the slope break to the coast, and
526 the marine delta from the coast to base of the subaqueous delta foresets. We apply mean
527 subsidence rates and mean eustatic sea level to each of these regions using a bulk density of
528 1.5 t/m³ typical of the upper 20 m of sediment. Additional details on calculation steps are
529 provided in Figure 3.

530

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- 866

867 **ACKNOWLEDGEMENTS**

868 This work was supported in part by U.S. National Science Foundation grants OISE-0968354 to
869 S.L.G., M.S.S., and C.P., RISE-1342946 to S.L.G., OCE-1600319 to S.L.G., J.C.A., J.M.G., OCE-
870 1600258 to C.A.W., BCS-1716909 to C.A.W., K.G.R., and J.M.G., and U.S. Office of Naval
871 Research grant N00014-11-1-0683 to S.L.G., J.C.A., M.S.S. and J.M.G. The authors also thank
872 contributions from Rachel L. Bain and Thomas R. Hartzog and field support from the
873 Department of Geology, University of Dhaka and Nazrul Islam Bachchu of Pugmark Tours and
874 Travels.

875

876 **AUTHOR CONTRIBUTION STATEMENT**

877 S.L.G., C.P., and M.S.S. designed the original project, and all authors contributed to its
878 intellectual development and success. J.L.R., J.L.P., R.S.S., M.S.H., C.A.W., D.R.M., J.-L.G., C.J.G.,
879 K.G.R., M.D., R.P.H., M.G.M., and L.A.W. conducted the field sampling and lab analyses. J.L.R.,
880 S.L.G., J.L.P., R.S.S., and C.A.W. developed and analyzed the dataset. J.L.R. and S.L.G. wrote the
881 manuscript with contributions from J.L.P., R.S.S., J.C.A., C.A.W., C.P., M.S.S., C.J.G., K.G.R.,
882 E.A.C., and R.P.H. All authors reviewed and commented on the manuscript.

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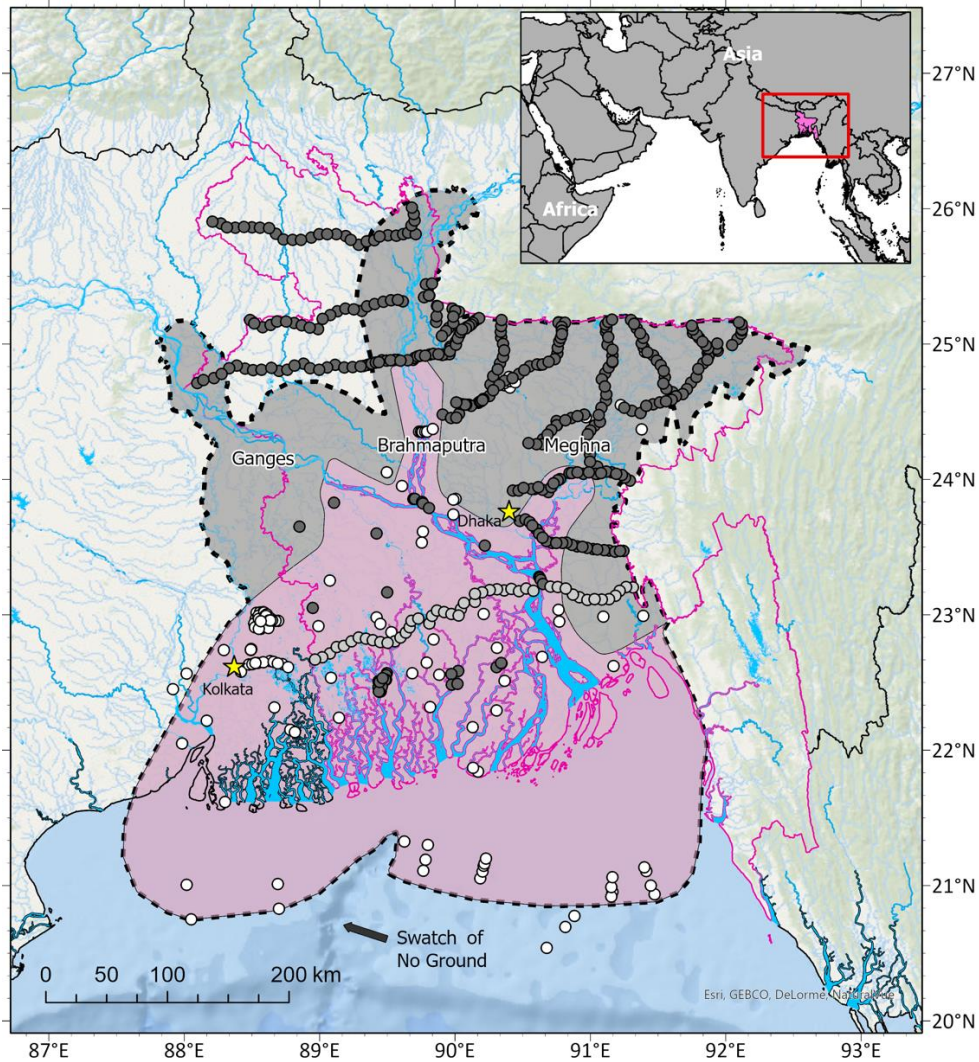
884 **COMPETING INTERESTS STATEMENT**

885 The authors declare no competing interests.

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887

888 **Figure 1.** Map of Bengal basin and the Ganges-Brahmaputra River (G-B) delta in South Asia
889 showing the study area and sampling and data locations. The G-B delta and lower Ganges and
890 Brahmaputra rivers are located in Bangladesh and West Bengal, India. The Holocene delta
891 developed on an incised Pleistocene surface and the boundary of Holocene deposits is shown
892 by the black dashed line. The subaqueous portion of the Holocene delta is located on the shelf
893 and bordered by the Swatch of No Ground canyon and Bay of Bengal to the south. Over 450
894 boreholes from this study are denoted by the dark and light gray--filled circles ^{115,127,128}, with
895 the light gray circles demarking Transect G cores shown in Figure S3. Core and acoustic-flection
896 data from other studies used to define the thickness and extent of Holocene delta deposits are
897 shown by white-filled circles ^{99–104,106,108,110–112}. The border of Bangladesh is outlined in pink, and
898 the pink-shaded region represents the higher-risk coastal zone based on the model domain
899 used in Akter et al. (2021) ⁸³. World Ocean Base layer is from Esri, GEBCO, NOAA NGDC, HERE,
900 Garmin, and other contributors; the world countries shapefile is from Esri, Garmin
901 International, Inc., and the U.S. Central Intelligence Agency (The World Factbook); and the
902 hydrology shapefiles (World Water Bodies and World Linear Water) are from Esri and Garmin
903 International, Inc.



905 **Table 1. STILL GOING TO UPDATE THIS TABLE TO REMOVE the 'a' onshore-only values and just**
 906 **include the 'b' total values for the 6-0 and 8-6 ka periods.** Average mass storage rates and grain
 907 size distributions for deposits stored on the Ganges-Brahmaputra delta over the last 12 kyr.
 908 Highest rates of sediment delivery and storage in the delta occur between 10—8 ka and
 909 correspond with a sandier sediment load.
 910

Years	Mud (Mt/yr) (<62.5 μm)	Fine sand (Mt/yr) (62.5-250 μm)	Medium-coarse sand (Mt/yr) (250-1000 μm)
6-0 ka ^a	226	249	137
6-0 ka ^b	389	294	162
8-6 ka ^a	262	474	284
8-6 ka ^b	425	519	309
10-8 ka	505	824	671
12-10 ka	171	277	371

^a Onshore material only included. ^b Offshore mass distributed with 75% of material contained in the 6-0 ka unit and 25% of material contained in the 8-6 ka unit.

911

912 **Table 2.** Average mass storage rates and percent contribution for each river system throughout
 913 the Holocene. The Brahmaputra is the main contributor of sediment in the early-mid Holocene
 914 (12–6 ka), while the Ganges delivers most of the sediment over the last 6 kyr. Storage rate data
 915 are plotted in Figure 2C.
 916

6–0 ka		
Source	Storage Rate (Mt/yr)	Percent Contribution
Ganges	426	50.4%
Brahmaputra	377	44.7%
Mixed G+B	7	0.8%
Other	35	4.1%
Total	845	

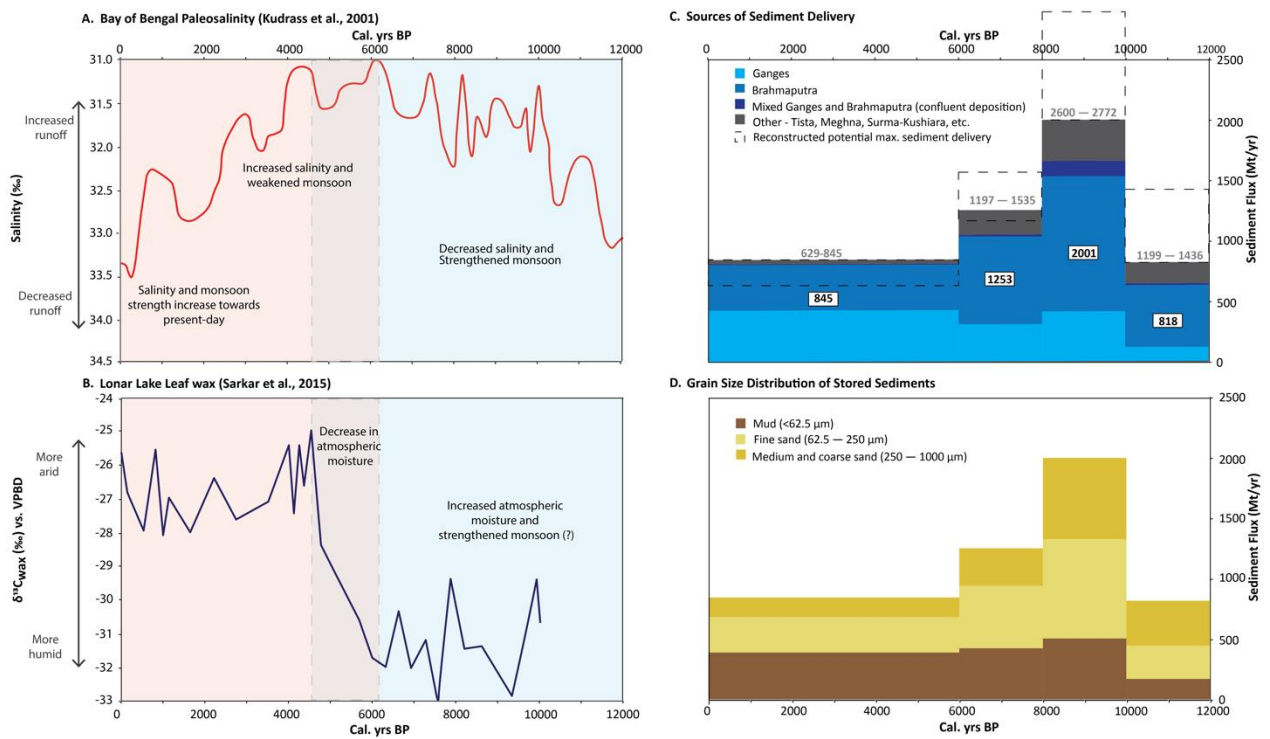
8–6 ka		
Source	Storage Rate (Mt/yr)	Percent Contribution
Ganges	308	24.6%
Brahmaputra	726	58.0%
Mixed G+B	17	1.3%
Other	202	16.1%
Total	1253	

10–8 ka		
Source	Storage Rate (Mt/yr)	Percent Contribution
Ganges	413	20.7%
Brahmaputra	1119	55.9%
Mixed G+B	128	6.4%
Other	340	17.0%
Total	2001	

12–10 ka		
Source	Storage Rate (Mt/yr)	Percent Contribution
Ganges	116	14.2%
Brahmaputra	512	62.6%
Mixed G+B	16	2.0%
Other	174	21.2%
Total	818	

917

918 **Figure 2.** Changes in paleosalinity (A) and atmospheric moisture (B) correspond with observed
 919 changes in the mass and caliber (C-D) of sediment stored on the Ganges-Brahmaputra delta. A)
 920 A paleosalinity record from sediment cores collected in the northern Bay of Bengal ⁴¹ provides a
 921 proxy record for an enhanced early Holocene monsoon, when runoff and river discharge
 922 increased and lowered salinity of the surface mixed layer. Salinities decrease after 6 ka under
 923 weakening monsoon precipitation and reduced (but still large) river discharge. B) Terrestrial
 924 records of leaf-wax stable carbon isotopes from lacustrine sediments in Lonar Lake, central
 925 India ⁴⁰ provide evidence for increased atmospheric moisture during the early Holocene
 926 Climatic Optimum (~9-5 ka), with sharply decreasing moisture levels with monsoon weakening
 927 after ~6 ka. C) In the early Holocene, most sediment was deposited by the Brahmaputra river,
 928 followed by the Ganges. For the last 6 kyr, the two rivers have deposited a roughly equivalent
 929 mass of sediment on the delta but with few deposits reflecting any mixing between them.
 930 Other tributary sources have locally contributed sediment to the delta, but the amount is
 931 comparatively minor. Observed sediment delivery rates over the Holocene are denoted in
 932 white boxes and the reconstruction of the maximum potential reconstructed sediment load
 933 based on bypassing estimates are shown in gray text within the dashed boxes.



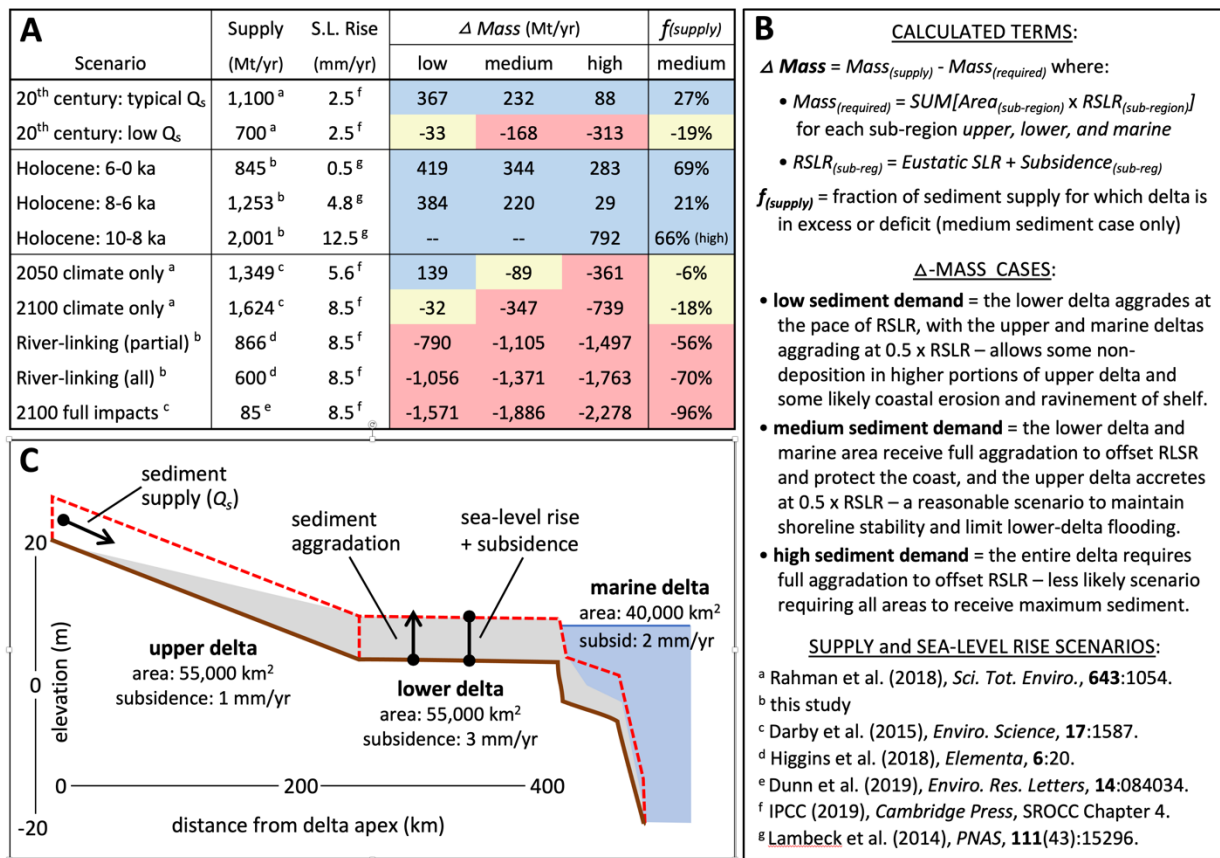
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Figure 3. Modern, Holocene, and future mass-balance calculations comparing rates of sediment delivery against the mass required to offset sea-level rise and subsidence. (A) Summary of the mass-balance scenarios, showing input values for sediment supply and sea-level rise and the calculated outputs for $\Delta Mass$ and $f_{(supply)}$. Calculations of required mass for each scenario can be found in Table S4. (B) An explanation of the calculated terms, the conditions for each $\Delta Mass$ case, and the data sources are provided along with (C) a schematic diagram of the mass-balance model for the delta. The Holocene: 10-8 ka scenario considers only the high sediment demand case, as the whole delta aggraded in response to rapid sea-level rise during this period.



948
 949

950 **Figure 4.** A) Comparison of future changes in sea level (shown relative to 1992 CE)¹²⁹ to B)
 951 Holocene changes in global sea level (shown relative to EGM96)¹²⁰. Local sea level (not shown)
 952 ¹³⁰ and relative sea level is expected to rise by ~1 m by 2100 (blue line, panel A). C) In the
 953 future, predicted changes in monsoon strength¹ and river damming with the National River
 954 Linking Project (NRLP)^{3,131} indicate that sediment fluxes reaching the delta may increase or be
 955 reduced. Minimum required sediment delivery is calculated using the whole delta area (Table
 956 S4), so less sediment delivery may still sustain the at-risk portions of the delta against rising sea
 957 level. D) The rate of sediment storage on the delta exceeded the necessary sediment required
 958 to keep pace with sea level between 10–8 ka, and for the last 8 ka, whole-delta storage rates
 959 have closely matched or exceeded sediment requirements contributing to progradation of the
 960 delta. Ultimately, changes in sediment delivery to the delta are likely to occur from river
 961 damming^{3,131}, sand mining (Sickmann et al., in prep), strengthening monsoon¹³², and
 962 anthropogenic climate change^{1,132}.

