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Sand mining across the Ganges–Brahmaputra–Meghna Catchment; assessment of activity and implications for sediment delivery

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Abstract

While issues of pollution, floods and drought in our rivers are widely studied, there is a hidden crisis with respect to the widespread global extraction of sand. Large volumes of sand are needed in the construction industry to make concrete. So far, calls for greater monitoring of sand mining activity have largely gone unmet. This is due to the fact mining is extensive, often hidden (e.g. underwater) and thus very difficult to properly assess. To meet this challenge, we use remote sensing methods to detect and monitor sand mining activities at the catchment scale, across the Ganges-Brahmaputra-Meghna River system (catchment size 1.72 million km^2). Based on this analysis, here we show that mining activity is diverse and pervasive across the Ganges–Brahmaputra–Meghna Catchment system for our study period of 2016–2021, with rates of extraction increasing within some of the rivers. Results show the total estimate for sand extraction is $\sim$115 Mtyr^{-1} $\pm$ 20 Mtyr^{-1}, which is of a similar order of magnitude to the natural bedload flux of the catchment. While there are some limitations to deriving estimates based solely on imagery, this work highlights both the widespread spatial extent and large magnitude of sand mining for one of the world's biggest catchments. Furthermore, given our estimated scale of sand extraction, it demonstrates the need to properly account for mining activities when considering delivery of sediment to deltas in terms of the management of these vulnerable systems in the face of rising sea-levels. Overall, this work stresses the urgent requirement for further similar studies of sand extraction in the world's large rivers, which is vital to underpin sustainable management plans for the global sand commons.

1. Introduction

Sand is a widely used commodity, being a key component of cement as well as other manufacturing (e.g. glass), industrial (e.g. fracking) and land reclamation projects. Demand for sand is especially high for construction purposes in rapidly developing economies globally, such that sand is now regarded as the world's most used natural material. A significant proportion of sand is mined from rivers where it has traditionally been regarded as a 'free' resource. Given extraction is often from under the water surface and thus 'hidden', large volumes of sand have been mined in an unregulated way with little consideration of environmental impact. However, a diverse range of responses have been reported in areas subjected to sand mining; typically, channel incision results which can trigger bank erosion, reducing connectivity with the floodplain that leads to reductions in biodiversity, loss of species and impoverished returns for those involved in agriculture. There is thus a growing realisation that this situation is unsustainable. Recent reports by Koehnken and Rintoul (2018) and Gallagher and Peduzzi (2019) have identified the environmental and social impacts of sand mining as an issue of international significance demanding urgent research. To put the scale of the problem in context, a conservative estimate for the global consumption of sand exceeds 40 billion tonnes a year (Steinberger *et al* 2010); this is double the annual sediment load of all the world's rivers (Milliman and Syvitski 1992, Syvitski *et al* 2022).

While it is agreed that unregulated sand mining has now become a global problem, there is little consensus on how to best manage this issue. Where laws do exist, these tend to be fragmentary and to vary widely between countries so preventing international cooperation and more sustainable practice. Another challenge to regulation is that sand mining cuts across multiple economic sectors and geographic scales, making negotiation among stakeholders complex and time-consuming. However, it is widely acknowledged that a significant stumbling block to evidenced-based management is the lack of basic data (e.g. Bendixen *et al* 2019). Generating data is problematic because mining is often unregulated, so that specific sites are unknown, in remote locations, distributed over large spatial areas, or are otherwise difficult to identify (e.g. if mining takes place underwater). The main focus of sand mining research to date has been largely confined to the two main channels (∼200 km in length) of the Mekong River delta which has a well reported and observed concentration of boat-based dredging activity, so called wet-mining (Bravard *et al* 2013, Brunier *et al* 2014, Anthony *et al* 2015). Recent work has demonstrated how remote sensing techniques (including machine learning approaches) can be used to count dredging boats from which estimates of wet mining sand extraction can be made (e.g. Hackney *et al* 2021, Ng and Park 2021, Gruel *et al* 2022, Smigaj *et al* 2023, Kumar *et al* 2024). Thus, while the Mekong River has received attention as regards the high levels of sand mining experienced, much less is known about other large river systems. Of particular note have been reports of widespread illegal river sand mining to supply increasing demand for construction across India (Koehnken and Rintoul 2018). In recognition of the need for data at a broader scale, Dujardin *et al* (2024) mapped river sand mining activity across India. While this work identified the pervasive nature of sand mining (over 60% of rivers they looked at showed evidence of mining) it was restricted to a simple presence/absence classification based on observation of one image per river reach. To develop this work further requires the quantification of the amounts of sand extracted. However, the methods developed for the Mekong are not easily transferable to the Ganges–Brahmaputra catchment because mining is pervasive across both the larger and smaller rivers of the catchment. This means the methods used to extract sand are more diverse with much less reliance on large boat-based dredging operations (wet-mining) and much smaller scale 'dry-mining' where sand is taken from exposed bar surfaces.

The purpose of this paper is to meet this challenge and assess the nature and extent of sand mining activity across one of the world's most iconic river systems, the Ganges-Brahmaputra. By taking a catchment focus (i.e. covering a range of different scales of river) we hope to provide the first quantification of sand mining sustainability, at scale, that will be readily transferable to other catchments at risk. The work will thus take the important step to move beyond the case study approach focussed only on individual sections of single rivers. Specific objectives are thus to: (1) illustrate the range of different mining activity that is taking place; (2) demonstrate how remote sensing data can be used to determine sand mining methods and quantify mined volumes of sand from both wet and dry mining sites and over large spatial extents; (3) provide an assessment of how much sand is being removed and whether there are hotspots of activity; and (4) compare estimates of sand extraction with riverine sediment loads, to determine to what extent mining is sustainable within the basin.

While the Ganges–Brahmaputra–Meghna system might initially be seen as resilient to mining given that these rivers have the world's largest sediment load (further details below), the highly populated delta region relies on the continued supply of sand from upstream to build the delta up to offset rising sea-levels. For example, recent papers highlight how climate change might increase sediment load from this system through a more intense monsoon, with estimates in the 25%–50% range (Darby *et al* 2015) but also that due to dams, sediment delivery may have declined by 50% over the period 1960–2008 (Rahman *et al* 2018). None of these studies have considered the role of sand extraction.

2. Methods

In this study, several methods and datasets were used to identify and record river sand mining activities as shown in section 1, which can be found in the supplementary materials. The purpose of this section is to outline the use of a range of common remote sensing techniques and assess their effectiveness in estimating sand mining extraction.

Study site: the work reported here, concerns the mainstem Ganges and Brahmaputra and also a

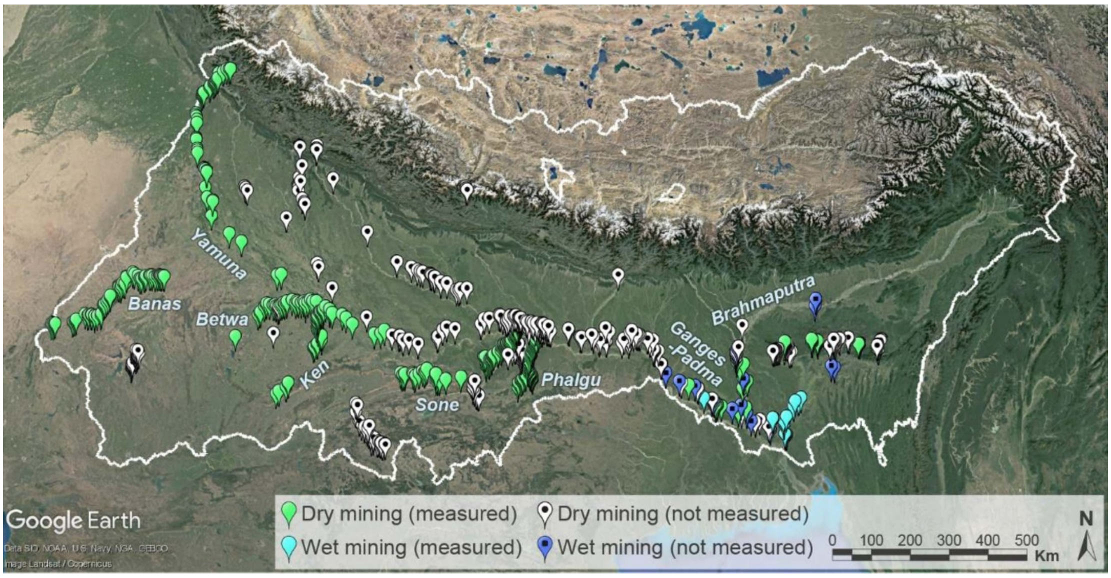

Figure 1. Map of rivers in the Ganges–Brahmaputra–Meghna catchment with locations of sand mining activities (Map data: Google Earth, Data SIO, NOAA, U.S. Navy, NGA, GEBCO Image Landsat/Copernicus). Locations are categorised depending on whether they relate to wet or dry mining (as shown in kml file that is presented in supplementary materials, section S2). Sites for which there was evidence of mining, but for which we did not manage to take measurements, are also indicated to illustrate the scale of the problem. Further details can be found in the supplementary materials (section S2, table S2.1).

number of significant tributaries; Sone, Phalgu, Banas, Ken, Betwa, Yamuna, Rakti, Lubha, Goyain, Wah Umngi, and Someshwari. The Ganges and Brahmaputra rivers (figure 1) individually lie within the top 30 of large rivers globally and together form one of the largest and most populous deltas. The Ganges flows through Nepal, India and Bangladesh and has a variable discharge, heavily influenced by the monsoon, ranging between 1000–60 000 m^3s^{-1} (Rahman *et al* 2018) with a mean annual flow of ∼15 540 m^3s^{-1} (Milliman and Farnsworth 2011). The Brahmaputra flows through China, India and Bangladesh also with a monsoon driven regime, with discharge varying between 3000–90 000 m^3s^{-1} (Rahman *et al* 2018) and a mean annual flow of ∼19 980 m^3s^{-1} (Milliman and Farnsworth 2011). The Ganges-Brahmaputra system is typically quoted as having the highest sediment load of any catchment, but specific estimates are wide ranging due to the difficulties of measuring sediment transport over such a large river network. Typically quoted figures (e.g. Rahman *et al* 2018) have ranged between 1.0–2.4 $Btyr^{-1}$ with a slightly lower contribution from the Ganges (260–680 $Mtyr^{-1}$) as compared to the Brahmaputra (390–1160 $Mtyr^{-1}$). However, in a more recent analysis of data collected from 1960–2008, Rahman *et al* (2018) suggests much lower figures of 150–590 $Mtyr^{-1}$ and 135–615 $Mtyr^{-1}$ for the Ganges and Brahmaputra respectively, with an average total flux of ∼500 $Mtyr^{-1}$. Moreover, they also suggest the data indicates the average flux is decreasing by ∼10 Mt for each year of the study period. Given that the boom in sand mining has taken place since this data was collected this makes the type of assessment outlined in this paper even more significant for those managing the delta and the ∼500 million people who live on it (Darby *et al* 2015).

Locating mining sites: given the scales involved, the focus of the research was on obtaining order of magnitude estimates over as wide a range of locations as possible. Typically, mining activity (figure 2) has been classified into three groups based on the location with respect to the river system (Sreebha and Padmalal 2011, Koehnken and Rintoul 2018); dry mining (typically from the floodplain), dry mining through bar skimming or scalping (extraction from exposed bar surfaces) and in-stream or wet mining (e.g. dredging). The latter two provide a more immediate and direct impact on the river system, as such dry mining in the floodplain was not directly quantified herein. Additionally, an extensive literature search, including grey sources, was undertaken to help locate mining sites. More details can be found in supplementary materials (section S4). Furthermore, Google Earth imagery that has high spatial resolution was used to check for mining activity and prioritise those locations with most widespread evidence of extraction and enable us to confirm the measurements of dredging boats, as it was difficult to obtain this information from surveys. On completion of the mining location exercise, it was concluded that there was a wider range of types of mining (figure 2) than has been previously reported. Dry mining overwhelmingly involved mechanical excavation of bar surfaces, often down to the water table, hence the

Map data:

(b) Google Earth, Data SIO, NOAA, U.S. Navy, NGA, GEBCO Image Landsat/Copernicus

(c) Google Earth, Image © 2023 Maxar Technologies

(d) © Mohd Imran Khan

(e) Top: Google Earth, Image Landsat/Copernicus
Bottom: Google Earth, Image © 2023 Maxar Technologies

(f) Google Earth, Image © 2023 Maxar Technologies

(g) Google Earth, Image © 2023 Maxar Technologies

Figure 2. Images to illustrate the diversity of the different types of sand mining within the catchment and hence the different methods required to quantify rates of extraction. (A) Location of study region. (B) Location of images within the study site. (C) Example of dry mining with sand extracted direct from the bank edge. (D) Example of manual mining. This type of activity was at too small a scale to be measured reliably using remote sensing. Photo Credit © Mohad Imran Khan. (E) Example showing how dry mining of exposed sand bars can lead to their complete removal through time. The sand pits visible in the 2013 image are just water by 2022 with complete removal of the original sand bar. (F) Example of wet mining where a dredger extracts sand from the river bed and then loads it into an adjacent sand barge for onward transport. (G) Example of wet mining where a dredger extracts sand and deposits it directly onto the adjacent bank. In this instance onward transport is via fleets of lorries.

extraction sites appear as large rectangular water filled areas within the remote sensing imagery (figure 2(E)). However, direct extraction of sand from the bank edge (figure 2(C)), leading to a very unnatural crenulated appearance, was also observed. It should also be noted that we identified numerous sites where dry mining has been reported (figure 1), but for which we could not make reliable estimates. Typically, this was because mining involved manual methods (figure 2(D)) that could not be properly measured using imagery. Similarly, wet mining may involve a dredging vessel which pumps sand from the riverbed into an adjacent sand barge (figure 2(F)). However, in the Sone River, for example, sand is extracted from the river bed by being scooped up using buckets attached to long poles which are deployed manually and used to fill the boats with sand. Finally, in the largest rivers in the catchment (e.g. the Brahmaputra) wet mining also takes a slightly different form in that dredging vessels pump sand direct onto the bank edge (figure 2(G)) rather than into adjacent sand barges. As a result of this observed diversity, no one method was suitable for quantifying extraction at all locations. The methods used, and described below, were focussed on providing simple, relatively easy to apply techniques that could be readily used elsewhere.

Quantifying dry mining extraction rates: the PlanetScope surface reflectance (Planet Team 2018) product was used to quantify mining activity for the period January 2016 to December 2021. These monthly composites provide high resolution (3.7 m at the equator) red (650–680 nm) green (547–583 nm) blue (465–515 nm) images with cloud cover (Zero–minimal) projected in WGS84 Mercator. The spatial resolution of these images is suitable for identifying smaller scale sand mining activity e.g. areas typically ∼50–60 m in length and ∼60–100 m wide, thereby covering multiple pixels within the images. Images with zero cloud coverage were selected for use, which necessarily limited the available imagery that was useable. Sand mining sites were digitised manually and a shapefile created for each year. The analysis of sand mining change was then done for each pair of consecutive years for the period 2016–2021. To avoid any double counting between years, after identifying and digitizing sand mining sites for each year only those sites that were apparent in the year of interest but absent in the previous year were used. These estimates of area were then converted to volume assuming a mining depth of 3 m. The value of 3 m was chosen as this is the typical depth of extraction permissible for legal sand mining (Ministry of Environment, Forest and Climate change 2020). These volumes were then converted to mass assuming a sediment density of 2650 kgm^{-3} and a porosity of 35%. By comparing sites between years temporal trends in mining activity were quantified.

Quantifying wet mining extraction rates: for dredging into sand barges the methodology of Hackney *et al* (2021) was used. As above, the Planet labs PlanetScope Surface Reflectance (Planet Team 2018) product was used for the period January 2016 to December 2021. A monthly composite image was created from available daily imagery (this composite has the benefit of eliminating most cloud cover found in daily images), the resolution of which is appropriate given sand mining boats are of the order ∼25–60 m in length and ∼6–10 m in width. Thus, much bigger boats (e.g. container shipping) could be readily identified and discounted from the analysis while the smaller local fishing boats, for example, are typically below the resolution of the imagery, and hence could be automatically excluded. Google Earth imagery was used to quantify the size of the sand barges and hence calculate the overall volume of sand that had been extracted. For 76 boats, the boat length (m), Lb, boat width (m), Wb, the length of the boat hold (m), Lh and the width of the boat hold (m), Wh, were recorded providing an average of; $Lb = 24.7$ m, $Wb = 5.9$ m, $Lh = 12.6$ m, $Wh = 4.0$ m. By assuming the height of the boat in this river is approximately 3 m as a maximum, the volume of sand transported by each boat was calculated as 151.2 m^3 ($Lh \times Wh \times Hv$; 12.6 m $\times$ 4 m $\times$ 3 m). This volume can then be converted to mass as described above. To obtain the overall estimate of sand extracted on an annual basis, the boat counts per day are multiplied by the number of days in each month and then these are summed for each month. Following the procedure of Hackney *et al* (2021) it should be noted that not all sand mining boats will necessarily be active all of the time. To account for this, those boats within a 30 m distance of the banks were classed as inactive and removed from the analysis. Of the remaining 'active' boats it is assumed that they fill, transit to where they are to be unloaded and then offload the sand only once a day given the time it takes to undertake this.

For wet mining where the sand is pumped directly onto the adjacent bank, the piles of sand were monitored from 2016 to 2021. It was then possible to calculate the total amount of sand accumulated during this period and analyse the change. The piles of sand typically had a flat-topped pyramidal shape. Google Earth Pro was used to measure the dimensions of each sand pile and calculate the areal footprint in square metres. An estimate of height was made, assuming the slope of the sand pile was at 30 degrees (i.e. angle of repose), from which the volume of the sand pyramid could be established. Finally, because the shape of the sand pile was flat topped, the volume of the 'missing' uppermost part of the pyramid was also calculated which was then removed from the final estimate of the sand pile volume. The volume was converted to mass based on the same assumptions of density and porosity as described previously.

Uncertainty in extraction estimates: it should be noted that there are uncertainties associated with the estimates of sand mining extraction using the methodologies described above. Underestimates will relate to factors such as the inability to measure sites due to insufficient resolution (temporal and spatial) of imagery, potential for missing boats when counting dredging activity, mining activity being missed if pits are excavated and then filled via transport processes over a short period of time and the assumed mining depth of 3 m being too low. Overestimates will predominantly relate to the depth of mining being shallower than the assumed value for some sites and where the porosity value may be greater than 0.35 (perhaps due to the additional presence of water in dredged sediment mixtures). It would be difficult to properly assess these uncertainties without an extensive ground truthing exercise. However, we note that there is more potential for underestimates in our approach hence our figures should likely be viewed as conservative. More information on the values of uncertainty of sand extraction with different mining depths can be found in figures S3.1–S3.4 in supplementary materials, section S3.

3. Results

Data from all the measured sites across the catchment provide an estimate of annual sand extraction of the order 115 Mtyr^{-1} (figure 1, table 1), which, while lower, is of a similar order of magnitude to recent estimates for the catchment bedload flux based on field data of 162 Mt yr^{-1} (Raff *et al* 2023). As discussed above, there is uncertainty associated with our estimates, but our value is similar to data within The Sand Mining Framework published in 2018 by the Government of India Ministry of Mines. Taking just the Ganges catchment, that covers 11 states, in the report for just 6 of these states the published sand production is 141 Mt for 2017. Also, in the report are estimates of actual sand consumption based on use of cement. Applying the typical ratio for cement to sand of 1:2.5 that is used in concrete production yields an estimate of 222 Mt in 2017 for the same 6 states. As discussed above, while our estimate is of the right order of magnitude it likely represents an underestimate of the true scale of the mining. The style of mining is diverse over the whole catchment and tends to vary with the scale of the river (figure 1). Thus, dredging from boats into sand barges (wet mining) is largely restricted to the largest rivers in the downstream parts of the catchment. Bar skimming/scalping is the dominant method of extraction elsewhere, and in smaller upstream rivers this can lead to removal of entire bars over time. More typically, there is a dense network of sand pits which are excavated on large sand bars on an annual basis. Overall, for our estimate of 115 $\mathrm{Mtyr}^{-1} \pm 20\ \mathrm{Mtyr}^{-1}$, only 5 $\mathrm{Mtyr}^{-1} \pm 1\ \mathrm{Mtyr}^{-1}$ was quantified as wet mining with the remainder classified as dry mining.

Data show that while sand mining activity was becoming evident in remote sensing imagery from 2010 onwards there have been significant increases recently. For our main analysis there has been a broad increasing trend of sand extraction through time for most rivers. For example, extraction on the Sone River increased from $\sim$32 $\mathrm{Mtyr}^{-1} \pm 5\ \mathrm{Mtyr}^{-1}$ in 2016–17 to $\sim$40 $\mathrm{Mtyr}^{-1} \pm 7\ \mathrm{Mtyr}^{-1}$ in 2020–21. However, a notable exception in this regard is the Banas River where mining activity decreased from $\sim$48 $\mathrm{Mtyr}^{-1} \pm 8\ \mathrm{Mtyr}^{-1}$ to $\sim$15 $\mathrm{Mtyr}^{-1} \pm 3\ \mathrm{Mtyr}^{-1}$ over the same period (figure 3).

There is a lot of variability in mining activity between the different rivers studied. The overall rate of sand extraction does not scale simply with river size. Thus, the highest absolute rates of sand removal are typically found in the somewhat smaller rivers (e.g. Sone, Banas, Yamuna), as compared with some of the much larger systems such as the Brahmaputra and Meghna. This may be due to both physical (e.g. ease of access, ease of logistics) as well as more economic factors (e.g. proximity to ultimate market).

Regardless of the absolute volumes of extraction, in terms of potential sustainability of mining activity, it is useful to compare the sand extracted from a river with its sediment load. In the absence of detailed field data across all the rivers investigated we compare our data with flux estimates generated using the WBMsed numerical model, which is freely available (see Cohen *et al* 2022). Given the sand extracted is likely to be predominantly transported as bedload or suspended bedload (rather than wash load) we compare our estimates of sand extraction with the simulated bedload data (table 1) in a similar way as reported by Dujardin *et al* (2024). The simulations of Cohen *et al* (2022) are conducted at a global scale and use the Lammers and Bledsoe (2018) equations to derive bedload based on slope, discharge, width and grain size. Spatial resolution of estimates is 6 arcminutes and the temporal resolution represents an average over 1990–2019. For most rivers the ratio of sand extracted to bedload exceeds 1, in some cases by over an order of magnitude (e.g. Sone, Banas, Ken, Betwa, Someshwari and Goyain rivers). The relatively lower incidence of observed mining activity in the much larger Meghna and Brahmaputra rivers means ratios are below 1 for these rivers. Table 1 also shows the number of mining sites identified within the imagery. While this is the easiest observation to make from the images, there is no simple relationship between number of sites and the potential sustainability ratio of extraction amount/bedload. However, relatively small rivers with a higher incidence of mining sites (i.e. >1 per km) will likely be susceptible to unsustainable mining and so even a simple measure such as this might help to focus efforts for river managers. As noted above, the hotspots of unsustainable activity would currently appear to be focussed on smaller rivers across the overall catchment (table 1).

Table 1. Details of the rivers studied (measured) with some metrics for identifying unsustainable mining activities, see text for details. Data relating to natural sediment bedload and water discharge are both derived from WBMsed dataset. Note that sand extraction values include both wet and dry mining where this has been measured. The greatest uncertainty relates to the assumed depth of extraction so ± values relate to assumed depths of 2.5 m and 3.5 m as compared with the quoted figures which assume a depth of 3 m.

River	Sand extraction ($\mathrm{Mtyr^{-1}}$)	Discharge ($\mathrm{m^3 s^{-1}}$)	Bedload ($\mathrm{Mtyr^{-1}}$)	Extraction/ Bedload	Length of river (Km)	Number of sand mining sites	Number of sand mining sites per Km
Sone	42.0 ± 7.1	1179	0.9	43.3	325	172	0.53
Phalgu	3.2 ± 1.1	620	0.4	7.0	135	111	0.82
Banas	28.1 ± 4.7	128	0.6	49.5	303	77	0.25
Meghna	0.6 ± 0.1	3710	3.5	0.1	165	15	0.09
Brahmaputra	2.1 ± 0.4	12 900	2.3	0.9	262	43	0.16
Ken	5.0 ± 0.8	427	0.2	22.6	200	44	0.22
Betwa	5.2 ± 0.9	617	0.3	18.3	294	26	0.09
Yamuna	10.4 ± 1.7	2032	1.7	6.1	1237	60	0.05
Ganges-Padma	13.6 ± 2.2	8165	4.2	3.2	170	12	0.07
Rakti	0.9 ± 0.1	263	0.3	2.6	18	7	0.39
Lubha	0.5 ± 0.1	344	0.3	1.6	19	4	0.21
Goyain	0.9 ± 0.2	96	0.0	28.5	18	35	1.94
Wah Umngi	0.4 ± 0.1	263	0.3	1.2	8	5	0.63
Someshwari	1.8 ± 0.3	186	0.1	19.0	11	27	2.45

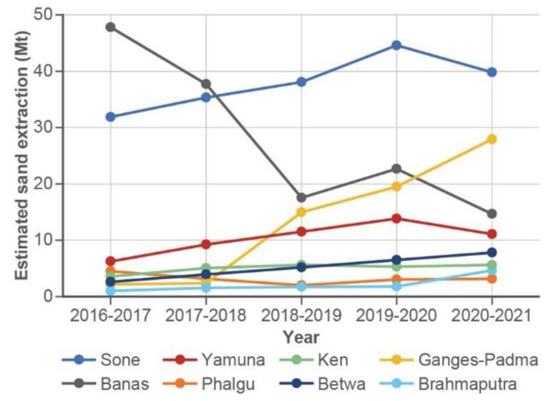

Figure 3. Estimates of sand mining extraction (dry mining) for each year of the study period (2016–2021) for selected rivers within the catchment. To account for uncertainty in our calculations, we vary depth of sand extracted with an upper value of 3.5 m and the lower limit of 2.5 m with a porosity of 0.35. We subsequently report all values using a central estimate of depth of 3 m. Further information on how uncertainty is determined can be found in the supplementary materials (section S3), with accompanying data and graphs (see figures S3.1–S3.3 and table S3.1).

4. Discussion and conclusion

This work has provided the first catchment scale quantification of sand mining for one of the world's largest rivers. By using a simple methodology, it has been demonstrated how significant sites of sand mining can be readily quantified and assessed through time. This thus develops the detailed case study approach as exemplified by work focussed on the Mekong River (e.g. Bravard *et al* 2013, Brunier *et al* 2014, Anthony *et al* 2015, Hackney *et al* 2021, Ng and Park 2021, Gruel *et al* 2022, Smigaj *et al* 2023, Kumar *et al* 2024, Yuen *et al* 2024) as well as broader but more qualitative approaches (e.g. Dujardin *et al* 2024). One of the primary findings of this study has been to highlight how diverse the range of sand mining activity is within just one river catchment. This represents an additional challenge to those seeking to quantify sand mining activity as this diversity does not lend itself to quantification by one single methodology. While it must be acknowledged that it is not possible to capture all mining activity using remote sensing methods (e.g. small-scale artisan type mining) it has been demonstrated that large scale order of magnitude estimates across entire catchments are possible. Resources such as Google Earth Imagery now provide a relatively easy means with which to monitor sand extraction of all types. While it should be acknowledged that such approaches will only ever provide estimates of the true scale of sand extraction, they are still useful for identifying hotspots, temporal trends and assessing sustainability through comparisons with estimates of the natural bedload. For example, the decrease in sand mining noted above on the Banas River may have been a result of the Supreme Court ban which came into effect in late 2017 for this river. Thus, while this act may have had some impact, significant mining activity is clearly still taking place in violation of the ban.

Regarding sustainability, as reported above, the level of sand removed across the rivers studied exceeds the simulated estimates of bedload in most cases. Taking the catchment as a whole, estimates of bedload yield vary between 50 $\mathrm{Mtyr^{-1}}$ (assuming bedload typically represents 10% of the total load of 500 Mtyr^{-1}) and 162 Mtyr^{-1} (Raff *et al* 2023). Our data for sand extraction is thus of a similar order of magnitude to the highest recent estimates. The balance between sand extraction and the natural sediment load is key to ensuring the sustainability of mining practices and to dampening the negative environmental impacts on the morphology and stability of the river channel (Vasilopoulos *et al* 2021). The level of mining activity across the Ganges-Brahmaputra catchment would thus appear unsustainable. An example from the Betwa River gives a useful illustration of likely river response to sand mining (figure 4). The pre- and post- mining imagery suggests incision of the main channel with the thalweg moving away from the outer bank, which is typical for meandering rivers, and into the centre of the river. The point bars have become more fragmented, vegetated and with a crenulated appearance (figure 4) as sand has been removed and underlying bedrock exposed that has led to a significant change in the shape of the wet/dry interface and increased variability in channel width through the reach. These changes overlap with the onset of recent sand mining activity, and thus may be largely a result of mining given that the last major dam further upstream on the Betwa was completed in 2000. Recent work by Kumar *et al* (2022) also suggests that changes due to climate and land use have reduced the average monsoon flow of the river by 16% for the period 2001–2020 as compared to that from 1982–2000. Thus, with likely decreasing discharge over our period of investigation the morphological changes seen in the Betwa are most likely a direct result of the sand mining activity. The implication is that mining is likely leading to a loss of natural functioning of many rivers across the catchment with implications for channel-floodplain connectivity, sediment, nutrient and pollutant cycling and ecosystems.

The scale of mining identified here may also represent a significant challenge to those living some distance away from mining sites and especially in the downstream delta area. The natural delivery of sand from upstream is vital to build up the delta elevation in order to offset rising sea level, supply sand to the coastal zone to prevent erosion and maintain channel depth to prevent salt intrusion (e.g. Anthony *et al* 2015). Rahman *et al* (2018) have already reported that from 1960 to 2008 sediment loads for the Ganges-Brahmaputra catchment decreased from ~1000 Mtyr^{-1} to ~500 Mtyr^{-1} largely due to sediment being trapped behind dams. Given that their study was based on work prior to the recent expansion of sand mining activity, it is probable that sediment loads are reducing at a greater rate than indicated by their data. Thus, based on our estimate of 115 Mtyr^{-1} extracted due to mining, sediment load may now have now declined further to a maximum of 385 Mtyr^{-1} and quite possibly much less than this given the conservative nature of our estimates. It should be noted that sand mined from parts of the catchment upstream of the Farakka barrage on the Ganges may never reach the delta (Khan *et al* 2018). However, while sediment accumulation behind dams is now routinely incorporated into global efforts to simulate sediment budgets (e.g. WBMsed), sand removed through mining activity is not monitored, hence managers remain largely unaware of its potential significance.

Map data: (a) Google Earth, Image Landsat/Copernicus
(b) Google Earth, Image © 2023 CNES/Airbus

Figure 4. Example from Betwa River showing changing morphological change through time between 1988 (a) and 2023 (b).

Official estimates of sand mining have thus recently been reported to be limited and not fit for purpose (Bendixen *et al* 2019, Gallagher and Peduzzi 2019). Existing and future plans for the sustainable management of large river systems globally need to be informed by up-to-date and more reliable estimates of sand extraction.

To date, effective regulation of sand mining in the Ganges-Brahmaputra basin has been limited by lack of data on the sheer magnitude of extraction. Existing and future plans for the sustainable management of large river systems globally need to be informed by up-to-date and more reliable estimates of sand extraction. The visual techniques reported here offer, for the first time, a credible method to assess extraction across the whole basin that can underpin setting of realistic mining quotas by the Bangladeshi and Indian governments. Moreover, they could be used to help rebuild threadbare trust in the state among riverine communities affected by escalating mining, by involving them in sensitivity analyses of remote sensing techniques as a means of building local accountability into national enforcement policies. In turn, this would enable improved metrics to evaluate current extraction methods, and to encourage implementation of more equitable and sustainable freshwater mining practices in future. These could be built around, inter alia, more rigorous licensing of dredgers, a comprehensive database of resource extraction monitoring, and raising awareness among miners and other stakeholders of environmentally sensitive mining techniques.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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