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ORIGINAL ARTICLE

Present to future sediment transport of the Brahmaputra River: reducing uncertainty in predictions and management

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Abstract The Brahmaputra River in South Asia carries one of the world's highest sediment loads, and the sediment transport dynamics strongly affect the region's ecology and agriculture. However, present understanding of sediment conditions and dynamics is hindered by limited access to hydrological and geomorphological data, which impacts predictive models needed in management. We here synthesize reported peer-reviewed data relevant to sediment transport and perform a sensitivity analysis to identify sensitive and uncertain parameters, using the one-dimensional model HEC-RAS, considering both present and future climatic conditions. Results showed that there is considerable uncertainty in openly available estimates (260–720 Mt yr^{-1}) of the annual sediment load for the Brahmaputra River at its downstream Bahadurabad gauging station (Bangladesh). This may aggravate scientific impact studies of planned power plant and reservoir construction in the region, as well as more general effects of ongoing land use change and climate change. We found that data scarcity on sediment grain size distribution, water discharge, and Manning's roughness coefficient had the strongest controls on the modelled sediment load. However, despite uncertainty in absolute loads, we showed that predicted relative changes, including a future increase in sediment load by about 40 % at Bahadurabad by 2075–2100, were consistent across multiple model simulations. Nevertheless, for the future scenarios we found that parameter uncertainty almost doubled for water discharge and river geometry, highlighting that improved information on these parameters could greatly advance the abilities to predict and manage current and future sediment dynamics in the Brahmaputra river basin.

Keywords Sediment transport · Brahmaputra River · Climate change · Sediment load · Sensitivity analysis

Introduction

Sediments carried by river systems are vital from environmental, economic, and social perspectives, not least since sediments contain essential nutrients and material for ecosystems and agricultural lands (Apitz 2012). The natural variability in hydrological conditions, as well as changes in land use, water use, and climate all affects the quantity and quality of sediments (e.g., Chalov et al. 2015). For control and management of sediment flows in future, responses to changes in ambient conditions therefore need to be predicted, especially in regions where livelihood depends on river systems and their natural processes.

The highly dynamic Brahmaputra River in South Asia carries one of the world's highest sediment yields (Islam et al. 1999). The region's dense and largely poor population is expected to become 50 % more urbanized by 2025 compared to today, causing even larger pressures on energy

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demand and natural resources (Singh and Goswami 2012; Ray et al. 2015). Present land use changes and expansion of river infrastructure in the Brahmaputra river basin are already affecting both the sediment and hydrological conditions in the basin (Sarma 2005; Ray et al. 2015). There is a large potential to expand both the downstream agricultural production and the upstream hydropower generation to increase the low living standards (Dikshit and Dikshit 2014), and such expansion would strongly influence hydrology.

Even though basin-wide integrated resource management is fundamental for a sustainable development in this region (Rasul 2014; Liu 2015), management of sediment and erosion has so far mainly been a national concern (Ray et al. 2015). The consideration of larger spatial perspectives and the development of cross-boundary collaboration are thus key challenges for the region, particularly with ongoing climatic changes, causing altered precipitation and temperature patterns that could leave an imprint on riverine sediment transport.

A prerequisite for developing basin-wide process understanding and assessments of sediment transport is the access to long-term and spatially distributed hydrological data (Azcárate et al. 2013; Bring and Destouni 2014). For example, discharge data can be used for testing hypotheses regarding hydrological and geomorphological processes that govern erosion and sediment transport in the Brahmaputra River. Current monitoring of river characteristics and discharges of the Brahmaputra are, however, not freely accessible (Kibler et al. 2014), and the lack of publically available data sets constrains the reproducibility of previously published results (e.g. Goswami 1985; Islam et al. 1999; Sarma 2005). To overcome this lack of data, recent studies have focused on extracting basin data from satellite imagery, including river data (e.g. Jung et al. 2010; Woldemichael et al. 2010; Mersel et al. 2013) and land cover and land use data (Prasch et al. 2015), but these methods still cannot fully replace in situ measurements. To the best of our knowledge, Coleman (1969) is the only author who has published series of average monthly discharge data coupled with simultaneous sediment data. With regard to international databases, both the Global Runoff Data Centre (GRDC) and the Global River Discharge (RivDis) data sets provide some data on the Brahmaputra River and its tributaries, but unfortunately, stations in these data sets are widely spaced with many large record gaps. Data on river sediment load are even scarcer, which limits the possibility of detailed analyses based on these openly available data sets.

Despite the underdeveloped transboundary information exchange and low data availability in the basin, there are ongoing political efforts aiming to develop integrated water management plans, such as the South Asia Water Initiative and the Abu Dhabi dialogue, both facilitated by the World Bank Group (2015). The successful implementation of such plans will likely require improved basic information on the functioning of the river system. Similarly, the lack of adequate knowledge was recently highlighted (Kilroy 2015; Ray et al. 2015) for development of agriculture and hydropower, specifically with regard to variable discharge and sediment load dynamics in the face of climatic and other anthropogenic changes. There is thus an emergent need for science-based advice on how to prioritize efforts to target existing knowledge gaps.

Our overall objectives are to synthesize fragmented knowledge on hydroclimatic and geomorphological conditions that govern sediment transport in the Brahmaputra river basin and investigate how current uncertainties and data gaps influence predictive capabilities in sediment transport dynamics. We expect that this will aid in identifying needs for monitoring refinements and complementary field investigations, which in turn could improve present to future projections. Specifically, we aim to:

i. Synthesize reported Brahmaputra basin data regarding key hydroclimatic and hydromorphological input parameters needed in quantitative sediment transport models.
ii. Determine the sensitivity of model prediction results to such key parameters.
iii. Combine information in (i) and (ii) to identify weak points in parameter knowledge, by investigating how current uncertainties in input parameters propagate into result uncertainty.
iv. Combine information in (ii) with projections of future climate changes, to address how the present hydrological and geomorphological state of the Brahmaputra River can be expected to change under future conditions.

Materials and method

Site description

The Brahmaputra River originates in the Tibetan plateau and runs on the northern side of the Himalaya before flowing into India (Fig. 1). In India, the elevation drops drastically into an agricultural floodplain valley. Below the Himalayas, the basin has a mean annual temperature of 23 °C and a sub-tropical climate controlled by the South-East Asiatic monsoon (Datta and Singh 2004). Mean annual precipitation at Pandu (Fig. 1) is 2600 mm year^{-1}, of which more than 65 % falls between June and September (Rajeevan et al. 2006). The monsoon is the dominant contributor to the Brahmaputra discharge apart

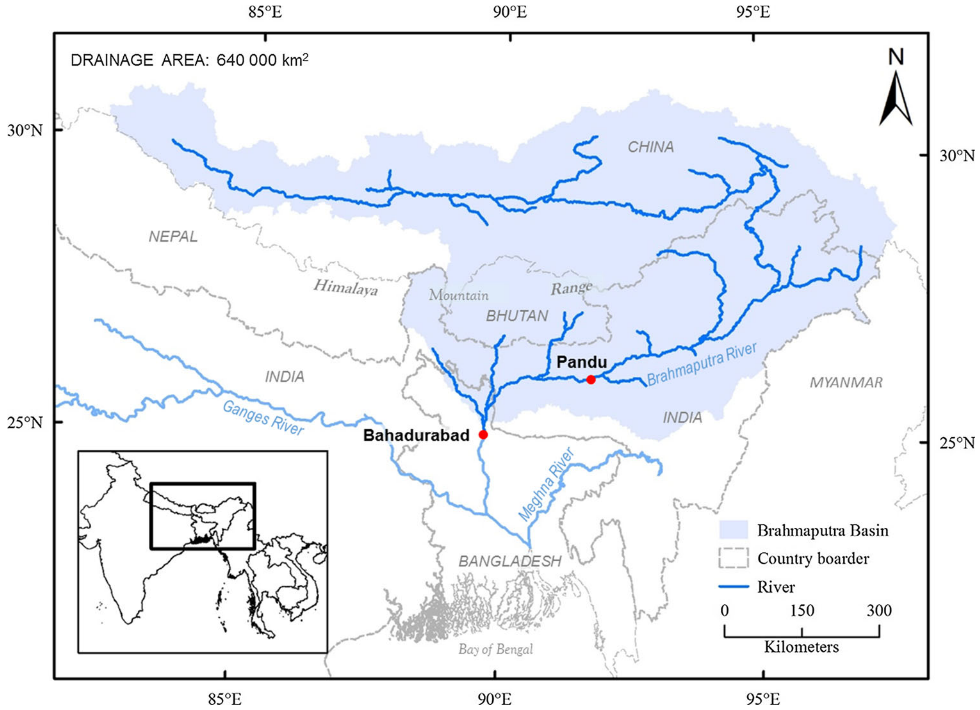


Fig. 1 Map of the Brahmaputra river basin. The focus reach is located between the Pandu discharge station in India and the Bahadurabad discharge station in Bangladesh

from glacier melt water (Immerzeel 2008). Past climate conditions in the region show an increasing trend in temperature of 0.6 °C during the last century (Immerzeel 2008), while studies on precipitation are still inconclusive (Nepal and Shrestha 2015; Ray et al. 2015). No long-term trend in discharge is apparent, only a slight increase in mean discharge of the last few decades (Sarker et al. 2014; Ray et al. 2015).

Synthesizing input data

Regarding the present state of the Brahmaputra River, we synthesized hydroclimatic and geomorphological data for parameters that are needed in (essentially) all quantitative sediment transport models. These parameters include: discharge and its variation in time and space, water temperature, bed sediment grain size distribution, Manning's roughness coefficient, and river geometry. The search included publications indexed in ISI Web of Knowledge and Google Scholar, and reports and data sets published by governmental agencies such as India Meteorological Department, Geological Survey of India, Central Water Commission, India, and Bangladesh Water Development Board. From available data, we synthesized mean values and plausible ranges (based on reported values, not their unknown true physical range) of all considered parameters. The mean value was calculated as the ensemble mean of compiled data, or taken from already reported calculations, if available. For parameters with long records available, we estimated the physically plausible range based on their respective coefficient of variation (CV), using the highest available resolution. For parameters with less observation data available, we used the entire range of available data based on reported minimum and maximum values. The mean value and range of each parameter were then used as input to the quantitative modelling according to the "Quantitative model and sensitivity analysis" section. Regarding the future state of the Brahmaputra River, the parameters discharge and water temperature were adjusted to represent altered hydroclimatic conditions. Literature estimates of projected relative change between future (2075–2100) and present average annual values of these parameters were synthesized with the same methodology as for the present state literature review.

Quantitative model and sensitivity analysis

For the quantitative analyses, sediment transport simulations in the one-dimensional model HEC-RAS 4.1 were performed. They were set up from geometric and hydraulic data using computational settings according to the methodological steps of Pietroń et al. (2015). In summary, the largest part of our model domain consists of an adjustment reach, representing the Brahmaputra River between Burhi Dihing tributary and the Pandu station. The function of the adjustment reach is to diminish (and ideally eliminate) effects of assumed model boundary conditions on the main results. The adjustment is obtained through allowing deposition and erosion along the reach, such that the inflowing sediment to the focus reach between Pandu and Bahadurabad (from which results are reported) should be only marginally affected by the chosen boundary conditions. To account for sediment input from the basin upstream of the model area, equilibrium load conditions were assumed at the model inlet next to Burhi Dihing tributary. Furthermore, to account for lateral water inflows along the modelled river reach, the lateral inflow boundary of HEC-RAS was used, which accounts for water inflows but neglects the sediment transported by the lateral inflows. We tested the sensitivity to the chosen simplifying assumptions by moving the equilibrium load boundary much closer to the Pandu station, such that approximately all lateral inflows between the Burhi Dihing tributary and the Pandu station were loaded with sediments (hence adding the previously neglected sediment apportions from the sub-basins along this stretch). Sediment transport was estimated from calculations of the sediment mass passing a downstream cross section representing the Bahadurabad station per unit time, hereafter referred to as the modelled sediment load (SL_M). See also further details given in the Online Resource.

For the sensitivity analysis, we used the physically feasible ranges, defined according to the "Synthesizing input data" section, in line with Lenhart et al. (2002). This contrasts with traditional sensitivity analysis, where fixed bounds or predetermined percentages of change are often used. Starting with the mean values of all the parameters defined above (hereafter called the base mode), we first calculated monthly SL_M representing the present sediment state of the Brahmaputra River. This simulated value was compared against reported observations of monthly sediment loads from the Bahadurabad station. The sensitivity analysis was subsequently carried out by altering one parameter at a time to its lower and upper bound while keeping the other parameters fixed. The resulting SL_M for each of the model runs was compared to the loads of the base mode to evaluate the relative changes in monthly and annual SL_M. Finally, considering the possible future sediment state of the Brahmaputra River, an additional sensitivity analysis was run for an altered base mode, where the mean value of the discharge and water temperature parameters were adjusted to represent a projected future climate ("Synthesizing input data" section). The same relative changes around the mean value as in the present state calculations were applied in the sensitivity analysis of predicted future SL_M.

Results

Synthesis of reported parameter values: present state

Values and bounds of key parameters that influence sediment transport predictions are listed in Table 1A, together with how they were derived from the independently reported values in the original sources. Below follows a synthesis of present state parameter values (of parameters 1–6 in Table 1A) found in the literature:

1. *Water discharge* (Q_{Total}) River monitoring in India is carried out by the Central Water Commission and in Bangladesh the Bangladesh Water Development Board. Discharge data for the Brahmaputra River are, however, not freely accessible. Dai et al. (2009) produced reanalysis data for a 50-year period, and recent investigations have often relied on their own measurement campaigns (e.g. Wasson 2003) or conducted their analyses in cooperation with local state agencies (e.g. Sarma 2005). The GRDC (1995) holds data from three stations in the basin on the main channel: Bahadurabad (Bangladesh), Pandu (India), and Yancun (China), where the Bahadurabad station has several years of consistent data. We used the available six-year data set (1986–1991) from the Bahadurabad station, where the average annual discharge of 23,800 $m^3 s^{-1}$ (which is the only available data with a daily resolution) is in the same magnitude as other estimates of between 19,000 and 22,000 $m^3 s^{-1}$ for the same time period (Islam et al. 1999; Darby et al. 2015; Ray et al. 2015; Prasch et al. 2015).
2. *Lateral inflow* ($Q_{Lateral}$) Some tributaries to the Brahmaputra (Teesta, Manas, and Jia Bharali) have discharge records published by the GRDC, but they are too few to give a clear representation of the total lateral inflow to the main channel. The Q_{Lateral} was instead derived from the increase in discharge measured in the main channel over the considered stretch (see Online Resource for details) and was estimated to represent 26 % of the total flow to the main channel stretch. This was based on annual data for the periods of 1957–1958, 1960–1961, and 1977–1978. The derived Q_{Lateral} of 26 % is consistent with the fact that the area that drains directly into the modelled focus reach constitutes approximately 20 % of the total catchment area and also has a level of precipitation that is among the highest in the basin (Rajeevan et al. 2006).
3. *Water temperature* ($T_{Monthly}$) Limited information is published concerning the river's water temperature. The UN Global Environment Monitoring System (GEMStat.org) has monthly water quality data between 1979 and 1995 from the only available station within the basin, the Bahadurabad station. They estimated the mean annual water temperature to 27.5 °C which is consistent with different seasonal reference values (e.g. Singh et al. 2005; CPCB 2011).

Table 1 (A) Tested parameters essential to sediment transport for the present state simulation. The mean value (base mode), lower and upper bounds are used in the sensitivity analysis. (B) Literature estimates of projected annual change in hydroclimatic parameters for the Brahmaputra river basin by 2075–2100. The maximum and minimum estimates of each parameter (the upper and lower bounds) are used to derive the mean value that constituted the future state base mode settings

Parameter	Lower bound Base mode Upper bound	Lower and upper bound deviations based on:	Sources
A. Present state			
1. Water discharge	Q_{Total}: −26 % Q_{Total}: 4814–56,119 $\text{m}^3\ \text{s}^{-1}$(a) Q_{Total}: +26 %	Monthly CV	GRDC (1995), consistent with Islam et al. (1999), Darby et al. (2015), and Ray et al. (2015)
2. Lateral inflow	Q_{Lateral}: −11 % Q_{Lateral}: 1252–14,591 $\text{m}^3\ \text{s}^{-1}$(a) Q_{Lateral}: +11 %	Annual CV	GRDC (1995) and Dai et al. (2009)
3. Water temperature	T_{Monthly}: −3 °C T_{Monthly}: 23–32 °C(a) T_{Monthly}: +3 °C	Monthly CV	GEMSTAT (2015), consistent with Singh et al. (2005) and CPCB (2011)
4. Sediment grain size distribution	0.004–0.25 mm (d50: 0.04) 0.077–0.50 mm (d50: 0.15) 0.150–0.75 mm (d50: 0.25)	Minimum and maximum reported values	Goswami (1985), consistent with Coleman (1969) and Das (2004)
5. Manning's roughness coefficient	0.018 0.025 0.035	Minimum and maximum reported values	Jung et al. (2010)
6. Effective river width	3000 m 8000 m 10,000 m	Minimum and maximum reported values	Goswami (1985) and Coleman (1969), consistent with Datta and Singh 2004 and Mersel et al. (2013)
B. Future state			
Future air temperature	+2.3 °C(b) +3.6 °C +4.8 °C(b)	Minimum and maximum reported values	Immerzeel (2008), Darby et al. (2015) and Masood et al. (2015)
Future water discharge	+13 %(b) +26 % +39 %(b)	Minimum and maximum reported values	Darby et al. (2015) and Masood et al. (2015)

(a) Running mean values of several days were used in the modelling; the given base mode range reflects the interval of this running mean over a year. The monthly coefficient of variation (CV) of column 3 reflects a variation around this mean due to fluctuating daily values, which we use to define lower bound and upper bound deviations (column 2)

(b) Not used in the sensitivity analysis

4. *Sediment grain size distribution* Data on the river bed sediments are collected by the Central Water Commission, India, and the Bangladesh Water Development Board but are not publically available. Goswami (1985) reported grain size distributions from several locations along the Brahmaputra River. The average grain size distribution was calculated from Goswami's (1985) finest (bed sample) and coarsest sample (bar sample) and gave a mean distribution within the fine sand spectra (with d50 = 0.15 mm), both collected within our modelled reach. This estimate lies within reported ranges of Coleman (1969) and Das (2004) (see Online Resource for details).
5. *Manning's roughness coefficient* The Institute of Water Modelling Bangladesh hosts bathymetric cross section information and discharge data of the river reach

located in Bangladesh. Jung et al. (2010) used those data to estimate the Manning's roughness coefficient to a possible range of 0.018–0.035 and chose 0.025 to represent the river's channel close to Bahadurabad, a value that was later used by Woldemichael et al. (2010).

6. *Effective river width* The Brahmaputra has a large spatiotemporal variation in river width and reported values range from 2400 to 18,500 m (Datta and Singh 2004) with a mean width of 8000 m (Goswami 1985; Datta and Singh 2004) for the downstream Indian part. Estimates of river width usually include the bars and islands in between the braided channels, and applying these minimum and maximum values uniformly along the modelled reach would give an unrealistic representation of the river. Coleman (1969) reported a range of 3000–10,000 m for the section in Bangladesh, consistent with LANDSAT satellite images (USGS 2000) from the modelling period (1986–1991). Thus, that range was used as a more reasonable downscaled effective river width.

Estimation of present sediment load

When we used average estimates of the input parameter data (the base mode for the model), our model results showed an annual average SL_M of 264 Mt yr^{-1} for the Brahmaputra at the Bahadurabad station. For comparison, Milliman and Syvitski (1992) reported the annual average sediment load at Bahadurabad to 540 Mt yr^{-1}, while Islam et al. (1999) estimated a suspended sediment load of 721 Mt yr^{-1} from using a sediment rating curve with sediment and discharge data collected in 1989–1994. Darby et al. (2015) used a climate-driven water balance and transport model and obtained a simulated load of 595–672 Mt yr^{-1} from observed flow data at Bahadurabad of 1981–1995. Coleman (1969) measured the suspended sediment load at the same location to 607 Mt yr^{-1}, however for the earlier period 1958–1962. Since Coleman (1969) is the only one reporting monthly sediment loads, we include it for illustrative purposes in Fig. 2a, b. Due to differences in considered periods, detailed comparisons between measured and modelled values in Fig. 2a, b are not recommended.

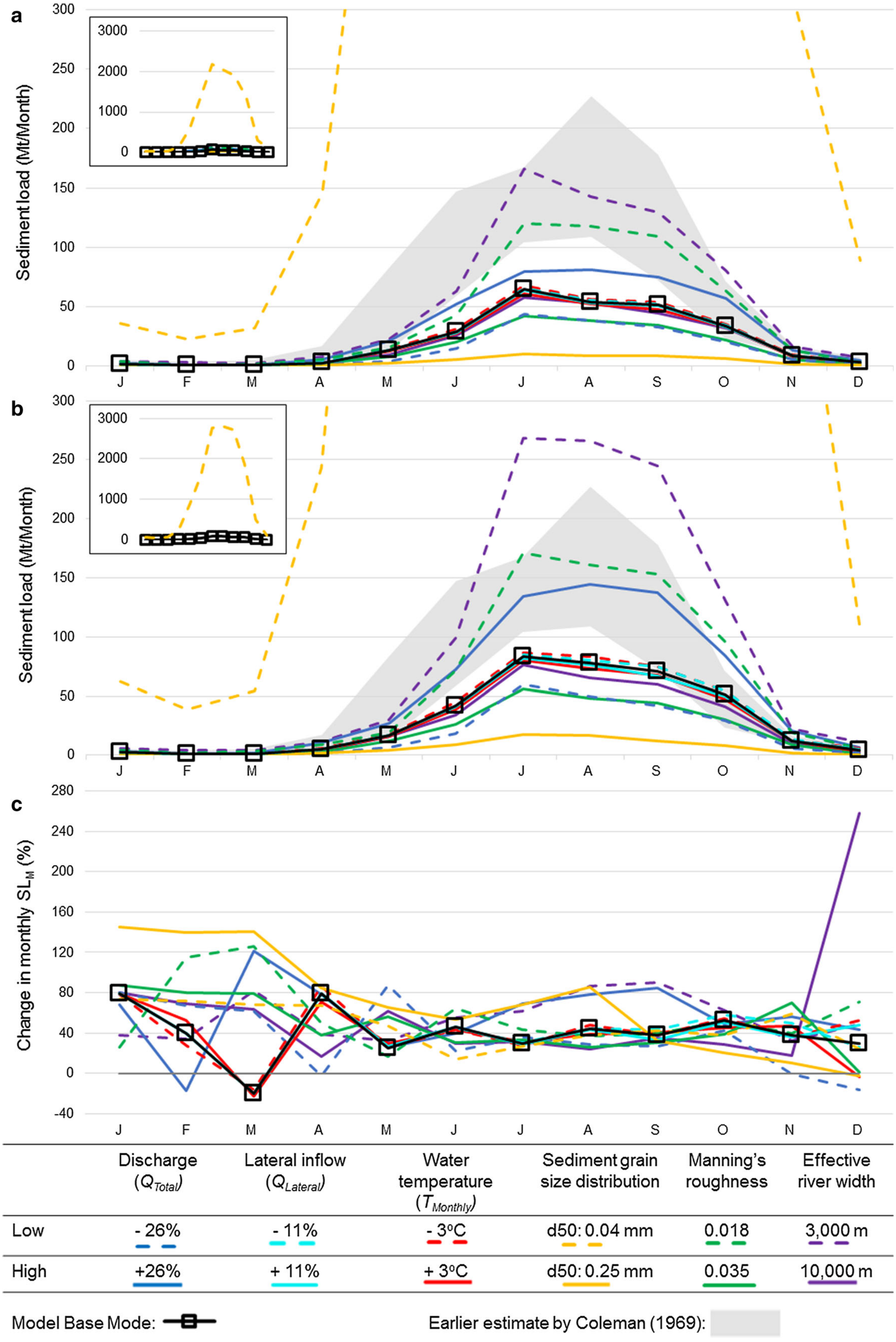
Of the parameters we tested in the sensitivity analysis, changes to assumed fine sediment properties gave the most distinctive effects on simulated loads (Fig. 2a). On an annual basis, the finer sediment grain size assumption (i.e. the lower bound of $d50 = 0.04$ mm, Table 1A) gave approximately 40 times higher SL_M than the base mode assumption, hence shifting our annual average SL_M estimate of 264 Mt yr^{-1} from being a factor two below the Coleman (1969) observation to being at least an order of magnitude above it. Although the sensitivity of the model was smaller to all other parameters, considerable impacts were seen when varying the effective width, Manning's roughness coefficient, and discharge (Fig. 2a) between the reasonable bounds of Table 1A. For example, a use of the high end bound of discharge (+26 %) resulted in an annual SL_M increase of 49 % compared to the base mode, corresponding to an increase from 264 to 394 Mt yr^{-1}. The change in water temperature and amount of lateral inflow had a very small effect (±5 and ±2 %, respectively) on the estimated output load.

Results furthermore showed that the model sensitivity was small considering the alternative boundary conditions described in the Methods section (difference in the SL_M results between the alternatives around 5 % or less). Although the model accounted for sediment inputs upstream of the Pandu station, they were neglected along the focus reach (Pandu–Bahadurabad). Previous observations (Jain et al. 2007) indicate that this contribution represents about 10 % of the annual sediment load at Bahadurabad which is non-negligible; however, we note that it is smaller than the wide range of different sediment loads evoked through our above-described parameter sensitivity analysis.

Fig. 2 Monthly values of **a** absolute SL_M in the present state simulation, **b** absolute SL_M in the future state simulation, and **c** the relative changes from the present simulation to the future simulation. The *insets* in **a**, **b** show the full extent of the model result from the finer sediment grain size distribution (d50: 0.04 mm) in relation to the base mode ▶

Synthesis of reported parameter values: future state

Projected increases in air temperature were assumed to affect water temperatures with the same magnitude. For the end of the century (2075–2100), projected increases in air temperatures within the basin range from 2.3 °C (Immerzeel 2008) to 4.8 °C (Darby et al. 2015; Masood et al. 2015; Table 1B) relative to their respective reference periods within the years 1960 to 2000. Reported projections of future discharges of the Brahmaputra River span a wide range, in part because even current conditions are uncertain (Nepal and Shrestha 2015). Lutz et al. (2014) estimated increases with 1–13 % by the mid-twenty-first century compared to 1998–2007, arguing that the loss of glacier area would be compensated by increases in melt rates. However, after a limited period of increased discharge from glacier melt, the decrease in ice volume would result in a reduced melt water production. This decrease in melt water was estimated by Immerzeel and van Beek (2010); even though rainfall is projected to increase, they


a
Sediment load (Mt/Month)
300
250
200
150
100
50
0
3000
2000
1000
0
J F M A M J J A S O N D
b
Sediment load (Mt/Month)
300
250
200
150
100
50
0
3000
2000
1000
0
J F M A M J J A S O N D
c
Change in monthly SL$_M$ (%)
280
240
200
160
120
80
40
0
-40
J F M A M J J A S O N D
Discharge (Q_{Total})
Lateral inflow ($Q_{Lateral}$)
Water temperature ($T_{Monthly}$)
Sediment grain size distribution
Manning's roughness
Effective river width
Low
- 26%
- 11%
- 3°C
d50: 0.04 mm
0.018
3,000 m
High
+26%
+ 11%
+ 3°C
d50: 0.25 mm
0.035
10,000 m
Model Base Mode:
Earlier estimate by Coleman (1969):

estimated an overall decrease in discharge by 19 % for the years 2045–2065 compared to the years 2001–2007. Similarly, Prasch et al. (2015) projected a decrease in run-off of 28 % for the upper Brahmaputra for the years 2051–2080 compared to the years 1971–2000. By the end of the century, however, both mean and extreme discharges are consistently projected to increase in the low-lying Brahmaputra (Gain et al. 2011). Estimates for Bangladesh due to projected increases in precipitation range between increases of 13 % (Masood et al. 2015) up to 39 % (Darby et al. 2015), compared to their respective reference periods both within the years 1980–2000 (Table 1B). These projected long-term average discharge increases are also consistent with the synthesis of climate model run-off projections in the latest IPCC report (Collins et al. 2013).

Estimation of future sediment load

The tabulated mean values in Table 1B represent modifications of base mode parameters for water temperature and discharge (Table 1A), used here to model plausible future states of the Brahmaputra River. Figure 2b shows the results of the sediment load simulations for the future period (2075–2100), considering modified mean values of water temperatures and discharge according to Table 1B. Compared with present conditions (Fig. 2a), an upward shift towards higher sediment load values is visible in the monthly SL_M for all the parameter combinations (Fig. 2b), especially for a smaller effective river width, smaller Manning's roughness value, and increased discharge values. The future base mode annually produced 368 Mt yr^{-1} SL_M, which is 40 % more than the present state base mode (264 Mt yr^{-1}).

The difference in SL_M between the present and the future base mode outputs was mostly governed by the changes in the discharge parameter. When the high end bound of the discharge range (+26 %; Table 1A) was used in combination with the increased discharge levels from the projected future climate change (+26 %; Table 1B), the SL_M more than doubled (245 %) compared to the present state base mode. Further, Fig. 2c shows the monthly relative change between the future and present state simulations, given the identified uncertainty bounds of the key parameters. Although sediment transport is strongly connected to river discharge, it has no direct linear relationship (Pietroń et al. 2015). Still, the largest relative differences due to parameter uncertainty are seen in the low-flow season (November–April), while more stable results are found during the high-flow season (May–October, also transporting about 93 % of the annual total loads). On average, all parameters in the high-flow season show a SL_M of 37 % larger than the present state loads, except for the

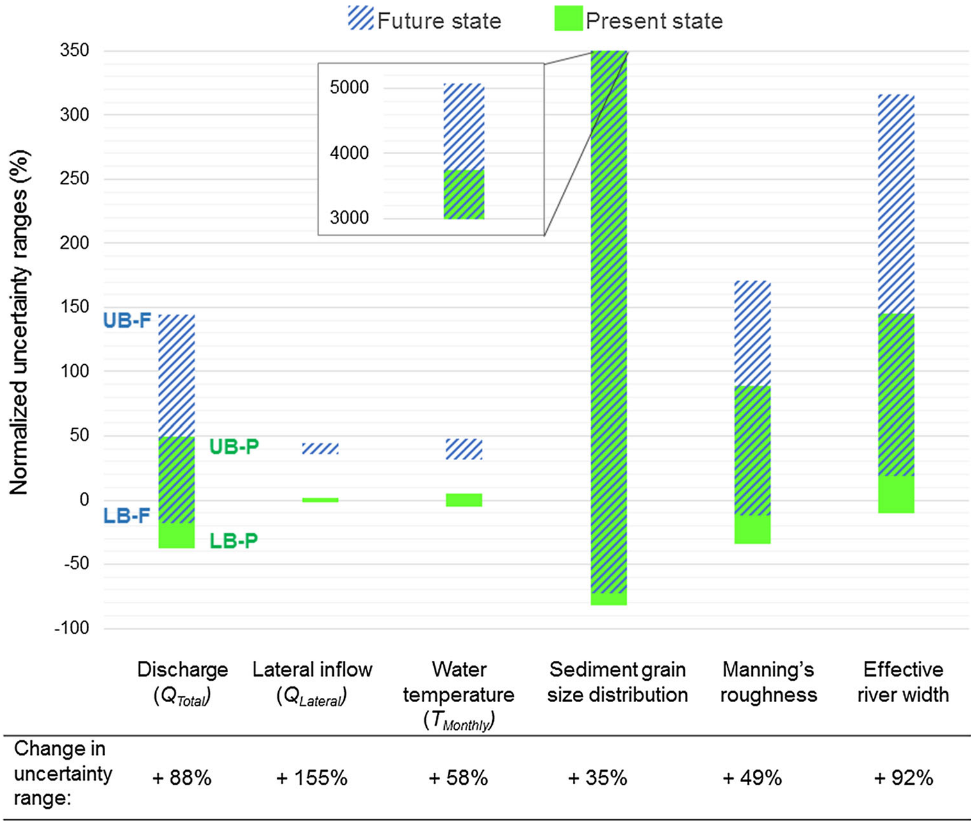


Fig. 3 Changes in annual SL_M and uncertainty ranges, by parameter, are presented as normalized to the present state base mode (see text for details). The percentage figures to each parameter show the change in the extent of the uncertainty range in future compared to the present state uncertainty range. Upper (*UB*) and lower (*LB*) bounds for the present (*-P*) and the future (*-F*) state simulations are used to derive the percentage figures as (*UB-F* − *LB-F*)/(*UB-P* − *LB-P*)

narrow effective width, elevated discharge levels, and coarser sediment sample that show average loads that are up to 64 % larger.

Figure 3 further illustrates the difference between the future and present state simulations, in how much each parameter variation increases the uncertainty ranges of the annual SL_M. To enable comparison between the present and future simulations, the annual SL_M is normalized to the present state base mode (i.e. the annual loads from the upper/lower parameter alterations from both the present and future simulations are divided by the annual result of the present state base mode). Sediment grain size distribution remains the most influential parameter in the future simulation. Nonetheless, the uncertainty range for this parameter only increases with 35 % compared to the present simulation (dashed blue bar versus green bar in Fig. 3), the smallest relative change of all parameters in the magnitude of the uncertainty range. For the parameters with a small range in absolute uncertainty, such as variation in lateral inflow, the relative increase in uncertainty range is very large (up to +155 %). Still, the absolute increase in uncertainty due to these parameter ranges is very small (in the case of lateral inflow, the absolute size of the range grows from approximately ±2 % to ±3 %). The parameters river discharge, Manning's roughness, and effective width are presently, and will remain, the largest uncertainty factors next to sediment grain size distribution, and their uncertainty ranges grow substantially in future. For river discharge and effective width, the change corresponds to almost a doubling in magnitude.

Discussion

Our synthesis of reported peer-reviewed data on the Brahmaputra River reveals that data gaps are severe, especially for discharge and sediment characteristics, which hinders analyses and modelling efforts. In particular, restricted amount of publically available sediment measurements for the Brahmaputra River made it impossible to constrain the average natural variation of grain size distributions to be used in the modelling. This range therefore included relatively fine sediment grain size distributions. Finer sediments can be resuspended easier from the bed material, which leads to extremely high model quantifications of SL_M (Fig. 2). Access to sediment load data from multiple locations along the river could aid in identifying sediment sources distribution in the basin (de Vente et al. 2007). Moreover, data from the main tributaries could improve identification of varying sediment sources and estimations of sediment budgets (e.g. Singh et al. 2008).

If more data were available, an alternative approach would be to interpolate the available data to obtain a more spatially distributed representation with, for example, an incremental change in grain sizes or the bed roughness values between upstream and downstream reaches. Open questions regarding temporal variation of parameters between the seasons could then potentially also be addressed. However, present results show that without accurate measurement data to limit the modelled ranges, the grain size distribution remains a highly sensitive parameter. Consequently, the choice of the default sediment grain size distribution used in the base mode plays a dominant role in the model output SL_M. Furthermore, the uncertainties in predicted SL_M for projected future conditions (Fig. 3) indicate that, in addition to the above-discussed high uncertainty in grain size distribution, the uncertainty related to river discharge and effective width will grow in future, when flows are projected to increase. This reinforces the importance of adequate monitoring and mapping of river discharge and geometry, not only to maintain a record of flows and to increase understanding of the system, but also to accurately detect future changes, as the consequences of not fully knowing the variation in flow and effective width will likely become larger in future.

Tributaries of the Brahmaputra River are important to monitor, especially those from the northern Himalayan slopes since they are contributing with glacial melt water and monsoonal run-off that are likely to be affected by climate change and anthropogenic river regulation. The Indian Himalaya is seen as a major source of India's future hydropower production, and several power plants and reservoirs are planned in the region (Grumbine and Pandit 2013). To avoid construction damages from high flows and maintenance of high sedimentation rates, these dams need to take into account the total sediment loads. Hence, absolute values of annual discharge and sediment inflow are needed (Salas and Shin 1999; Ran et al. 2013), which are currently lacking. Independent environmental impact assessment from openly available data is crucial, especially when social or ecological values are in conflict with hydropower construction (He et al. 2014).

Despite the large range of estimated absolute sediment loads, our results on relative future annual changes (of about 40 % increase) were stable due to relatively small differences in predicted change during the high-flow season, when more than 90 % of the annual load is transported. A possible explanation for these more precise results is that during conditions of higher flow, there is enough energy provided by the discharge to efficiently remobilize and transport most of the bed sediments, despite the parameter variations in the different simulations. However, during lower flows (November–April, when less energy is provided by the discharge), the differences in results for different simulations can be more pronounced, showing high sensitivity to changes in the parameters.

Furthermore, our results are comparable to estimates by Darby et al. (2015) who reported increases of 52–60 % in total sediment load for the end of the century compared to 1981–2000. Their estimates were derived from precipitation and temperature data downscaled from several Regional Climate Model simulations for the SRES A1B. This consistency, despite different methods and input data, builds confidence in the expected relative changes and implies that management applications where such information is sufficient to enable future adaptive measures should at least consider these values as appropriate starting points. Some examples of areas where confidence in relative changes may allow a first-order planning for adaptation include agricultural practices [such as rice plantations that need sediment deposition for fertilization (Prokop and Ploskonka 2014)], mobilization of upstream arsenic sediments (Li et al. 2011), and siltation of the river, which puts pressure on riverine ecology. Compared to other basins, the Brahmaputra is still rather unchanged by anthropogenic activities and has a very large potential for incorporating environmental protection into development plans.

Sediment transport in the Brahmaputra River is controlled by the monsoon climate, which explains the large depositional fluctuations within the braided channel system (Roy and Sinha 2014). These regular changes in the river morphology make efficient livelihood and agricultural practices difficult, and bank stabilization is a high priority in the region (Nakagawa et al. 2013). However, fixating the river width with embankments to secure floodplain communities would result in higher velocities and increased scour and erosion from a smaller cross-sectional area. For example, Mosselman (2006) observed increased rates of erosion in the Brahmaputra, specifically where bank protection measures were applied. Our sensitivity analysis showed that keeping the effective river width fixed to a smaller cross section more than doubled the annual SL_M. By combining a narrow width and a future increase in discharge, the model gave almost three times higher annual SL_M. Taken together, this conveys the importance of looking at the net benefits of sediment control measures, also pointed out by Ray et al. (2015). Information on the relative changes in sediment transport is in this case sufficient to adapt ongoing embankment projects to sustain future altered conditions.

A potential future increase of 40 % of transported sediments would be beneficial to the downstream Bengal Delta since it depends on a continuous deposition of sediments to counteract the ongoing net subsidence. The compaction of the delta is currently exceeding even the globally high rate of sea level rise in the Bay of Bengal (Rahman et al. 2011; Syvitski et al. 2009). However, the construction of reservoirs can considerably reduce the sediment load transported to the seas (Walling and Fang 2003), and large-scale damming of the upper Brahmaputra and its tributaries could counteract the increase in sediment delivery to the delta by keeping the elevated levels upstream. For example, after construction of the Farakka Barrage in 1975 in the Ganges River, approximately 30 % of the flow was diverted from the main channel (Rahman et al. 2011). That decrease in flow, combined with the reservoir trapping the sediments, possibly contributed to large-scale erosion of the Sundarbans mangrove forest occupying almost half of the delta in Bangladesh and India. An integrated basin analysis, coupling impacts from land use changes, river regulation, and climatic changes, is needed for a sustainable management of the delta environment. For future studies, a more distributed modelling approach could be developed, for instance including land use and land cover changes and their influence of soil erosion being routed to the river networks. Considering also the wider impacts of changes in this region, and the research community's ability to project them, improvements in the representation of land surface hydrology in climate models are needed to decrease projection uncertainty. Limitations in this regard have likely contributed to highly uncertain projections in other major basins (Raje and Krishnan 2012; Bring et al. 2015; Asokan et al. 2016).

Conclusion

There is substantial uncertainty in present sediment transport of the Brahmaputra River, due to insufficient availability of observation data on sediment load and parameters needed as input to sediment transport models. This hinders development of robust predictive models that can underpin management decisions related to sediment flows. Our analysis shows that there is considerable uncertainty in openly available estimates (270–720 Mt yr^{-1}) of the annual sediment load for the Brahmaputra River at the Bahadurabad gauging station. This may, for example, aggravate scientific impact studies of planned power plant and reservoir constructions in the region. Furthermore, better information regarding sediment grain size distribution and, to a lesser degree, water discharge and Manning's roughness along the river course, would substantially improve our ability to estimate current sediment load.

Although absolute values are uncertain, estimates of the relative changes in sediment load due to projected future changes in the climate were more robust, with the future annual sediment load estimated to increase by roughly 40 % by the end of the century (2075–2100) compared to levels in 1986–1991. This is an effect mostly due to projected increases in water discharge levels. However, because of such increased average discharges, we furthermore show that the uncertainty will grow in predictions of absolute levels of future sediment load. We suggest that priority should be given to open up and share sediment and hydrological data on the main channel and its tributaries, for the possibility to evaluate basin-scale effects from river regulation, changes in glacial melt water rates, and monsoonal run-off. This would not only improve transboundary cooperation but also provide the research community with vital means to project future changes. The increasing energy and food demand of the basin's population will intensify development in the upcoming decades. It is therefore critical to predict and assess consequences of future conditions while plans are still on the table.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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