Appendix - Supplementary Material

Journal: Regional Environmental Change

Article Title: Present to future sediment transport of the Brahmaputra River: Reducing uncertainty in predictions and management

Authors: Sandra Fischer*[1,2], Jan Pietroń[1,2], Arvid Bring[1,2,3], Josefin Thorslund[1,2], Jerker Jarsjö[1,2]

Affiliations

[1] Department of Physical Geography, Stockholm University
[2] Bolin Centre for Climate Research, Stockholm University
[3] Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, USA

Corresponding author
Sandra Fischer, Department of Physical Geography, Stockholm University, SE-106 91 Stockholm, Sweden. E-mail: sandra.fischer@natgeo.su.se, telephone +46701508477

Contents of this file:
The following supplementary material provides details of the method and contains a description of the model used in the study as well as the preparation of the model components: river geometry, streamflow and sediment settings.

1. Model: HEC-RAS 4.1

To investigate sediment transport parameters in the Brahmaputra River (see overview in Figure 1), the one-dimensional modelling software HEC-RAS 4.1 was used. HEC-RAS allows modelling of steady flow, unsteady flow, water quality and sediment transport (movable boundary sediment transport computations). In the sediment transport model the hydraulics are represented by a quasi-unsteady flow which is an approximation of a continuous flow hydrograph from a series of discrete steady flows (USACE 2010a). In general, in the steady flow calculations the program estimates water stages for each cross-section using an iterative procedure of solving the energy head equation together with the Manning's flow velocity equation (USACE 2010a). HEC-RAS includes several sediment transport functions mainly developed for non-cohesive transport computation. This methodology does not account for neither bank interaction nor braid confluence scour holes. Nevertheless, similar studies on sediment transport using HEC-RAS have been reported to reproduce absolute values of sediment load reasonable well (Chalov et al. 2015; Pietroń et al. 2015).

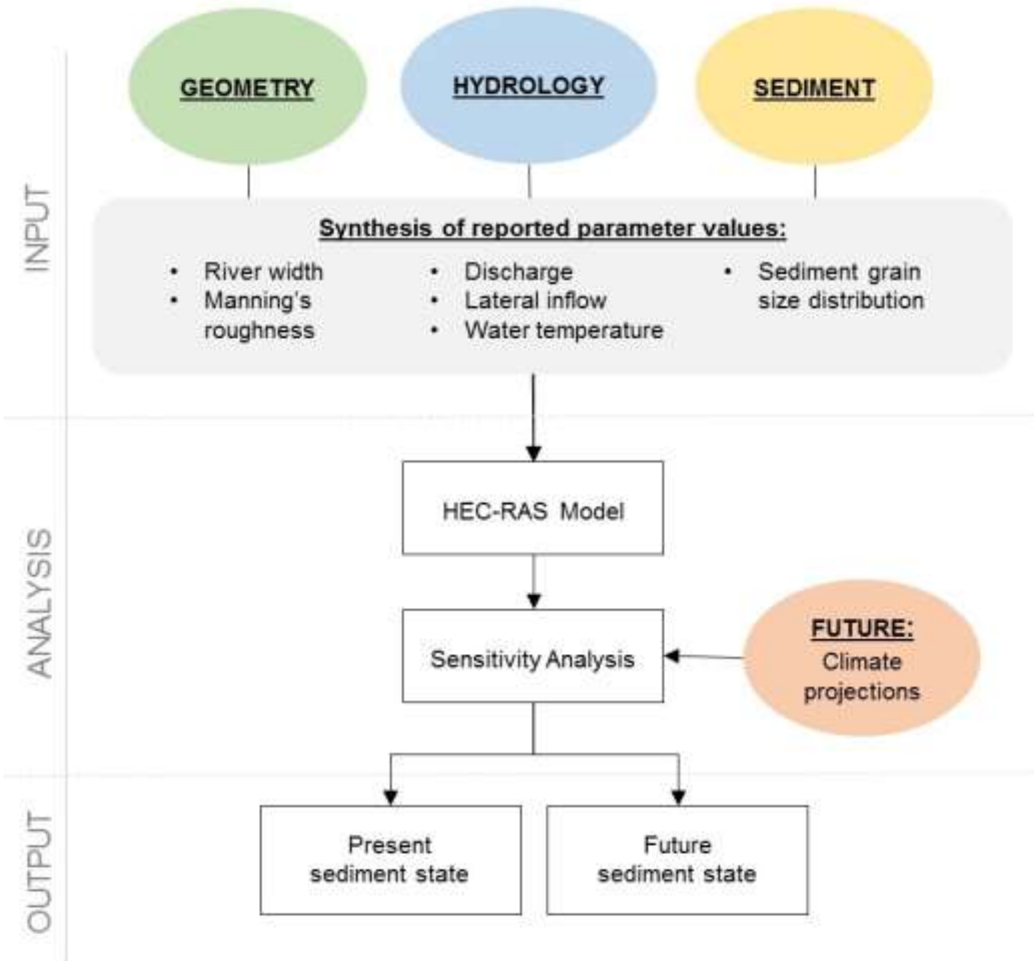

Fig 1 Flow chart of the modelling procedure and input data.

2. River geometry development

The geometric data used as input to the model was developed using a SRTM 3 arc-second resolution digital elevation model (DEM) and LANDSAT satellite images (USGS 2000; 2014). It was developed using HEC-GeoRAS in ArcGIS 10.1 and HEC-RAS. To determine the longitudal profile of the river, the main stream centerline was outlined in the DEM. To define the dimensions of the channel geometry, bathymetry maps are usually needed. Since no bathymetry information was openly available for the river, the lowest lying water level of the channels in the DEM was set to represent the deepest part of the river bed. That water level was found through the Flow Accumulation tool in ArcGIS. The model was tested for representing the Brahmaputra River as either several parallel-running channels or as a single channel. As these tests revealed no substantial impact on the simulated downstream sediment load, the braided morphology of the river was collapsed into one channel for reasons of computational simplicity. Perpendicular cross sections were drawn along the river course where all the elevation coordinates were changed into a uniform rectangular shape (Figure 2b) to minimize the heterogeneity and model complexity as well as adapt to the large scale of the modelling reach. These simplified cross sections required an overestimated channel depth to avoid any overbank flow. Hence, a depth of 20 m was applied to keep all the water within the river banks. To reduce the influence of spatial variation in river characteristics, the river width and Manning's roughness coefficient were kept equal for all the cross sections. The focus area of the river stretch lied between the stations Pandu (India) and Bahadurabad (Bangladesh) where cross sections were placed more densely (Figure 2a). Since the model requires stretches to stabilize both the upper and lower boundary conditions, the reaches upstream (Burhi Dihing-Pandu) and downstream (Bahadurabad-Sirajganj) were used as adjustment reaches for the model, where the final reach ends approximately 75 km north of the Ganges River confluence. The total reach of the river in our study stretches approximately 700 km where the focus reach constitutes less than half of that extent. A total of 56 cross-sections were necessary to provide an even gradation of the slope, with an average distance of 13.5 km between the cross-sections.

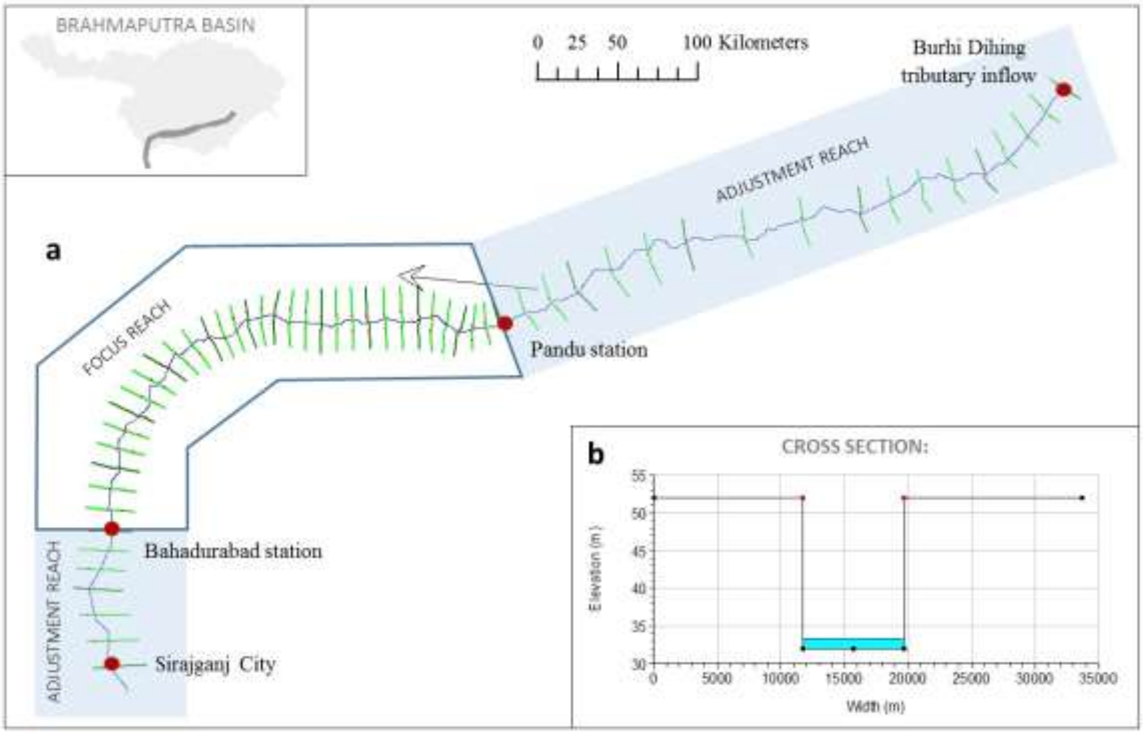

Fig 2 (a) Total modelled extent with the upstream adjustment reach, the focus reach in the middle and the downstream adjustment reach. (b) Example of a rectangular cross section

3. Streamflow settings

To represent the flow conditions over an annual cycle, we acquired the available six years of daily discharge (1986-1991) from the Bahadurabad gauging station from the Global Runoff Data Centre (GRDC 1995). A weekly moving average was applied to minimize the impact of extreme events, and the six years of data were averaged into one year of daily average discharge values. As an upper boundary condition at the most upstream cross-section (Burhi Dihing), discharge values were defined using a series of flows defined at certain time intervals. To calculate these flows, the available hydrological data from the downstream part of the river (Bahadurabad) were extrapolated upstream to this point. By using measured discharge data from the Pandu gauging station (located at the half-way point of the reach in Figure 2; GRDC 1995) and reanalysis data from Bahadurabad (Dai et al. 2009) a relationship could be established. This relationship could then be used to estimate the lateral contributions over the entire reach, and from that in turn derive the main water inflow data to the model at the upstream boundary Burhi Dihing (Q_{Main}), by use of the following equation:

$$Q_{Main} = Q_{Total} - Q_{Lateral}$$

where Q_{Main} is the calculated average annual discharge at Burhi Dihing (km^3 yr^{-1}), Q_{Total} is the measured average annual discharge at Bahadurabad station (km^3 yr^{-1}) and $Q_{Lateral}$ is expressed as:

$$Q_{Lateral} = \frac{\Delta_D (Q_{Total} - Q_{Pandu})}{\Delta_P}$$

where Q_{Pandu} is the measured average annual discharge at Pandu station (km^3 yr^{-1}), Δ_P is the distance between Bahadurabad and Pandu (km) and Δ_D is the distance between Bahadurabad and Burhi Dihing (km).

To simulate a gradually increasing flow, the $Q_{Lateral}$ was distributed evenly over all the cross sections down to Bahadurabad using the HEC-RAS tool *Uniform Lateral Flow*. The impact on the simulated sediment transport from varying shares of lateral inflow and main channel flow was tested in the sensitivity analysis. To simulate the water stage at the last downstream cross section, i.e., the downstream boundary condition, the average slope of the reach adjacent to Bahadurabad (7.4 cm km^{-1}; Woldemichael et al. 2010) was applied. Water temperature was defined together with the discharge data as a daily input over the year.

4. Sediment settings

To simulate the inflow of sediment to the river reach the Equilibrium Load boundary condition was used for the model inlet at Burhi Dihing (Figure 2). Thus, the inflow of sediment load for each grain size was set to be equal to the estimated transport capacity of that size (USACE 2010b). In an alternative model set-up, different boundary conditions were used, by moving the Equilibrium Load boundary condition from Burhi Dihing tributary to a more downstream location just above of the focus reach. A maximum bed scour depth was set to 14 m. This depth was judged as a reasonable value based on previous studies in the area (Best and Ashworth 1997; Mersel et al. 2013) and was applied uniformly to all the cross sections. A bed sediment grain size distribution was also applied to each cross section, based on reported measurements in previous studies (Figure 3). All the cross sections within the reach were assigned the same bed sample distribution. Sediment transport was estimated using the Toffaleti function. This formula was developed for large scale sand rivers with a large amount of suspended load (USACE 2010a) and the applicability of this transport function has previously been confirmed by Molinas and Wu (2001) for the Amazon and Mississippi Rivers. Consequently, sediment samples with finer grains (e.g. silt and clay) were outside the applicability range of this model setup and could be interpreted by the model (but also in reality) as an almost unlimited resource to be picked up and carried away (USACE 2010a). With this model setup we estimated sediment transport as the modelled sediment load (SL_M), which is given by the calculated sediment concentration multiplied by the input discharge data for a specific unit of time and cross-section (similar application to Chalov et al. 2015).

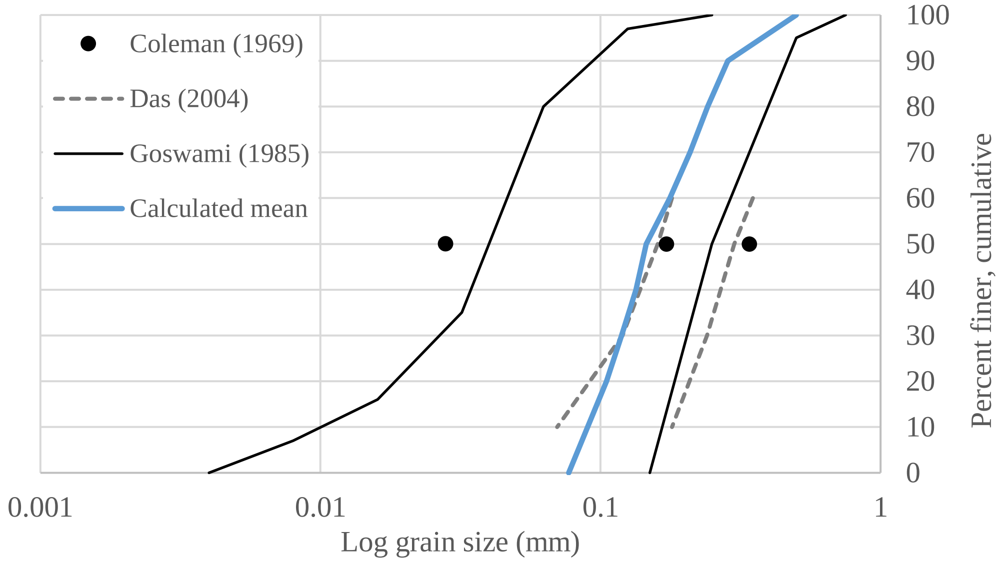

Fig 3. Literature samples of sediment grain size distributions along the modelled reach of the Brahmaputra River. Coleman's (1969) samples (min, mean, max) were measured at the Bahadurabad station, while min-max observed samples from Goswami (1985) and Das (2004) represent the whole reach from Burhi Dihing to Bahadurabad. The calculated mean sediment distribution (blue thick solid line) was derived from the min-max samples reported by Goswami (1985) and was used as the model base mode.

References

Best JL, Ashworth PJ (1997) Scour in large braided rivers and the recognition of sequence stratigraphic boundaries. Nature 387(6630):275-277. doi:10.1038/387275a0

Chalov SR, Jarsjö J, Kasimov NS, Romanchenko AO, Pietroń J, Thorslund J, Promakhova EV (2015) Spatio-temporal variation of sediment transport in the Selenga River Basin, Mongolia and Russia. Environ Earth Sci 73(2):663-680. doi:10.1007/s12665-014-3106-z

Dai A, Qian T, Trenberth K, Milliman J (2009) Changes in continental freshwater discharge from 1948-2004. J Climate 22(10):2773-2792. doi:10.1175/2008JCLI2592.1

GRDC (1995) The Global Runoff Data Centre, 56068 Koblenz, Germany. World Meteorological Organisation

Jain SK, Agarwal PK, Singh VP (2007) Hydrology and water resources of India. Springer Netherlands, Dordrecht, pp 419-472

Mersel MK, Smith LC, Andreadis KM, Durand MT (2013) Estimation of river depth from remotely sensed hydraulic relationships. Water Resour Res 49(6):3165-3179. doi:10.1002/wrcr.20176

Molinas A, Wu B (2001) Transport of sediment in large sand-bed rivers. J Hydraul Res 39(2):135-146

Pietroń J, Jarsjö J, Romanchenko AO, Chalov SR (2015) Model analyses of the contribution of in-channel processes to sediment concentration hysterisis loops. J Hydrol 527:576-589

USACE (2010a) HEC-RAS River Analysis System: Hydraulic Reference Manual Version 4.1, California. US Army Corps of Engineers

USACE (2010b) HEC-RAS River Analysis System: User's Manual Version 4.1, California. US Army Corps of Engineers

USGS (2000) United States Geological Survey, LandsatLook Viewer. http://landsatlook.usgs.gov. Accessed 30 May 2015

USGS (2014) United States Geological Survey, EarthExplorer. http://earthexplorer.usgs.gov. Accessed 10 March 2015

Woldemichael AT, Degu AM, Siddique-E-Akbor AHM, Hossain F (2010) Role of land-water classification and Manning's roughness parameter in space-borne estimation of discharge for braided rivers: A case study of the Brahmaputra River in Bangladesh. IEEE J Sel Top Appl Earth Obs Remote Sens 3(3):395-403. doi:10.1109/JSTARS.2010.2050579