Development of protocols for sediment management in the Ganga River: a geomorphic perspective

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1.0 Introduction

The Ganga is the trunk river flowing through the center of Bihar and splitting the state into two parts - north and South Bihar. Two highly sediment charged Himalayan rivers flowing from the north namely, Gandak and Kosi fall into the Ganga in this stretch and they add to the sediment budget of the Ganga significantly. In addition, two major rivers flowing from the southern craton namely, Sone and Punpun, also meet the Ganga at different points and their sediment fluxes are also sizable. The overall impact of such large sediment flux in this stretch of the Ganga has been overwhelming as manifested in the naturally aggradational behavior of the river in this region. This has also resulted in migratory nature of the river over a historical period and this has been well-documented in the literature (Phillip et al., 1993; Sinha, 1996; Rudra, 2010; Sinha and Ghosh, 2012).

Further, the Farakka barrage, commissioned in 1975 (construction started in 1961), has also influenced the river morphology and processes in a major way. Although the Ganga River has been naturally migratory in this region the Farakka barrage and associated structures have made the situation worse. The river has been migrating to the east in the reaches upstream of the Farakka barrage and to the west in the reaches downstream of Farakka. The apprehensions of the river flanking the barrage have forced more and more interventions in recent years (Rudra, 2000a, b). Unfortunately, these measures typically shift the trouble to upstream as well as downstream reaches and significantly increase the aggradation within the channel belt and the associated flood risk as evidenced in the several rivers of north Bihar (Sinha, 1998; Sinha and Jain, 1998). The reaches of the Ganga downstream of the barrage also form the international boundary between India and Bangladesh and such large-scale dynamics adds to the land disputes between the two countries.

The situation has become very grim in recent years around several important towns such as Patna, Bhagalpur and Farakka where the river has shifted several kilometers north leaving the banks of these cities high and dry. In several reaches acute drainage congestion exists because the longitudinal connectivity of the river has been seriously impacted due to siltation. There has also been a demand from certain section for decommissioning of the Farakka barrage. Moreover, the proposed navigation project of the Government of India has also become a matter of concern and there are apprehensions that this may further fragment the river into several parts due to the construction of a series of barrages

While it is agreed that some urgent action is needed to remedy this situation, it is not clear yet if the Farakka is the sole reason for these problems or if the

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decommissioning of the Farakka barrage would solve the problem or would not create additional problems. In particular, several issues need to be resolved before planning any mitigation measure for alleviating the region from the recurring problems of siltation and associated flooding.

First, there is still no good estimate of the total sediment flux and silt accumulated within the river channel. This poses a serious problem in planning any mitigation measures such as dredging of river channels. However, such estimates require a comprehensive dataset in terms of close interval sediment measurements, repetitive cross-sections and modeling studies. Very little data is available for the Ganga in spite of the fact that siltation in the river is recognized as the most serious problems for decades.

Second, the overall impact of the Farakka barrage on the morphodynamics of the Ganga river and siltation problem in the stretch of the Ganga flowing through Bihar needs to be assessed properly. In addition to the morphological changes it may also be useful to assess the ecological impacts due to this intervention. Further, an overall cost-benefit analysis accrued so far should also be done as quickly as possible.

Third, while a detailed study may be necessary to assess the situation fully, it is understandable that it may take long and some immediate steps may be necessary. Therefore, there is an urgent need to initiate a scoping study to provide a quick assessment and also to provide directions for detailed investigations and mitigation measured.

2.0 Sediment management across the globe: an overview

Before embarking upon sediment management in a river basin, it is important to understand that sedimentation/siltation in rivers is a natural process. When flow velocity reduces either due to lower gradient (entering into plain reaches) or widening of the channel (branching of river streams), suspended silt particles (0.002 mm and 0.063 mm) in the river settle down. This is called *siltation*. This phenomenon is normally called *sedimentation* when it occurs in a reservoir. Hence, erosion of silt particles and reduction in the flow velocity are the main causes for siltation / sedimentation. Siltation in rivers may or may not be accumulative whereas sedimentation in reservoirs is generally accumulative. The sediment inflow rate into a particular reservoir is, in general, a function of the watershed characteristics such as drainage area, average land and channel slope, soil type, land management and use, and hydrology. However, the human interventions in rivers results in imbalances which have a range of detrimental impacts on natural riverine processes that in turn affects the society, economies and the environment. In Anthropocene period, most of these interventions have been done using ‘Design life Approach’, without considering multiphase approach of development. This approach considers the societal and environmental concerns as static inputs that occur at project conception. Residual concerns such as decommissioning, unused physical resources, and unmet societal needs, are considered as external effects. It is also important to note that the actual rate of siltation is 2 to 20 times higher than the estimated value using design life approach. As a result, many rivers across the world have been aggrading significantly as a large fraction of sediments are trapped upstream and downstream of the invterventions.

The first and the foremost step towards mitigation of sedimentation problem in rivers is the quantification of sediment budget in different reaches – generally based on the sediment storage and flux rate of the river basin. Sediment budget of a basin is a conceptual framework that quantifies the rate and processes of sediment generation from hill slopes, transport through hills and channels, deposition and storage within the basin in form of bars, alluvial fans, and in other sites and weathering of sediments while in transport or storage (Dietrich et al., 1982). Such budgets can be constructed at a variety of scales ranging from a small river basin (Golosov et al., 1992; Owens et al., 1997; Walling et al., 2002) to a large basin scale (Meade, 1982). To calculate the sediment budget of a basin, spatial and temporal variability of sediment volume and flux rate must be considered as an important factor, as the measurement over a short period may not be representative of the long-term average conditions.

For long-term perspective, several traditional methods such as sediment archives, core logs, and boreholes have been used for the detailed analysis for the sediment flux at basin scale. Several long-lived cosmogenic nuclides ^{10}Be, ^{26}Al, and ^{36}Cl have been used for calculating catchment based erosion rates from fluvial sediments (Bierman and Nichols, 2004; Von Blanckenburg, 2005). Berendsen and Stouthamer (2000) used ^{14}C dates, lithological borehole descriptions, archaeological artifacts, and gradients of paleochannels to reconstruct the Holocene development (2000 years) of the Rhine–Meuse delta. Apart from these, short-lived radionuclides such as ^{137}Cs, ^{210}Pb, and ^{7}Be can also be used in sediment budget investigations that belong to the recent period (i.e. $<$ 100 years) (Walling, 2003). For even shorter time scales, Universal Soil Loss Equations (USLE) has been used extensively in different parts of the world. *A* Revised Universal Soil Loss Equation (RUSLE) is an empirical model for predicting the average rate of *SE* based on crop system, management techniques and erosion control practices). The RUSLE model is designed to predict the *long-term average* soil losses due to rainfall and runoff erosion. With the advancement in the technology, new techniques such as LIDAR altimetry (Carey et al., 2006) have been used to study the sedimentary sequence of a confluence area of a floodplain in Central England.

One of the most precise estimates of sediment accumulation in the channel belt is provided by repeated cross sectional surveys. This method can be supplemented by mapping the planform dynamics and identification of hotspots of aggradation in the channel belt. Such surveys are generally done through integration of ground based Total Station or RTK-DGPS with depth surveys using echo-sounder. Both data sets are then combined to generate a profile across the entire channel belt. The difference in channel bed over time gives an estimate of total sediments accumulated between the time interval represented by the cross-sections. Apart from providing estimates of sediment accumulation, this method also helps in assessing the flood risk due to the rise of river bed thereby reducing the channel capacity.

For measuring modern sediment volume and flux rate within the river channel, a large number of data sets such as channel cross-sections, average velocity, discharge, water surface width and its slope, sediment concentration, bed material samples as well as the specific gravity of bed sediments are considered. Bed load and suspended load in a river are measured at specific sites using standard methods. In India, bed load is not measured at any station and the usual procedure for measuring suspended load involves either sampling by point or depth integration and/or in-situ measurements. Depending upon the network for sediment load measurements, a sediment budget can be generated using the total sediment flow between the upstream and downstream stations and total aggradation or degradation can be computed between the two stations. This results in floods that would otherwise be contained by banks and embankments. It is important to note that above estimates are for long stretches along the river and there are significant spatial variations along the river in terms of pattern and amount of sediment accumulation. The estimation of precise volume in each reach is not possible without close interval cross-sections of the river. However, a first order assessment of hotspots of aggradation can be done through mapping of planform dynamics using repetitive satellite images.

We have recently applied the sediment budgeting approach to the Kosi River in north Bihar and Our first order estimates suggest that the total mass of sediments accumulated between Chatra and Birpur during the last 54 years (post-embankment period) could be 1082 million tonnes which translates to 411 million m^3 of volume and this may have accumulated at a rate as high as 23.33 mm /year. This is attributed to the relatively smaller area of sediment accommodation i.e. 324.27 km^2 between the two stations. Between Birpur and Baltara, the available depositional area is almost 5 times of the area between Chatra and Birpur stretch. Also, the barrage at Birpur acts as the barrier for a large fraction of sediments (coarse and medium fraction). As a result, sedimentation rate in this stretch is low (8.7 mm/year) but the total sediment accumulation is very high, 2009 million tonnes, that translates to 760 million m^3 of sediments.

Based on our mapping of planform dynamics in the Kosi River, we have identified the hotspot of aggradation in the river in the alluvial plains. Based on the aggradation pattern, we have classified the entire stretch between Chatra (upstream) and Baltara (downstream) into five zones: (I) Recent aggradation zone (reaches 1-6), (II) Variable aggradation zone (7-10), (III) Continuous aggradation (11-22) and (IV) No/little change (reaches 22-33). Zone III is interpreted to be most serious in terms of siltation and the downstream reaches do not show any significant aggradation over the last 45 years. We have also attempted to estimate the sediments accumulated within the channel belt based on the bar area calculation and taking an average depth of sediments as 1.25 m for the reaches upstream of the barrage and 0.46 m for those downstream of the barrage (based on sediment budgeting method). Table 3 lists the values for each of the zones identified above and also lists the values for two stretches, Chatra-Birpur and Birpur-Baltara, to compares these values with those computed from sediment budgeting method. It is important to note here that this computation is for the active channel belt only and therefore the values lower that those estimated from sediment budgeting method that are based on accumulation between the two embankments.

3.0 Proposed sediment management framework for Bihar Rivers

Based on our understanding of the processes operating in the Ganga and other rivers draining through north Bihar, we would like to propose a sediment management framework. Conceptually, any such framework should be based the following questions:

(a) <u>Where is the sediment coming from and where is this getting deposited</u>?
This answer to this question requires a first order mapping of the sources and causal factors of sediment production and hotspots of sediment aggradation. This can be achieved through geomorphic analysis of the river catchment and planform mapping of the alluvial reaches based on high resolution satellite images. This could also include sediment connectivity analysis to understand sediment dynamics from source to sink.

(b) <u>How much sediments are getting deposited in the channel</u>?
This requires a first order estimate of modern sediment fluxes over time scales of 10-102 years. This can be achieved through analysis of sediment load data for the last couple of decades and repeated cross section surveys. A slightly longer (>100 years) of sedimentation rates can be obtained through isotopic measurements (^{137}Cs and ^{210}Pb) of sediments.

(c) <u>How to manage excessive sedimentation in channels</u>?
This requires a technical assessment of all available methods of sediment control including catchment treatment and in-situ controls such as sediment bypassing and flushing through the barrages and dams. If required, dredging can also be done at suitable locations and keeping the environmental concerns in mind.

(d) <u>What to do with excess silt/sediments</u>?
This requires exploring and assessment of utilization of silt for various applications such as agriculture, structural fill, road construction, bricks making. These measures should provide an end-to-end solution starting from dredging and transport, storage and utilization.

A sediment management framework should therefore consist of the following components (Figure 1):

I. Problem identification: Process understanding of sediment dynamics, causes and problems associated with siltation, both natural and anthropogenic.
II. Measurements: Sediment load and rating curves, empirical equations and ANN models, cross sections and isotopic measurements
III. Management practices: Three R's - **R**educe sediment production, **R**oute sediment and **R**emove sediments each requiring an assessment of suitable methods based on the terrain, hydrology and engineering intervention.
IV. Benefit/Cost (B/C) analysis: Critical assessment of benefits related to agriculture, filling material, fisheries etc. to the costs or losses related to operation, silt removal and ecological losses.

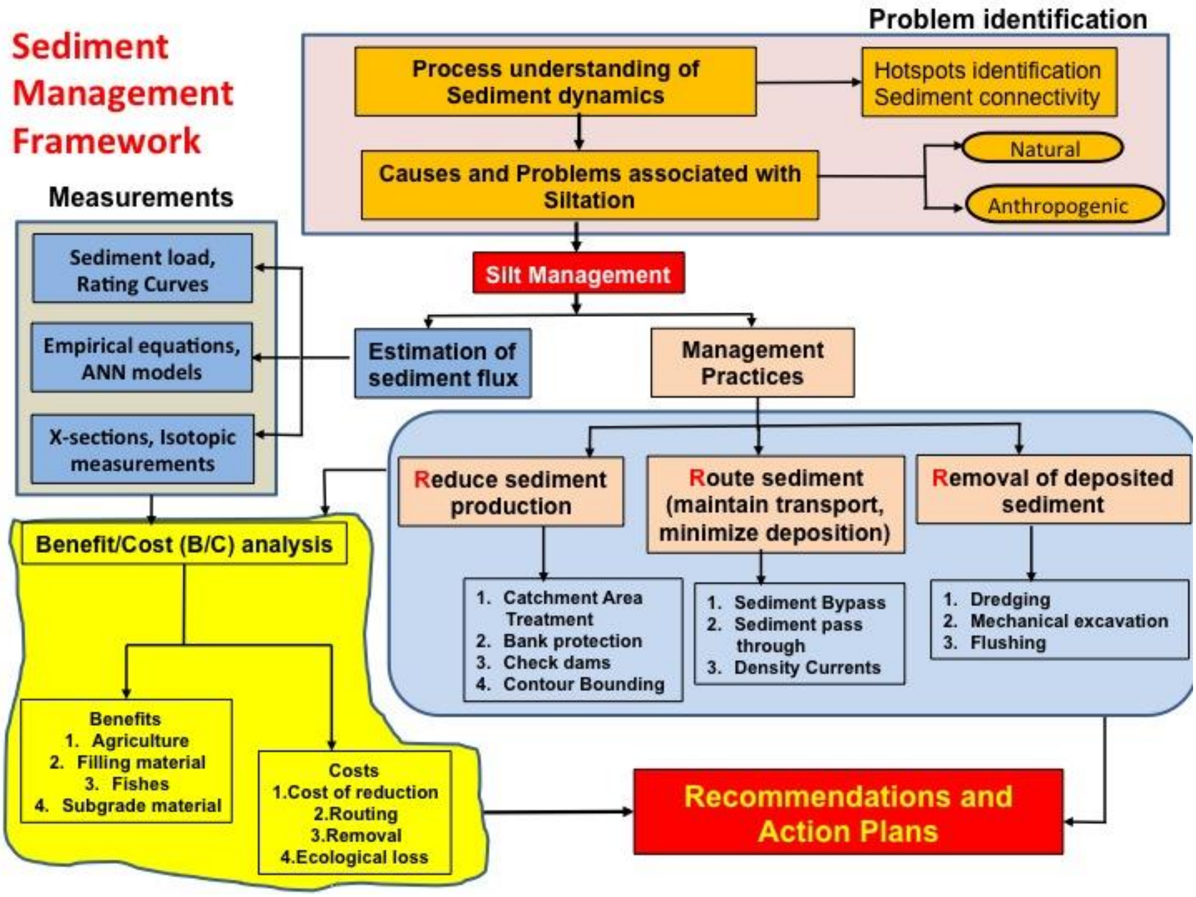

Figure 1: Proposed sediment management framework for Bihar Rivers

Based on the Results/outputs from each of these components, a series of recommendations and action plans can be drawn up specific to the basin.

4.0 Summary and Policy Recommendations

The Ganga is one of the largest river systems in the world and the sheer dimension of this river poses serious challenges for its sustainable management. The alluvial plains of north Bihar incidently fall in the lower reaches of the river and several sediment-charged rivers from the north meet the Ganga in this stretch. They add to the already high sediment budget of the river significantly and the river is naturally aggrading in this stretch. The human interventions such as embankments and barrages have seemingly aggravated the problem. Although a comprehensive assessment of the anthropogenic impacts is still due, it is time to bring sediment management of these rivers in the forefront. This can happen only if a thorough scientific understanding of the processes and causal factors of sediment production and dynamics is developed based on high quality data. The following set of recommendations should help in defining the roadmap for sediment management.

Recommendation 1: Sediment management should become an essential part of river management strategies, particularly for flood risk assessment and management for all rivers of Bihar. Most of the Himalayan rivers draining through north Bihar are known to be highly sediment charged but some of the cratonic rivers such as Sone may also need special attention.

Recommendation 2: Sediment management plans must be based on strong understanding of sediment dynamics for which detailed studies may have to be initiated, wherever needed. While there is some information available for rivers such as the Kosi, similar studies are urgently needed for other rivers of north Bihar.

Recommendation 3: Additional data on sediment load and cross sectional surveys are urgently required to improve the estimates of siltation within the channel. It is recommended to set up additional silt measurement stations on all major rivers of north Bihar and regular cross sectional surveys must be carried out at these stations as well as at other strategic points to monitor the changes in bed configuration and for computing the sedimentation rate. Short cores at some these locations may also be raised for deriving sedimentation rates based geochemical methods.

Recommendation 4: Sedimentation in the Ganga and other rivers of north Bihar is strongly linked to river dynamics and flooding through breaches in the embankment. Therefore, the identification of vulnerable stretches in terms of breaching and flood risk must include the data on in-channel sedimentation. Suitable measures must be planned in such reaches where excessive aggradation has decreased the longitudinal slope thereby increasing the risk of breaching.

Recommendation 5: Sediment management plans should be linked to river health assessment and habitat suitability. For example, while bar complexity is an essential ingredient for river health, excessive aggradation may affect the longitudinal connectivity thereby hampering river health. Therefore, a balance is needed between maintaining the morphological complexity and excessive aggradation.

Recommendation 6: There is a strong need to work with the neighbouring countries falling in the hinterland of the Himalayan rivers draining north Bihar. More specifically, serious efforts are needed in collaboration with Nepal in terms of soil conservation both in the hinterland and alluvial plains. Similar collaboration is required with Bangladesh in terms of flood control.

Recommendation 7: All efforts should be made to involve the local community in sediment management. They can be encouraged to use the dredged silt for agricultural and other purposes. At the same time, their awareness can help in reducing the soil erosion in the hinterland as well as in stabilization of banks and monitoring of embankments.

Recommendation 8: It is extremely important that river managers understand the good practices of sediment management as well as implications and risks involved in not following these practices. Therefore, regular programmes for capacity building on sediment management should be organized by experts at regular intervals.

Recommendation 9: Since the understanding of issues related to sediment management is rather limited at this stage, the precautionary principle should be applied on the basis of perceived threats as described above.

Recommendation 10: A sediment management policy is urgently required for the rivers of Bihar and the Government of Bihar should initiate the process for the same at the earliest. The recommendations above could form a good framework for developing the policy document.

5.0 Concluding remarks

Most rivers draining north Bihar plains have created havoc in this region due to multiple problems of frequent migration and floods and both of these problems are strongly linked to excessive sedimentation in the river. The interventions such as embankments and barrages have constrained the river to flow in a very narrow area and this has increased in-channel sedimentation in a significant way. This has aggravated the problem of instability of the channel and sedimentation within the embankment. As a result, the river bed has risen by several meters at several locations thereby increasing the risk of breaching and flooding. However, detailed assessment of impacts of these interventions is yet to be done and therefore any serious mitigation measures cannot be planned. It is recommended that these assessments be taken up urgently and that sediment management plan should become an integral part of river management of the all rivers in north Bihar.

Finally, we recommend a ‘Life Cycle Approach’ instead of ‘Design Life approach’ for river management so that consideration of societal and environmental concerns occurs throughout the life cycle of the project, allowing for project reevaluation. Residual concerns, such as decommissioning, are taken into account throughout the life cycle in such a way that encourages sustainable use, including through sediment management. We hope that the recommendations in this paper would serve as a useful framework to draft a sediment management policy for the rivers draining the Bihar plains.

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