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Deep-Channel Dynamics: A Challenge for Erosion Management in Large Rivers

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Abstract

In this paper, we present flow and erosion problems in selected reaches of two large and dynamic river systems in South Asia, namely the Koshi River in Nepal (and India) and the Lower Brahmaputra (Jamuna) in Bangladesh. We attempted to analyse large- and meso-scale (short- and medium-term) morphological changes with a focus on the dynamics of deep-channels, revealing their importance for the river and riverbank erosion management. This focus on deep-channels is a key change of perspective as most morphological studies and analyses of large rivers are usually focused on sandbar and braiding dynamics. We used ground data, satellite imagery, and explorative morphological modelling to quantify and analyse the flow and morphological processes. We demonstrate how multispectral satellite imagery can be processed using Google Earth Engine to assess the spatiotemporal dynamics of morphological processes and changes. We also analysed bathymetric surveys to assess short-term changes of meso-scale morphology that are not fully captured by the satellite data analysis. The morphological modelling provided first results on reproducing essential processes, such as growth and migration of meso-scale features, particularly deep-channels, under varying flow conditions. Some features of these reaches of two rivers differ, but particularly the importance of deep-channel dynamics was revealed for both. We infer that the seasonal and annual discharge variabilities are key factors for the dynamic behaviour of bank, char (island), sandbars and deep-channels, particularly regarding short- and mid-term changes. We also infer that morphologically extreme situations do not always occur during high flows, but rather through the concentration of the flow along the deep-channels during medium and lower flows.

Keywords: Large rivers; Deep-channel; Aqua Monitor; Morphological modelling; Delft3D

1 Introduction

Understanding the dynamic behaviour of large rivers is important for river management considering hydraulic and morphological evolution and stability of the primary and secondary channels and anabranches. The concern becomes more vital when the banks and lands are highly erodible with the presence of important areas, settlements and infrastructures along the banks on the floodplain and chars (islands).

There is a large amount of studies on meso- and large-scale river dynamics that include sandbar dynamics, braiding dynamics and river bank shifting (Ashmore, 2013; Nicholas et al., 2013; Vanoni, 1975). Many past studies have provided good fundamental insight into the morphological behaviour of the rivers, mostly associated with sandbar dynamics. However, it is not always easy to apply these knowledge and tools for real-world river management for various purposes, such as flood and erosion management, river stabilization and land recovering, improvement of river navigability etc. This is particularly valid for the large rivers with high flow and sediment dynamics and erodibility. This paper contains a short review and illustration of our comprehensive studies on two large rivers in South Asia, namely Koshi River (upstream braided reach, located in Nepal) and Lower Jamuna (downstream braided reach with a major bifurcation, located in Bangladesh). These rivers are the parts of Ganges and Brahmaputra river systems that originate from China and eventually flow into the Bay of Bengal.

The Koshi River is the largest river of Nepal which flows in the eastern part of the country starts journey at a height more than 8,000 masl. After passing through about 150 km mountainous reaches of Nepal, the Koshi river emerges through a narrow gorge near Chatara; 42 km upstream of the Nepal-India border, making a large alluvial fan with braided planform. The transition from braiding to meandering river is evident in downstream reaches before its confluence with the Ganges River in India. In this study, our focus is the upstream reach from the Chatara (end of the gorge) till the barrage as well as some downstream meandering part in lowland areas of India. The upstream is an important and dynamic reach of about 40 km length, influenced by the interventions like a barrage at the downstream and the embankments on both sides. The morphology of this reach has been largely triggered by these interventions for last 50-55 years. Regardless of many past studies and investigations (Chakraborty et al., 2010), there are still some issues about the dynamic nature of the river reach, induced by the interventions, that must be addressed for proper management of this reach in future. A first brief study has been carried out by Devkota et al. (2018).

The Lower Brahmaputra River in Bangladesh is one of the largest rivers in the world. Unlike the Koshi, the lower reach of Brahmaputra is located in rather erodible lowland delta, and most of the morphological activities is caused by large upstream flow variability and land erosion. The discharge may vary within the range of 1000 to 100 000 m^3/s, while the land erosion may occur in the range of hundreds of meters during just one season. The river (mainly its anabranches) are erodible even during low flow period. Our focus is lower part of Brahmaputra (Jamuna) until the confluence with Ganges (Padma in Bangladesh). This reach includes a major bifurcation (downstream of Jamuna bridge) with very dynamic behaviour of its right and left branches.

2 Landsat imagery analysis

Processing and analysis of satellite images have been carried out to assess the large-scale morphological evolution of upstream braided reach of the Koshi and the Lower Brahmaputra with major bifurcation. The analysis of satellite images has been made based on a recent advanced image processing technique using Google Earth Engine (Donchyts et al., 2016) to assess the medium- (last 15-30 years) and short-term (last 1-5 years) large scale changes, which mainly includes erosion and accretion of river banks and chars (islands).

2.1 Methodology

The changes in wet and dry areas (interpreted as spatial and temporal variation of accretion and erosion) have been quantified by detecting the changes in water bodies using multispectral satellite imagery based on number of steps, which enable automated calculation of changing water surface area using both cloud-free and partially cloud-free images (Donchyts, 2016). Advantages of the method are: (i) high frequency images with improved processing and analysis, (ii) automated processing like extraction of geometry and topology, (iii) robust and accurate method of water body detection and delineation, (iv) estimation of temporal changes in water surface area, and (v) monitoring and estimation of accretion and erosion (spatial and temporal variation, but not the volume).

The analysis process has been automated and developed an interactive tool 'Deltares Aqua Monitor'. The Aqua Monitor establishes water-land and land-water occurrence on-the-fly by estimating the MNDWI spectral index values and performing trend analysis for these MNDWI values over both user-selected periods. To decrease noise for the high latitudes, all Landsat images acquired during night time are excluded. Additionally, we apply a topographic mask based on Height Above the Nearest Drainage (HAND) to decrease the noise in the hilly areas, occurring due to mismatches between sun elevation and azimuth parameters in both periods. All pixels representing mountain hills (HAND > 150m) are excluded. The final estimation of the surface area (land to water and water to land) is obtained by including pixels where significant slope changes were observed. The threshold was found empirically. The Google Earth Engine backend of the Aqua Monitor prepares all computations and visualizations on-the-fly (Donchyts, 2016).

3 Large scale changes in Koshi River reach

We present some examples of large-scale morphological analysis with the application of satellite images and Aqua Monitor.

3.1 Upstream reach

The reach, upstream of the barrage, is in Nepal. The reach has been affected by the narrowing due to the barrage and embankment. This has led to sedimentation of the western part and disappearance of the anabranches. The river has been narrowed significantly, leading to reduction of the conveyance as well as eastward shifting of deep-channels and their active and short-term formation and migration. This has made the east embankment and floodplain very vulnerable. The embankment breach in 2008 is one of the aftermaths of this, and now also a few vulnerable points can be noticed along this reach. In a very recent flood (July 2019), it has been observed that the river upstream of the barrage can accommodate much less water (more than twice) comparing to a few decades back, causing overflow of the barrage.

The satellite images and the result of processing using Aqua Monitor, presented in Figure 1, Figure 2 and Figure 3 clearly illustrate the changes and the problems. The changes, seen in images, have well been replicated by Aqua Monitor as can be inferred from Figure 1. The changes during two different periods, quantified by Aqua Monitor, show that the deep-channels were migrated significantly towards the east embankment during 1987 to 2007, which eventually resulted in the breaching in 2008. After the breaching, the deep-channels appear to have been shifted away from the east bank. This can be attributed to the fact of morphological changes during breach event (more sediment deposition along the east belt) and probably also some local interventions (and maybe change in gate operation) to divert the channel towards the west part. Similarly, Figure 2 illustrates how the river has been narrowed near the barrage, and it was well quantified by Aqua Monitor.

3.2 Downstream reach

The reach downstream of the barrage is in India. We have briefly assessed the downstream impact as well based on Aqua Monitor. Figure 3 shows the changes in deep-channel pattern immediate downstream of the barrage before and after the breaching event. One of the reasons for this could be the changes in gate operation (although we do not have information about it). Figure 4 shows the changes in further downstream (lowland part in India) revealing formation of meandering channel during 1987-2007 and cut-off of meandering during 2007-2018. Such dynamics is usually caused by predominantly upstream flow variability as well as sediment transport condition, e.g. less upstream transport causes active deep-channel formation and migration leading to bed and bank erosion in downstream lowland reaches.

4 Large scale changes in Lower Brahmaputra

4.1 Image analysis using Aqua Monitor

Analyses of medium and short-term morphological changes have been made based on the results of image processing using Aqua Monitor as mentioned above. Figure 5 shows the large-scale morphological changes in Upper (in India) and all Lower Brahmaputra (in Bangladesh) during last 31 years, which has been split over different characteristic period to quantify the erosion-sedimentation trend, quantified using Aqua Monitor. Similarly, Figure 6 shows these changes for Lower Brahmaputra (Jamuna) at a major bifurcation. The changes, quantified using Aqua Monitor, has been split over two different characteristic period, i.e. first period between 1987 and 1998, while second period between 1998 and 2018. The result shows that there was erosion trend during first 11 years (until 1998), while there was accretion trend during last 20 years. It is to be noted that the major bifurcation started to form already in 1992 (based on Landsat image). It is also important to note that there was a large flood in 1998. The result shows that significant accretion has been occurred mostly along the right channels and anabranches up to the confluence with Ganges River. The confluence has been moved downward (see Figure 6). This could be attributed to the increase in upstream supply and stabilization of upstream reach after construction of Jamuna bridge. This can also be partly due to long-term effect of Ganges confluence, particularly given that fact that accretion has been occurring along the right channel (as Ganges flows from the right side). This accretion trend before 1998 seems to have caused bank erosion in both branches of the bifurcation, particularly this is more pronounced in the left channel. This may be due to the fact that accretion along the right channel has led to increase in flow entering to the left channel. This can also be attributed to the changes in upstream morphology and deep-channel patterns (shown below in bathymetry data analysis).

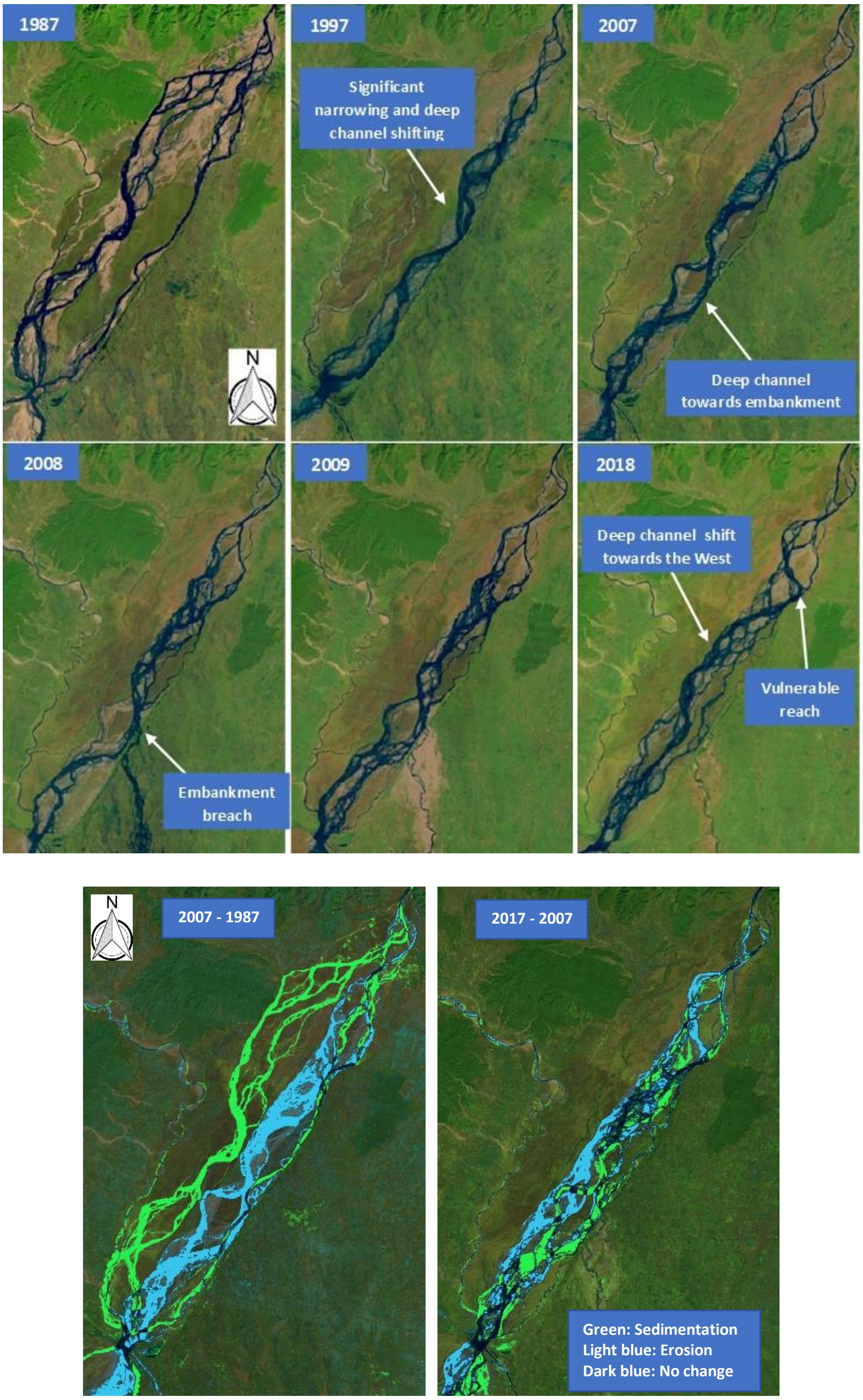

Figure 1. Narrowing of Koshi reach with deep-channel shifting apparently caused by the barrage (upper images), and quantified by Aqua Monitor for two different periods (lower images)

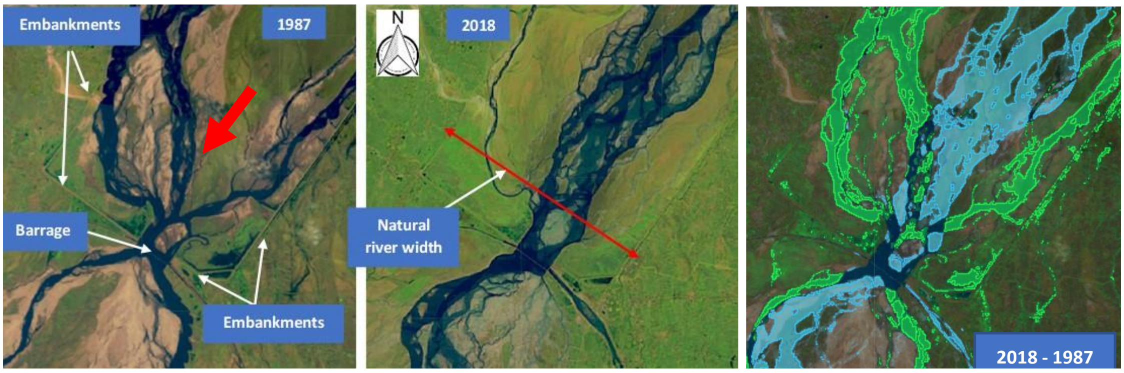

Figure 2. Narrowing of the Koshi near the barrage, quantified by Aqua Monitor (right plot)

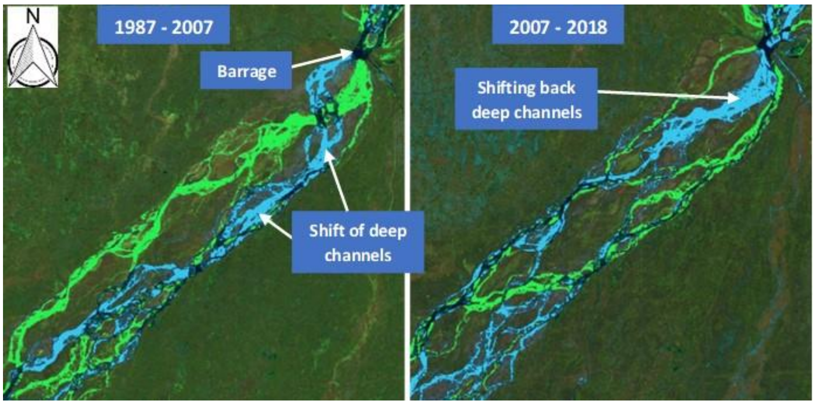

Figure 3. Morphological changes immediate downstream (in India) of the barrage

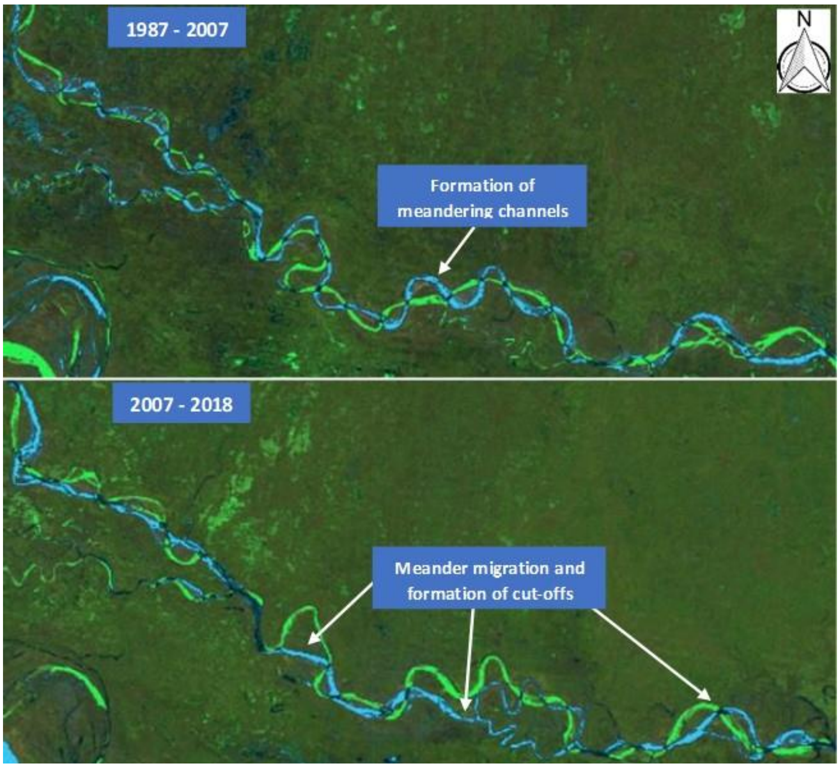

Figure 4. Impacts of upstream changes in flow and sediment transport in downstream reach (in India)

The Aqua Monitor result replicates well the formation of new chars (islands) at both side and stabilization of the narrow straight channel between the Jamuna bridge and the bifurcation after the construction of the bridge (in 1996). However, it is evident that this channel has been widening since last few years and mid channel bars have been appeared that can be inferred from Figure 7. It must be emphasized that capital dredging was carried out near the Jamuna bridge during dry period of 2012. As a result, a new deep-channel appears to have developed upstream of the bridge, thereby leading to active morphological development at the reach downstream of the bridge. Consequently, formation of sandbars in the reach between the bridge and the bifurcation seems to have resulted in bank erosion at this reach. This could be attributed to the changes in upstream condition at the bridge leading to formation and migration of deep-channels (shown below in bathymetry data analysis) and could be unfavorable for bifurcation stabilization.

4.2 Analysis of ground data at Lower Brahmaputra (Jamuna)

We have attempted to compare the bathymetry data, measured in 2011, 2012, 2016, 2017 and 2018 (measured after high water season). It is to be noted that the resolution and extent differ for some of the measurement. The analysis has been made to assess the formation and evolution of meso-scale morphological pattern with a focus on deep-channels and bend scour.

In 2011 and 2012, there was apparently one main approaching deep-channel at the upstream of the bifurcation, which was propagating towards the left channel having a meandering pattern that can be inferred from Figure 8. Such meandering pattern of deep-channel, which propagated towards the bend at left branch, appears to have caused large bank erosion there (quantified by Aqua Monitor as well, shown in Figure 7). In 2016, there were two deep-channels at the upstream, apparently due to formation of a mid-channel bar (see Figure 8). This might be attributed to the changes in upstream condition such as large erosion at Jamuna bridge, triggered by the dredging. This mid-channel bar formation led to bank erosion of both banks at immediate upstream of the bifurcation. Analysis of Aqua Monitor result above shows this trend. The deep-channel pattern has become sharper in 2016, which appears to have caused erosion of the central char right after the bifurcation point (at left branch). The latest bathymetry of 2018 (rightmost plot of Figure 8) shows two clear deep-channels at upstream reach of the bifurcation and propagating to both branches.

The dynamics of deep-channels (scour) along the outer bend at the left branch, where large bank erosion occurred, is shown in Figure 9. It is evident from the data that a deep-channel was present at this bend already in 2011, which could be one of the triggers for the bank erosion in later years. The bank was protected in 2016, therefore local deep erosion along the protected bank is visible in the bathymetry data of 2016 and later. This deep-channel (scour) along the bend is propagating downstream. It is important to follow this to manage the banks at downstream reaches. The changes based on reach averaged bed level are also presented in Figure 8 and Figure 9.

4.3 Morphological modelling

It is rather difficult to replicate and predict complex and dynamic morphological changes, particularly long-term changes, by using numerical modelling in such a large river system given the scale and variability (spatial and temporal). Nevertheless, application of computational models with continuous development and adaptation could be very useful to get insight into underlying physical processes. Besides, in complement with observed data, monitoring and satellite imagery, the morphological models can be very useful as a supplementary tool for scenario analysis of generic conditions, medium- and short-term assessment and predictions as well as for relative studies such as assessing impacts of the interventions. In this study, we have illustrated first computational results of short-term deep-channel formation and migration.

A depth-averaged morphological model, namely Delft3D, has been used. The Delft3D is a curvilinear model that solves two- and three-dimensional Navier-Stokes equations coupled with sediment continuity equation. The model incorporates various useful aspects, for example domain decomposition, consideration of floodplains including wet and dry processes, sediment transport over non-erodible layers, dry cell erosion, functionality for sediment management to assess dredging, dumping etc. Physically a depth-average model is not able to compute the secondary flow exerted by river bends as well as the effect of transverse bed slope on sediment transport. However, these effects have been incorporated in the model in parameterized way using approach of Koch and Flokstra (1980). This implies that the model is capable of simulating the morphological feature at bends. Mathematical formulations and relationships have not been presented here as the approach is well-known from the literatures on fluid dynamics and sediment transport theories and practices, and also mentioned in Delft3D reference manual. For computation of sediment transport, a user-defined general formula has been selected that approximately represents the FAP formula. This transport formula was specifically developed for Lower Brahmaputra in Flood Action Plan study (Delft Hydraulics and DHI, 1996). The river bed with uniform sediment has been considered (d_{50} = 0.15 mm).

Some first morphological modelling results on bed level changes with a focus on deep-channels including bend scour are illustrated in Figure 10 and Figure 11. These figures show short-term changes and migration of deep-channels, particularly at the upstream of the bifurcation and the left branch given that this branch is wider with formation of multiple deep-channels (anabranches). This is important to observe and quantify for proper river management along this branch as well as downstream reaches.

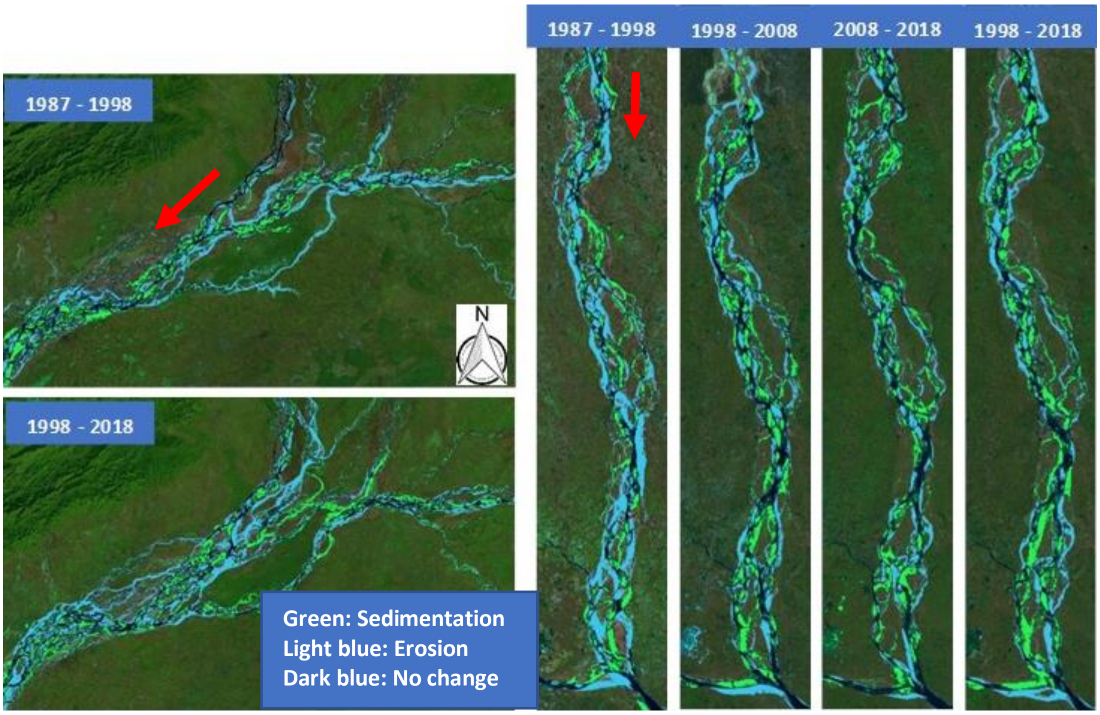

Figure 5. Morphological changes at upstream of the Brahmaputra in India (upper and lower right plots) and lower Brahmaputra in Bangladesh (left plots), quantified using Aqua Monitor

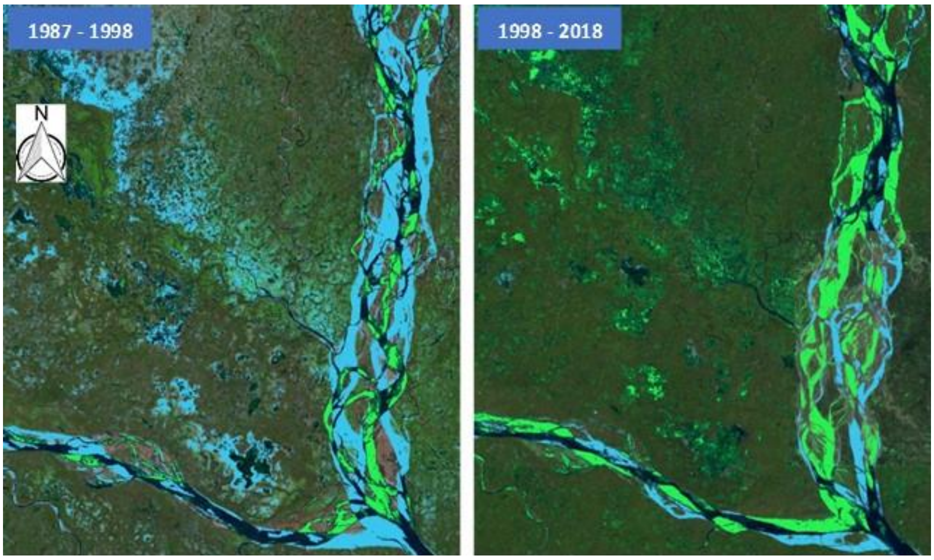

Figure 6. Large morphological changes at Lower Brahmaputra (Jamuna), quantified using Aqua Monitor, revealing erosion (left) and sedimentation trends (right) during two different period

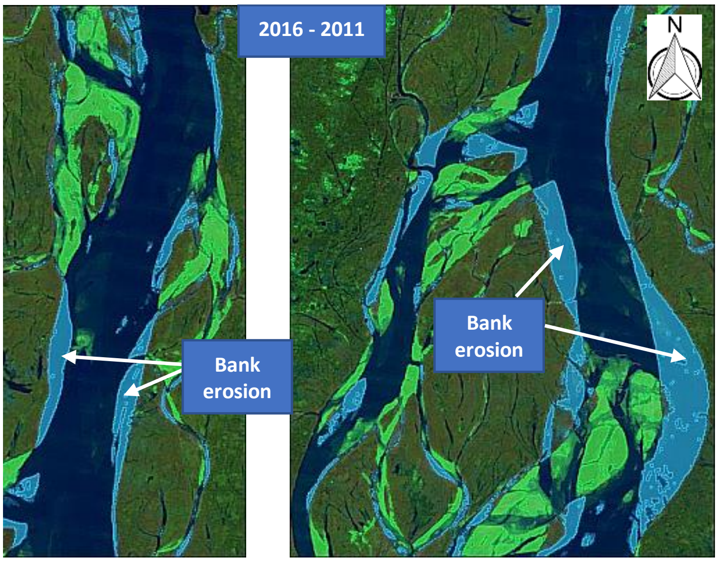

Figure 7. Large morphological changes (bank erosion) caused by deep-channel propagation at upstream (left plot) and left branch bend (right plot), quantified using Aqua Monitor

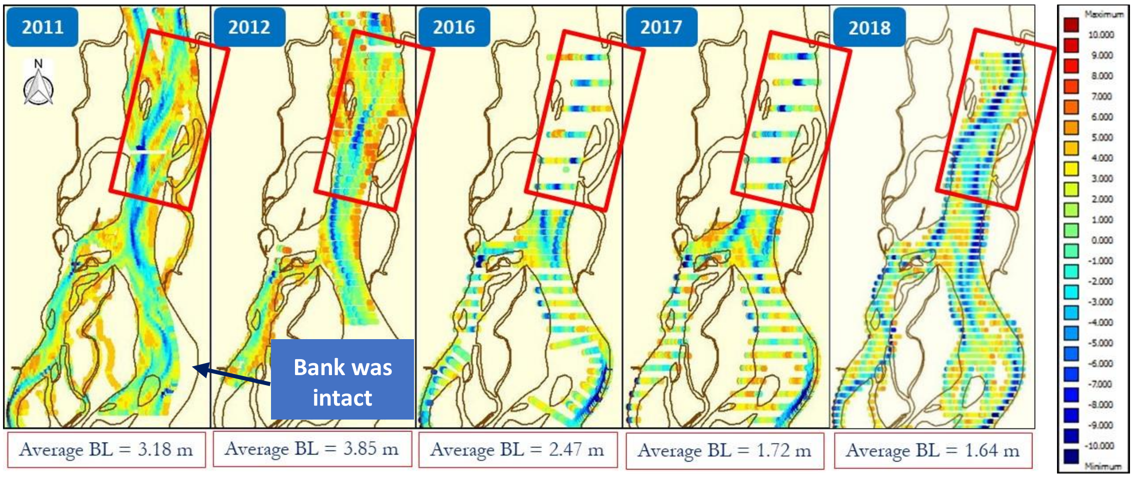

Figure 8. Bathymetry measurement, revealing changes in deep-channel patterns upstream of the bifurcation and branches (the average bed level is calculated within the upstream reach indicated by red rectangles, revealing how the reach has become deeper after the intervention)

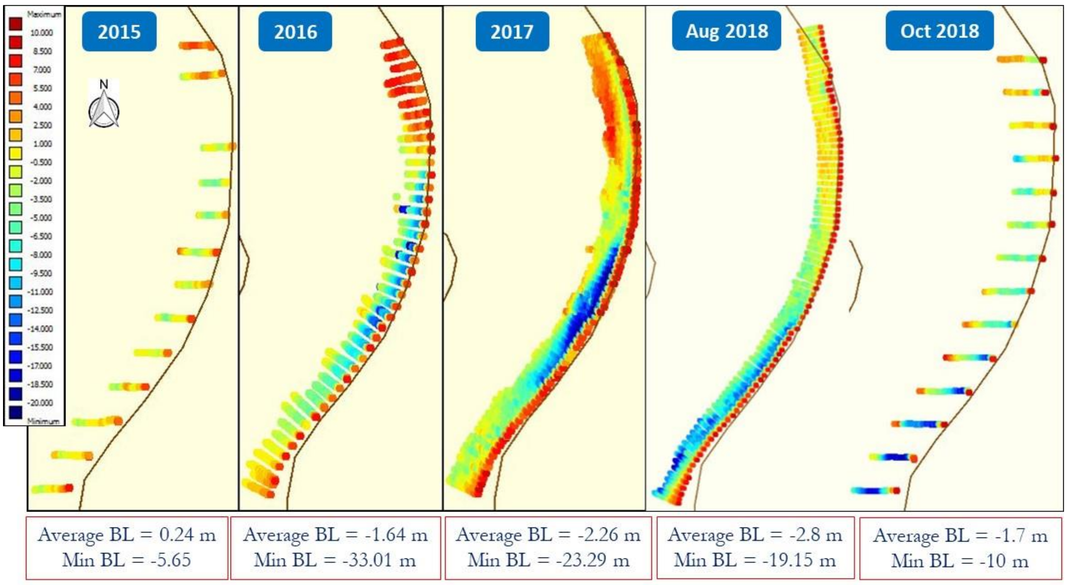

Figure 9. Bathymetry measurement, revealing evolution of bend scour along near-bank area of left branch channel

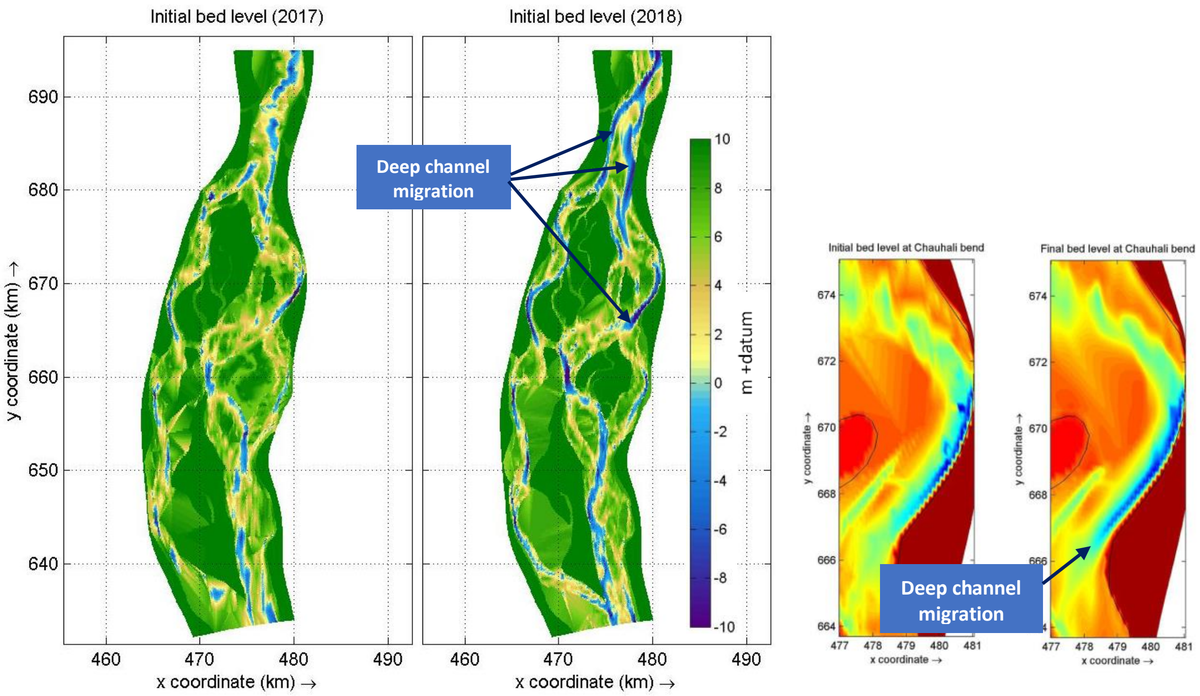

Figure 10. Measured deep-channel migration at Lower Jamuna (left plot) and an example of morphological modelling of deep-channel propagation along the bend (right plot)

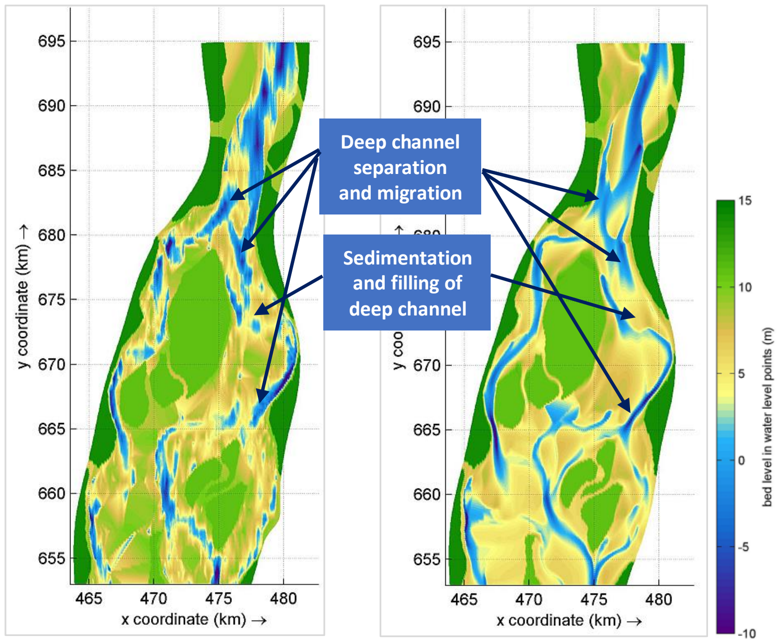

Figure 11. An example of morphological modelling result (right plot) of short-term deep-channel migration comparing to the observation (left plot)

5 Preliminary conclusions and future work

Upstream reach of the Koshi is an alluvial (inland) fan with high sediment load (in Nepal), while Lower Brahmaputra is an erodible deltaic river (in Bangladesh). Regardless the fact that these two large rivers are located in different region with different geology, sedimentology and landscape, there are some common features that are important for consideration in river management practices. The most important feature is evolution of deep-channels and their effect on river stabilization measures and interventions. Analysis of ground data, Aqua Monitor as well as morphological modelling have provided basis for following preliminary conclusions:

(i) Variability in upstream flow and morphological changes have large impact on downstream reaches

(ii) The barrage has resulted in narrowing of upstream reach of Koshi, leading to reduction of conveyance capacity as well as unfavorable activities of deep-channels threatening the eastern embankment (breaching in 2008 is a fatal example).
(iii) Upstream intervention (capital dredging near Jamuna bridge) resulted in transport of materials, particularly changes in deep-channel formation and patterns (although formation of sandbars plays a noticeable role as well) leading to destabilization of the bifurcation, branches and anabranches.
(iv) Sandbars are more active during higher flows while deep-channels are more active during lower flows due to the concentration of flows in the deep-channels, and the erosion is more dominant during the lower flows. Therefore, for the erosion management and design consideration, the extreme condition is not always associated with higher discharges.
(v) Time scale of deep-channel migration is much faster than sandbar migration.
(vi) In Lower Brahmaputra, sandbars are usually formed as a result of large bank and char (island) erosion, while deep-channels are important triggers to erosion of banks and chars. In upstream Koshi, there is large sediment supply from upstream steep (mountainous) reaches resulting in large morphological changes in alluvial fan. The changes of deep-channel pattern and their migration appear to be the impact of interventions (the barrage and embankment). In both cases, deep-channels create problems threatening the banks, chars and embankments.
(vii) Migration of deep-channel towards the bank and/or embankment can be considered as a risk and shall be considered and monitored well while erecting erosion management measures. The deep-channel causes toe erosion and during overbank flows, particularly during falling stage, there is high risk of land erosion (this is particular case at Lower Brahmaputra due to high erodibility of lands).
(viii) The process of short-term formation and migration of deep-channels is important to understand, quantify and monitor during any major interventions in such river systems.
(ix) Combination of image analysis using Aqua Monitor, ground measurement and monitoring as well as morphological modelling is an effective approach to assess the feasibility as well as adaptation of the river management efforts. It is important to mention that regular field surveys prior to and after erecting measures and interventions are one of the important and effective non-structural measures, since regular site and large-scale surveys serve the purpose to identify the adaptation approach and measures.

Following aspects have been considered in ongoing and future works:
(i) Proper quantification of spatial changes in large- and meso-scale river planform with Aqua Monitor (e.g. spatial and temporal changes in areas of erosion and sedimentation)
(ii) More detailed morphological modelling study
(iii) Making specific link to the adaptive approach for river stabilization and management, majorly depending on forecasting, particularly shorter term.
(iv) Deriving a new formulation referred to as “Deep-Channel Index (DCI)” for quantification of meso-scale morphological changes to be applied for river management and adaptation. The DCI should be based on evolution of channel bed and number of deep-channels.

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