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Hydro-morphology of Bangladesh rivers: Reflections from a large study

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ABSTRACT: Hydrological and morphological studies of about 50 rivers in Bangladesh have been done over the last few years. The studies were conducted in relation to 188number of bridges proposed to be constructed on these rivers. The hydrological studies included estimation of flood discharge, level, velocity, hydraulic depth, flow area, etc., based on flood frequency and/or model studies. Flood frequency analysis was carried out using the Lognormal, Gumbel's Extreme Value Type I, Pearson and Log Pearson probability distribution functions. One-dimensional hydrodynamic model was also used to generate design hydraulic parameters at the selected river locations. The morphological studies included assessment of stability of the river sites using time series satellite image analysis, quasi-three dimensional morphodynamic modeling, cross-sectional analysis and field observations. Spatial distribution of various parameters was then investigated. The findings indicate that some areas/rivers are hydro-morphologically more active and vulnerable than the others. Even the vulnerability of the same river varies depending on the location. Accordingly, hydraulic intervention in some rivers are found to be more challenging than in others.

1 INTRODUCTION

Bangladesh is a country of rivers. There are 410 rivers which crisscross the country. Fifty seven of these are Transboundary Rivers entering the country from India and Myanmar. The Ganges, the Brahmaputra and the Meghna (GBM) are the internationally known, mighty rivers of the country. They originate from the Himalays and flow through Bangladesh before emptying into the Bay of Bengal. These rivers and their tributaries and distributaries carry huge water and sediment during the monsoon season. The large flow causes flooding and bank erosion in different areas of the country.

The rivers of Bangladesh are highly dynamic in terms of both hydrology and morphology. The river flow, velocity, hydraulic depth, etc., vary from year to year and within each year. The rivers themselves show different hydrological characteristics depending on locations - some have a steep gradient and hence flashy, some are tidal and some are regular riverine flooded. Similarly, they are morphologically different - some are straight, some are meandering, some are braided, some are wandering and some are anabranched. They differ in sediment load and characteristics. The bank and bed erosion characteristics of the rivers also vary, not only from river to river but also from reach to reach within a river. However, a generic characterization of the rivers of Bangladesh in terms of hydrology and morphology has not so far been made.

The Bengal basin has been formed by the sediments (10^9 ton/year) of the Himalayan mountain range carried by the Brahmaputra and Ganges river system (EGIS, 2000). Almost the whole of Bangladesh is situated in a deltaic plain, which is the largest delta in the world. The available literatures suggest that the Brahmaputra is a braided river, the Ganges and the Padma are wandering rivers, and the Upper Meghna is a meandering river. Seasonality is strongly manifested in the flows of these rivers. The difference in water levels between high and low flow seasons is about 7 m on the Jamuna, 7 m on the Ganges, 5-6 m on the Padma and 3.5 m on the Lower Meghna (JICA, 2005). The average slope of the Brahmaputra is 7.5 cm/km, the Ganges 5 cm/km, the Padma 5 cm/km, the Upper Meghna 2 cm/km and the Lower Meghna 5 cm/km (EGIS, 2000). The average annual sediment transport is 590 Mt (sand 200 Mt) by the Brahmaputra, 550 Mt (sand 195 Mt) by the Ganges, 900 Mt (sand 370 Mt) by the Padma and 13 Mt by the Upper Meghna (EGIS, 2000). The average d_{50} is 0.20 mm at Bahadurabad, 0.15 mm at Hardinge Bridge, 0.12 mm at Mawa, 0.09 mm at Chandpur and 0.14 mm on the Upper Meghna (EGIS, 2000).

The hydrology and morphology of the Jamuna River were studied under the Jamuna Bridge Project (GoB and UNDP, 1989). The available secondary water level, discharge, cross sections, images, etc., were analyzed to select the bridge site and determine the bridge design parameters. Limited model studies with the WAF-LOW computer model were also done to assess the potential effects of some interventions, such as flood protection and dredging, on the hydrology of the river. A 1:100 year flood discharge of 91,000 m^3/s and flood level of 15m PWD were suggested as the key design hydrologic parameters. The scours at piers and guide bunds of the bridge were estimated based on this flood, and the maximum scour at piers was found to be 33 m below the 100-year flood level. Similar study was made for the Padma River during the feasibility study of the Padma Bridge (JICA, 2005). The 100-year design discharge was estimated to be 134,400 m^3/s and design high water level (DHWL) to be 7.35 m PWD. The design scour depths at the piers were estimated to be 36.4-50.3 m below the DHWL depending on the pier location. The Meghna bridge was commissioned in 1991 (Rahman et al., 2015) and experienced scours at its left abutment and three piers (Hoque et al., 2004) needing a major rehabilitation (Chowdhury et al., 2018). Recently, a parallel bridge has been constructed on the river using a 100-year design flood flow of 15,200 m^3/s and water level of 6.95 m PWD (JICA, 2013). The maximum scour depth at piers is estimated to be 32.68 m below the flood level for the new bridge using a numerical model simulation.

The above studies provide valuable information on hydro-morphological characteristics of major rivers in Bangladesh. Similar studies with lesser details are also available for some regional and smaller rivers on individual river/site basis. Most of these latter studies are consultancy reports, which are not generally available in published form. Hence, there is a scarcity of collated information on regional and smaller rivers. To fill in this gap, a large study on more than 50 rivers at 188 sites across Bangladesh was undertaken to assess the hydro-morphology of the sites and to estimate the potential bridge lengths and river training needs. The findings will be useful to other researchers, implementing line agencies and development partners to have a fair idea about the hydro-morphology of Bangladesh Rivers, and to plan and design structural interventions on these rivers. The figures presented in the paper will serve as baseline information for future hydro-morphological studies by other organizations.

2 METHODOLOGY AND DATA COLLECTION

2.1 *Study Area*

The study was conducted at 188 proposed bridge sites all over Bangladesh. The study sites had diverse geographic, climatic and hydrologic settings. The settings include hilly, flashy rivers in the south-east, low-lying, deeply flooded haors in the north-east, and tidal rivers in the southern coastal areas. While some of the rivers are morphologically very active, for example the Feni River in Sonagazi Upazila, the Arial Khan River in Sadarpur Upazila and the Dhaleswari River in Kalihati Upazila, and some are morphologically totally inactive, for example the Khalisha Dangi River in Baraigram Upazila, the Nura River in Paikgacha Upazila and the Kumar River in Faridpur Sadar Upazila, the majority of the rivers are low to moderately active. These diverse settings provided a unique opportunity for hydro-morphological characterization of the rivers, and helped develop valuable insights in proposing structural interventions to these rivers.

2.2 *Hydrological and Hydraulic Analysis*

The hydrological and hydraulic analysis included flood frequency analysis with available data, estimation of design floods at proposed bridge sites, determination of hydraulic parameters and evaluation of climate change impacts. The water level and discharge data required in flood frequency analysis were available from the Local Government Engineering Department and Bangladesh Water Development Board. Five probability distributions were considered in flood frequency analysis: two- and three-parameter Lognormal, Pearson and Log-Pearson, and Gumbel. The goodness-of-fit of the distributions was assessed by comparing their probability plot correlation coefficients (Filliben, 1975). For a gaged river, the discharge thus obtained was directly used as the design discharge. The water level obtained at a gage station needed adjustment with hydraulic gradient to obtain its value at the proposed bridge site. Where the bridge site was far away from the gage station and the hydraulic gradient of the river could not be estimated due to lack of water level data, the design water level was estimated from a hydrodynamic model simulation and/or an expert judgment based on local flood marks. A 20-, 50- or 100-year flood was taken as the design flood depending on a number of factors.

For an ungaged river, the discharge was invariably estimated from a hydrodynamic model simulation. Apart from the design discharge and water level, hydraulic depth and flow velocity of a river at the proposed site are important hydraulic design parameters. These parameters were also invariably estimated with a hydrodynamic model simulation. A widely used model called HEC-RAS and developed by the U.S. Army

Corps of Engineers (2005) was used in this purpose. Mondal et al. (2018) have used the model for the GBM river system in Bangladesh. Either a steady or an unsteady flow simulation, depending on available bathymetric and hydrologic data, was carried out with the model. Manning's roughness coefficients for the main river and adjacent floodplains were the main calibration parameters. Further details on calibration and validation of the model can be found in Mondal et al. (2018). The bathymetric data required in the model were collected through engaging a professional survey firm and the survey covered a reach length of 4 km to 60 km, depending on available budget and complexity.

2.3 *Morphological Analysis*

The morphological analysis included river planform analysis using satellite imageries, field observations, cross sectional analysis and morphodynamic simulation. Cloud free Landsat 5 Thematic Mapper and Landsat 8 images during the winter season of different years were analyzed for a reach of about 6 km for each bridge site. The Integrated Land and Water Information System (ILWIS) open source remote sensing and GIS software was used to process the satellite images and perform spatial analysis of the images. Using the multi-bands data, 'False Color Composite' images were developed to distinguish different land classes. The bank lines of a river were digitized on screen from such images. The bank lines for different years were then superimposed to determine the erosion and accretion processes of a river and the changes in its bank lines. In addition, the high resolution Google Earth images were also used when needed.

The observations and discussions with local people during the field visits to the proposed bridge sites provided important information on erosion and shifting characteristics of the rivers. Cross sectional analysis was carried out to assess thalweg position, bank slope, bank height, etc., which also indicated the morphological stability of the rivers. In addition, a morphodynamic model was setup using the Delft 3D software (Deltares, 2011) to assess the morphological risk of the bridge sites. The Delft3D has both flow and morphology modules and solves the governing equations by a finite difference technique on a curvilinear boundary fitted grid. When necessary, the vertical grid is defined following the sigma coordinate approach. The bank line shifting is accommodated by a grid movement method. The model was applied to simulate the flow and morphology of the rivers for the present condition as well as for a future scenario. The scenario for the future was generated by constructing a synthetic discharge hydrograph at the upstream and a synthetic water level hydrograph at the downstream. The synthetic hydrographs thus created for a single year were repeated until the target future year. In this way, an extreme hydraulic condition was created for each bridge site to generate a conservative picture of the future.

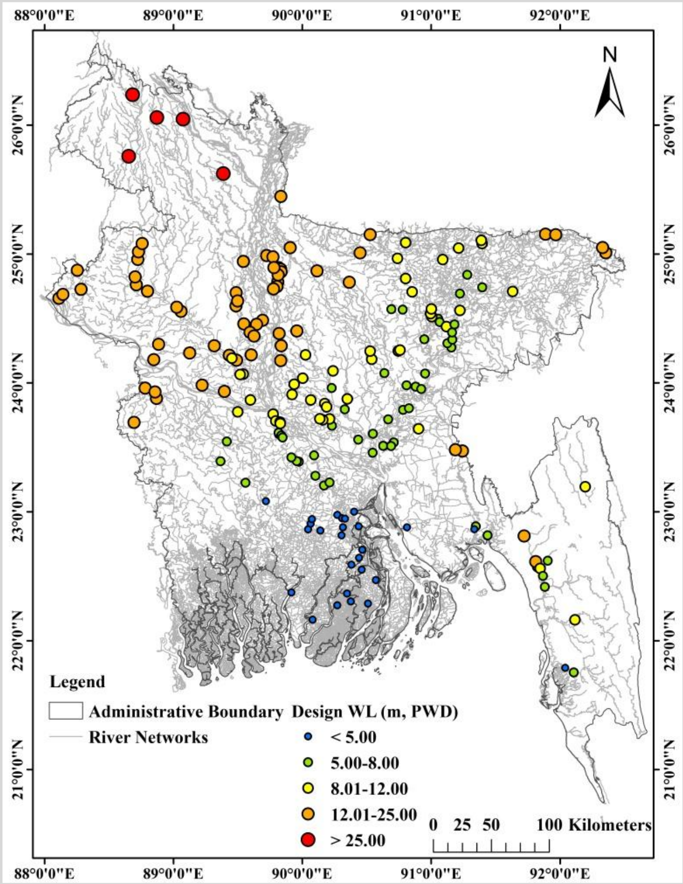
2.4 *River Training*

River trainings were designed for those sites which were judged to be morphologically vulnerable. The hydraulic and morphologic parameters required in designing the river training works were available from the studies as discussed in Sections 2.1 to 2.4 above. The alignment, length, height, width and slope of a revetment, the angle and radius of its upstream or downstream termination, the size of the revetment cover layer, the dimensions of the falling apron, the thickness of the granular filter, the specifications of the geo-textile filter, etc., were suggested for each site following standard design guidelines and manuals. The details can be found in IWFM (2020).

3 RESULTS AND DISCUSSION

3.1 *Design Flood Level*

The design flood level depends on the design return period adopted. A 20-, 50- or 100-year return period was chosen, depending on the size of the river, importance of the roadway & bridge, and navigational class of the river. The bridge site was usually away from the gage station. The design flood level at the bridge site was estimated from the design flood level at the gage station and the hydraulic gradient of the river. For an ungaged river, the design water level was estimated based on flood frequency analysis of a nearby river and correlating the highest flood levels of the two rivers. Figure 1shows the design flood levels at different locations across the country. It is seen from the figure that there is a large variation in flood level (2.63 - 60.32mPWD) depending on the location and the river. The design flood level in general increases from the coastal area in the south to the piedmont area in the north in Bangladesh.



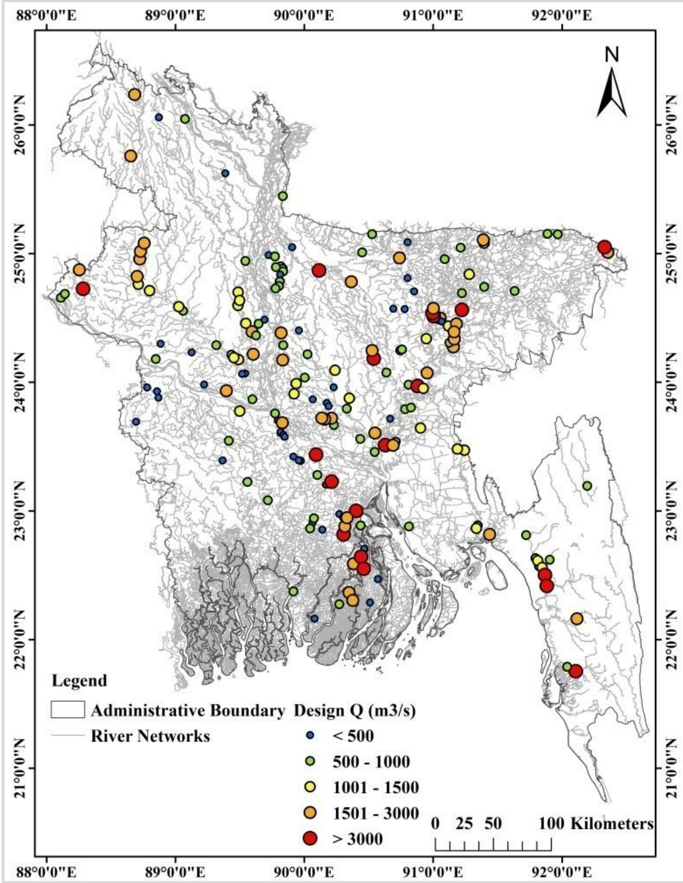


Figure 1. Design flood levels at different locations across Bangladesh.

Figure 2. Estimated design discharge at different locations across the country.

3.2 *Design Discharge*

Design discharge is among the important parameters required in bridge design. To estimate clear waterway opening under a bridge and to assess bridge scour, design discharge is required. For rivers with discharge measurements available, design discharge was estimated from frequency analysis. However, for most of the rivers of this study, discharge data were not available. The design discharges for these rivers were estimated from a one-dimensional numerical hydrodynamic model (HEC-RAS) (steady or unsteady). In a few cases in hilly environment, a hydrologic model (HEC-HMS) was also used. The variation in estimated design discharges is shown in Figure 2. The design discharge was found to vary from 116 to 11650 m^3/s depending on river size (flow area), bathymetric configuration (hydraulic gradient), and roughness characteristics.

3.3 *Design Velocity*

The magnitude of velocity at the design discharge condition is considered here as the design velocity. Such velocity is required in evaluating bank erosion and bed scour potential in a river, designing bank, abutment and approach protection measures, and estimating hydraulic loads on bridge structures. The average velocity in the main channel varies from 0.14 m/s to 2.60 m/s (Figure 3). The average velocity is found to be very high in the hilly rivers of Halda, Matamuhuri, etc.

3.4 *Hydraulic Depth*

Hydraulic depth is another important parameter used in prediction of local scour in a bridge pier and abutment, deciding pile cap position, estimating protection measures and so on. The variation of hydraulic depths in different rivers is also estimated (not shown). It is found that the hydraulic depth in the main channel varies greatly depending on location.

3.5 *Planform Change*

Bank erosion and shifting characteristics of a river, and hence its bank stability, can be greatly determined from analysis of satellite images over multiple years. A reach of about 6 km of a river, 3 km each in the upstream and downstream of the proposed bridge location, was considered in planform analysis for each site. Cloud free, winter season images were downloaded and processed using an image processing software (IL-WIS). On-screen digitization of river bank lines was done on each image and then the bank lines of different images were superimposed to assess bank stability of the river. Figure 4 shows such a planform analysis as an example. From this figure, it is seen that the river has a shifting tendency and is unstable. Construction of a bridge in this type of river poses a high risk to bridge structures and has economical, social, environmental and financial implications.

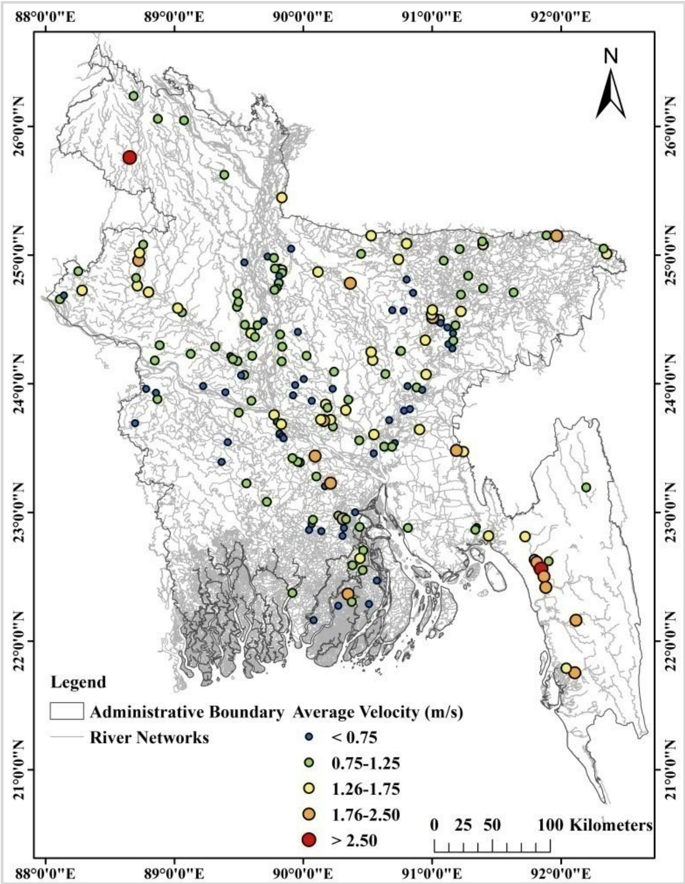


Figure 3. Variation of average velocity in main channel of Bangladesh rivers.

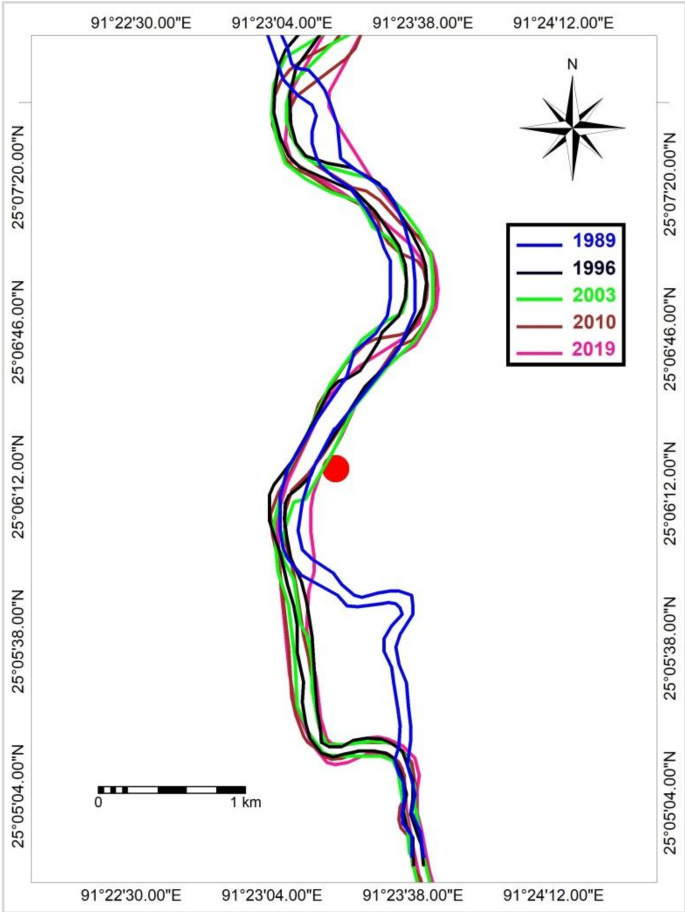


Figure 4. Variation in planform of the Cholti River at a potential bridge site in Sunamganj Sadar Upazila.

3.6 *Simulated Morphodynamics*

The velocity vector, velocity magnitude and water depth were simulated for both present and future conditions with the flow module of the Delft 3D model. The design water level and velocity at the bridge section, mentioned earlier, were compared with the model simulated water level and velocity to calibrate the model parameters. Then the bed shear stress and bed level were simulated with the morphology module of the model to assess the morphological stability of the river reach. Figure 5 shows such a comparison of bed levels for the present condition and future scenario.

3.7 *Bridge Length*

The length of a bridge depends on a number of factors including the design discharge at the proposed site, existing bank-to-bank width of the river, stability of the proposed site, design water level at the site, existing land elevation on both sides of the crossing, required navigational clearance, environmental use of the river, longitudinal slope of the bridge, girder depth, pier width and abutment slope, pile cap position and width, type of bridge, presence of parallel roads and embankments on which road traffic is to be allowed, and alignment of existing approach roads. The determination of bridge length and selection of approach road alignment require considerable expertise and experience, and communication between hydrologist, hydraulic modeler and structural designer. Settlements and markets are usually avoided in selecting a potential bridge site. A field visit to the proposed bridge site by senior water professionals, and discussion with local officials and people are prerequisites in selecting a bridge site. The bridge lengths suggested on various rivers are given in Figure 6. The lengths vary from 80 m to 1650 m. These lengths are substantially larger (42%) than those originally indicated by the government line agencies.

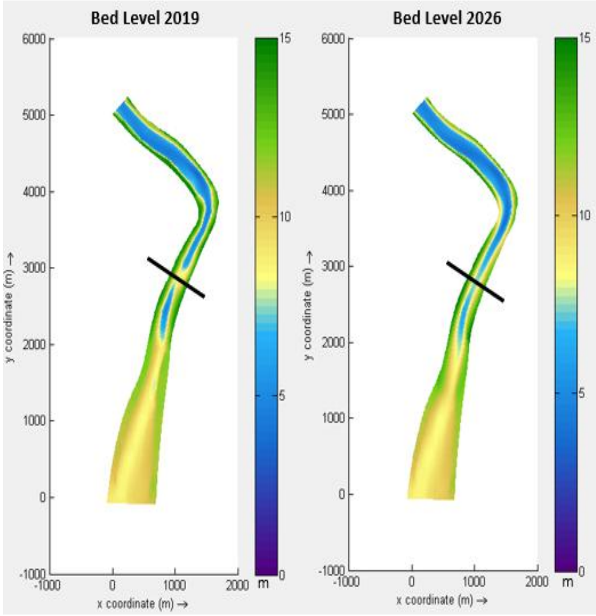


Figure 5. Comparison of bed levels of the Perua River at a bridge site in Sharishabari Upazila for present condition and future scenario.

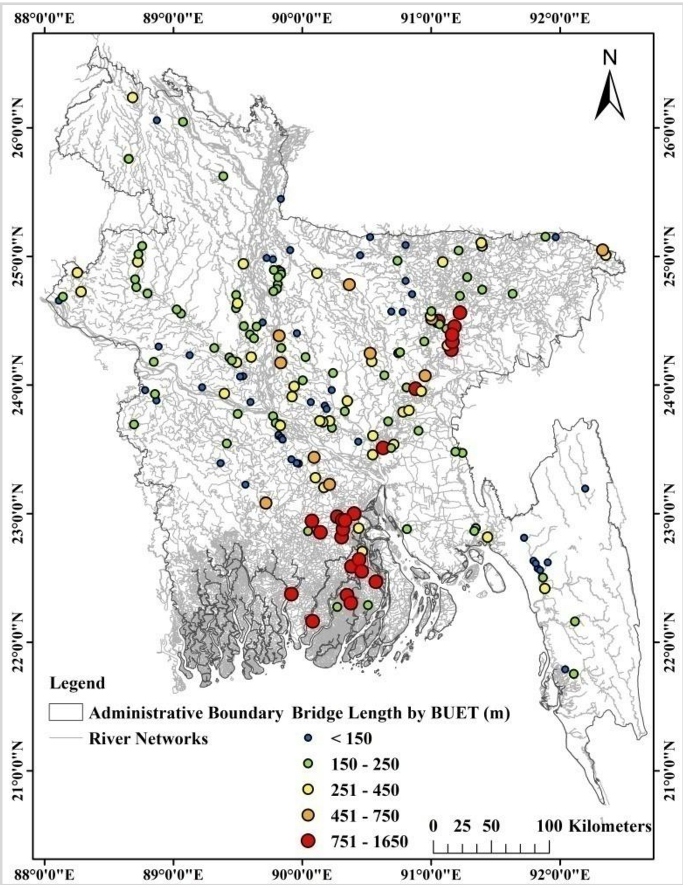


Figure 6. Suggested bridge lengths on various rivers in Bangladesh.

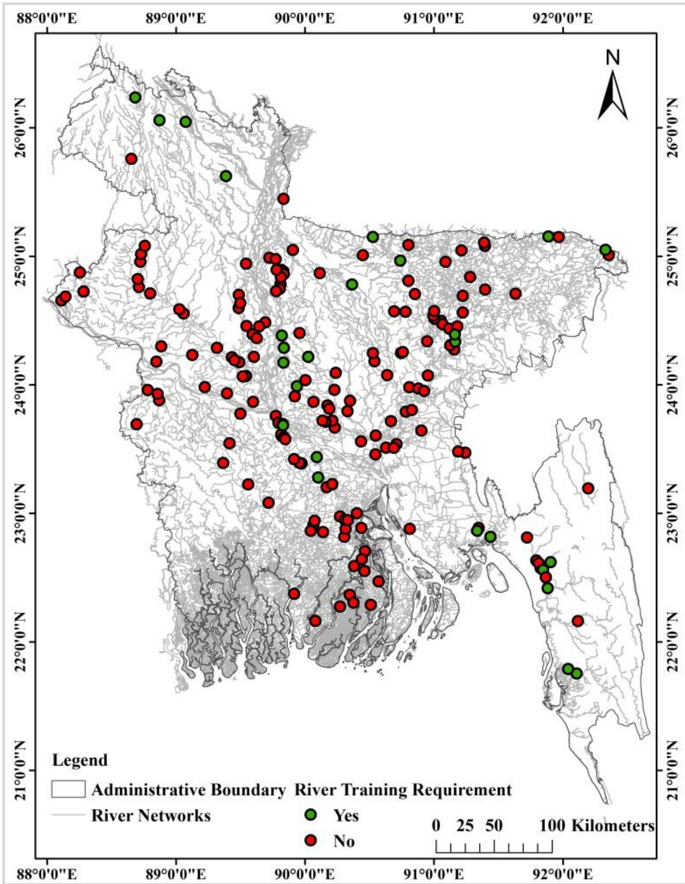


Figure 7. Requirement of river training works at different locations across Bangladesh.

3.8 *River Training*

The rivers having unstable banks with significant erosion and shifting were suggested with bank protection measures. Revetment structures, which are considered as passive measures, were suggested as the bank protection measures as these do not create any significant interference with the passing water (IWFM, 2020). A reinforced embankment with protected river side slope and falling apron was provided as each site as revetment structure. About 15% of the bridges required bank protection and their locations are shown in Figure 7. It is seen from the figure that the rivers in the far north-west, north-east and south-east parts of the country are flashy in character and are unstable, and hence required protection. Also, the Dhaleswari River near the Jamuna River and the Arial Khan River near the Padma River have large floodplains and are unstable, and hence required protection. The protections were usually provided at both the banks extending upstream and downstream of a bridge. The protection length varied from 172 m at the Shatra Khal in Raozan Upazila of Chattogram District to 1045 m at the Dhaleswari River in Tangail Sadar Upazila depending on the site conditions, the average length being 432 m. We suggested continuous monitoring of the bank protection measures for morphologically dynamic rivers. We also suggested continuous monitoring of the morphological change of a river in the vicinity of the proposed bridge where no river training is provided so that a bank protection decision can be taken later depending on the degree of morphological change.

4 CONCLUSIONS

The hydrological and morphological behaviors of 188 potential bridge sites on regional and small rivers in Bangladesh were studied. Among the hydrologic/hydraulic parameters, the design water level, discharge and velocity are the important basic parameters required in structural design of a bridge and associated protection measures. There is a general pattern in design water level, which increases from less than 5 m PWD in the south-central coastal region to more than 25 m PWD in the north-west piedmont plain. The very high velocity (more than 2.5 m/s) at design condition is rare in Bangladesh rivers, except for a few flashy rivers in the hills and piedmont plains. The discharge of the rivers is highly variable and needs careful assessment. The estimated bridge lengths are large (greater than 750 m) in the south-central region as well as in the Meghna-Kalni-Kushiyara river system because of navigational requirement. The hilly rivers as well as the Dhaleswari and Arial Khan upper reaches are morphologically active and require river training works.

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