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# Local Scour at Complex Bridge Piers in Bangladesh Rivers: Reflections from a Large Study

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**Abstract:** Many small-scale experimental, field, and empirical studies on bridge scour are available, however a large-scale study on local scour at a complex pier with wide variation in design parameters is still lacking. In this study, a country-wide assessment of local scour at complex piers of 239 bridges in Bangladesh is made. The hydrologic, hydraulic, and sediment data required in the assessment are obtained from secondary sources, primary measurements and samples, and numerical model simulations. An incredible number of 239 field visits are made, 1434 km of bathymetric surveys are carried out, and 478 samples of bed soils are collected and analyzed. The local scour depth is estimated using a complex pier configuration with pier, pile, and pile cap dimensions selected in consultation with structural and geotechnical engineers of bridge design. Flood frequency analysis and the HEC-RAS model simulation are used to estimate the hydrologic and hydrodynamic parameters needed in the assessment. A number of empirical formulations are used to estimate and compare the design local scours. The formulae of Melville and Coleman, Jain and Fischer, and Richardson are found to be dominant when deciding the design local scour depth at the bridge piers. Suggestions are provided to include a few additional equations in scour estimation and to develop a unified Bangladesh standard for scour depth estimation. The findings and recommendations of the study would be useful in planning and designing bridges in alluvial deltaic settings, particularly in the selection of empirical methods and mainstreaming of complex pier configuration in bridge scour assessment.

**Keywords:** local scour; complex pier; bridge; empirical equations; hydraulic variables; physical variables; Bangladesh rivers

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## 1. Introduction

Bangladesh is called a country of rivers. There are about 700 rivers in the country with a total length of 24,140 km [1]. These rivers are generally categorized into three classes: large, regional, and small [2]. The Ganges, the Brahmaputra, and the Meghna are transboundary and large rivers. The Teesta, the Gorai, the Dhaleswari, and the Arial Khan are among the medium and regional rivers. The Turag, the Balu, the Ichamati, etc., are the small rivers. These rivers are spread all over the country and together make an inter-woven network. The total length of the rivers, which serve as navigable routes, is about 6000 km during the monsoon season (June–October) and about 3900 km during the dry season [1].

For crossing the rivers by roadway and railway, bridges are constructed over the rivers. A 4.2-km bridge is constructed on the Brahmaputra River (known as the Jamuna River at the site), a 6.15-km bridge is recently constructed on the Padma River (the combined Ganges and Brahmaputra rivers) and a 930-m bridge is constructed on the Meghna River (to be more specific the Upper Meghna). Many such bridges have also been constructed on the regional and small rivers. The exact number of bridges is not known, but it would be a few thousand. Many such bridges are also under construction, under a feasibility study, and in the proposal stage. The Local Government Engineering Department (LGED), the Roads and Highways Department (RHD), Bangladesh Railway, Bangladesh Bridge Authority (BBA), Bangladesh Water Development Board (BWDB), and the Ministry of

Disaster Management and Relief (MoDMR) are the government agencies to implement these bridges. A hydro-morphological study has been made mandatory for bridges of length 100 m and above by the government [3].

The rivers of Bangladesh are alluvial in nature, in contrast to gravel-bed rivers in many countries. These rivers and their floodplains are formed by the alluvium carried with runoff from outside and inside of the country. The river slopes are generally mild, the water depths are usually shallow, and the sediment loads during the monsoon are generally high. Hence, the rivers are meandering and braided in planforms, and bend and bar formations are common in the rivers. Bank erosion-accretion, bed degradation-aggradation, and local scour are common phenomena of the rivers, particularly during the monsoon season. Of these, local scour is of particular interest while constructing a hydraulic structure on a river because of the empirical nature of the equations used, the risk and cost involved with the estimated scour depths, and the uncertainty associated with the various input variables used.

The Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology has recently conducted hydro-morphological studies in relation to the construction of 239 bridges spreading all over Bangladesh. The rivers on which the bridges are to be constructed are regional and small rivers and include non-tidal, tidal, hilly, and haor (large depression) rivers [4]. The estimation of scours at bridge piers, abutments, and river training works was within the scope of the studies. Since this was a large study, it would be useful to document and share the major learnings of the study with both local and global researchers, academicians, practitioners, and policymakers. The major objective of this article is to reflect on the findings of the local scour at complex bridge piers in the Bangladesh rivers. Some suggestions are also provided to improve the local practices of scour estimation by drawing upon global literature and practices. The findings could also be useful for other countries in deltaic settings for infrastructural planning and implementation, particularly for bridges.

### *1.1. Local Scour Phenomenon*

Local scour is the lowering of the stream bed around a hydraulic structure, such as bridge piers, abutments, guide bundhs, spurs, and breakwaters [5]. Such scour occurs due to the modification of flow pattern caused by the obstruction of the structure to stream flow [5]. In fact, due to the presence of a pier, flow deceleration occurs ahead of it. Such deceleration is the greatest on the face of a pier near the surface, where the stagnation pressure is the highest [6]. This stagnation pressure decreases downward and results in a downward pressure gradient at the pier face, which in turn generates a downflow ahead of the pier [6]. The downflow impinging on the bed acts like a vertical jet in cutting a groove immediately adjacent to the front of the pier [6]. The formation of the groove creates an eddy structure comprising of a horseshoe, wake or trailing vortex, or any combination of such vortices, around the pier [5]. The downflow together with a horseshoe vortex increases the local shear stress, which leads to the removal of bed material and hence scours. The increase in the average shear stress around a pier can be about three times that in the main channel, and that in the instantaneous shear stress can be about 9–11 times the average shear stress in the main channel [5]. The wake vortex arises from the flow separation at the sides of a pier and is translated downstream by the mean flow [6]. This vortex sucks up sediment from the bed and transports sediment downstream [6]. Further details on the local scour phenomenon can be found in [5,6].

The scour depth at a bridge pier is affected by many factors associated with flow, bed material, and flow obstruction. It depends on whether the incoming flow to a bridge pier is clear-water or sediment-transporting flow, depth of flow, size and shape of pier, inclination of pier with flow, opening ratio, bed material characteristics, bed stratification, and flow parameters [5]. The obstruction to the flow caused by a bridge foundation is of primary importance in the scour process [6]. The process of local scour is also time-dependent. Equilibrium between the erosive capability of the flow and the resistance to motion of the bed materials is progressively attained through erosion of the flow boundary [6]. In fine-grained materials, such as sand, the equilibrium or final depth of local scour is attained rapidly in live-bed conditions, but slowly in clear-water conditions [6].

*1.2. Works on Local Scour in Bangladesh*

The local scour at the 4.8-km long Jamuna bridge pier was estimated using a single equation [7]:

$$d = (1.6 \pm 0.16)b \tag{1}$$

where, $d$ is the local scour depth below the undisturbed riverbed, and $b$ is the bridge pier diameter. The pier diameter was taken as 2.5 m and the local scour depth was estimated to be only 4.0 m. However, the confluence or bend scour was added to the local scour to arrive at the total scour. Moreover, the confluence scour was found to be dominant over the bend scour in the study. The same approach was followed in the estimation of local scour at piers of the 6.15-km long Padma bridge [8]. The pier diameter was taken as 3.0 m and the estimated local scour was only 5.5 m. In contrast to the Jamuna bridge, the bend scour in place of the confluence scour was considered for the piers adjacent (300 m) to the riverbanks in the Padma bridge. The local scour at piers of the Meghna second bridge was calculated based on a technical guideline of the Public Works Research Institute (PWRI) of Japan [9]. The method uses graphical charts depicting the relationship between Froude number, ratio of depth of flow to particle diameter, and scour to pier diameter. The maximum pier scour depth was calculated with simulated hydraulic values from the Nays2D model. The maximum pier width was 3.2 m and the maximum scour depth was estimated to be 5.67 m below the river bed during a 100-year flood [10]. The same approach was followed for the Kanchpur and Gumti second bridges on the Sitalakhya and Gumti rivers, respectively. The scour depth at the piers of the 1.8-km long Hardinge bridge, which is a steel truss railway bridge, on the Ganges river was estimated based on the following equation [11]:

$$\frac{D}{b} = 2.32\left(\frac{q^{2/3}}{b}\right)^{0.78} \tag{2}$$

where, $D$ is the scour depth below the water surface, and $q$ is the discharge intensity.

All the above bridges in Bangladesh have complex pier type, that is, they consist of pier, pile cap, and piles. The pier, that is, the part above a pile cap, is either a single-column stem or a double-column stem placed along the flow direction. Depending on the location of the cap with respect to the riverbed as well as on the flow condition, the effective obstruction created by the pier to flow would vary [6]. In Bangladesh, the pile cap is usually located at a low water level or below. In class III and IV non-tidal rivers, the pile cap is now located at or below the initial bed level. Thus, the pier could initially behave as a simple pier, but with the progress of local scouring, the pile cap and piles also could take part actively in the scouring process, and ultimately the pier could work as a complex pier. In class I and II rivers, particularly the tidal ones, where there is a significant depth of water during the dry season, such as the major rivers, the pile cap is hardly constructed at or below the initial bed level. The piers in these rivers behave as complex piers from the beginning. However, this particular feature due to the complex pier configuration was not taken into consideration in any of the above studies on major bridges in Bangladesh. Moreover, only a single equation was used in each of the above studies. In fact, these equations are not any well-referred equations in Bangladesh as well as in the outside world. Thus, the local scour depths reported in the above studies remain highly uncertain. Hence, in this study, the local scour depth is estimated using a complex pier configuration along with a number of well-established empirical equations from global literature, which is expected to provide a more reliable estimate. This would also provide a fair indication of the choice of empirical equations and variation of local scour depths in the Bangladesh rivers.

## 2. Materials and Methods

### 2.1. Study Area

The present study covers 239 potential bridge sites on regional and small rivers across Bangladesh. Notable rivers include the Dhaleswari in the north-central, the Arial Khan in the south-central, the Atrai in the northwest, the Surma and the Kushiyara in the northeast, the Halda and the Matamuhuri in the southeast, and the Modhumati and the Shibsa in the southwest hydrological regions. However, the study does not include the mighty transboundary rivers like the Ganges, the Brahmaputra, and the Meghna, which have already been studied.

### 2.2. Methods

#### 2.2.1. Complex Pier Formulation

To estimate the local scour depths at bridge piers in this study, a complex pier configuration is used in contrast to a simple pier configuration. The complex pier configuration is used to account for the effects of pile cap and piles below the cap in the local scour process. This required the estimation of effective pier width rather than using the simple pier width. The effective pier width depends on the pier width, pile cap width, depth of flow, and the position of the pile cap top in reference to the riverbed. Depending on the above factors, four cases of pier configurations could emerge as depicted in Figure 1.

For case I, where the pile cap remains buried below the base of the scour hole, the local scour is unaffected by the presence of the pile cap and is estimated using the simple pier configuration. For case II, where the pile cap is at the initial bed level, local scour depth is typically reduced from that of the simple pier due to the interception of the downflow and a simple pier configuration would provide a conservative scour value. For cases III and IV, where the pile cap is above the initial bed level, there would be a combined influence of pier, pile cap, and piles on scour, and the obstruction would work as a complex pier. In these latter two cases, an effective pier width is used in estimating local scour depth.

There are a few empirical formulae to estimate the width of the effective pier, also called equivalent uniform pier, for the foundation on pile cap [6,12]. The formulation is based on the premise that the effective pier would induce the same or higher scour than the simple pier [6]. Hence, the effective pier width is equal to or more than the pier width itself. The formulation given in Melville and Coleman [6] is now often used in Bangladesh to estimate the effective pier width due to its simplicity and conservative value. Therefore, the effective pier width ($b_e$) is estimated using their formulation [6]:

$$b_e = b\left(\frac{y+Y}{y+b^*}\right) + b^*\left(\frac{b^*-Y}{b^*+y}\right) \quad (3)$$

where, $y$ is the average depth of flow, $b$ is the pier width, $b^*$ is the pile cap width and $Y$ is the distance of the initial riverbed from the pile cap top (positive for upward distance and negative for downward distance).

#### 2.2.2. Selection of Empirical Methods

In this study, the local scour at the bridge pier was estimated using empirical equations. Though numerical simulations and flume experiments are used to understand the scour process, to predict the bed shear stresses due to different pier configurations, and to understand the performance of different countermeasures in reducing the scour potential [13–15], the resource (human, technical and financial) and time constraints often do not allow the use of such methods in scour prediction, especially if a large number of bridges are to be studied within a short period. Moreover, the numerical investigation has so far been conducted with a uniform circular pier, square cross-section, and piles of different spacing [14], and no studies are reported on the complex pier. In contrast, empirical techniques are derived from a series of flume experiments, are easy to use, and generally provide conservative values. These are almost universally used in the estimation of design local scour. Therefore, a number of widely used empirical equations are used in this study to estimate the local scour at bridge piers. These include the equations of Laursen [16], Breusers [17], Neill [18], Jain and Fischer [19], Chitale [20], Melville and Coleman [6], and Richardson [21].

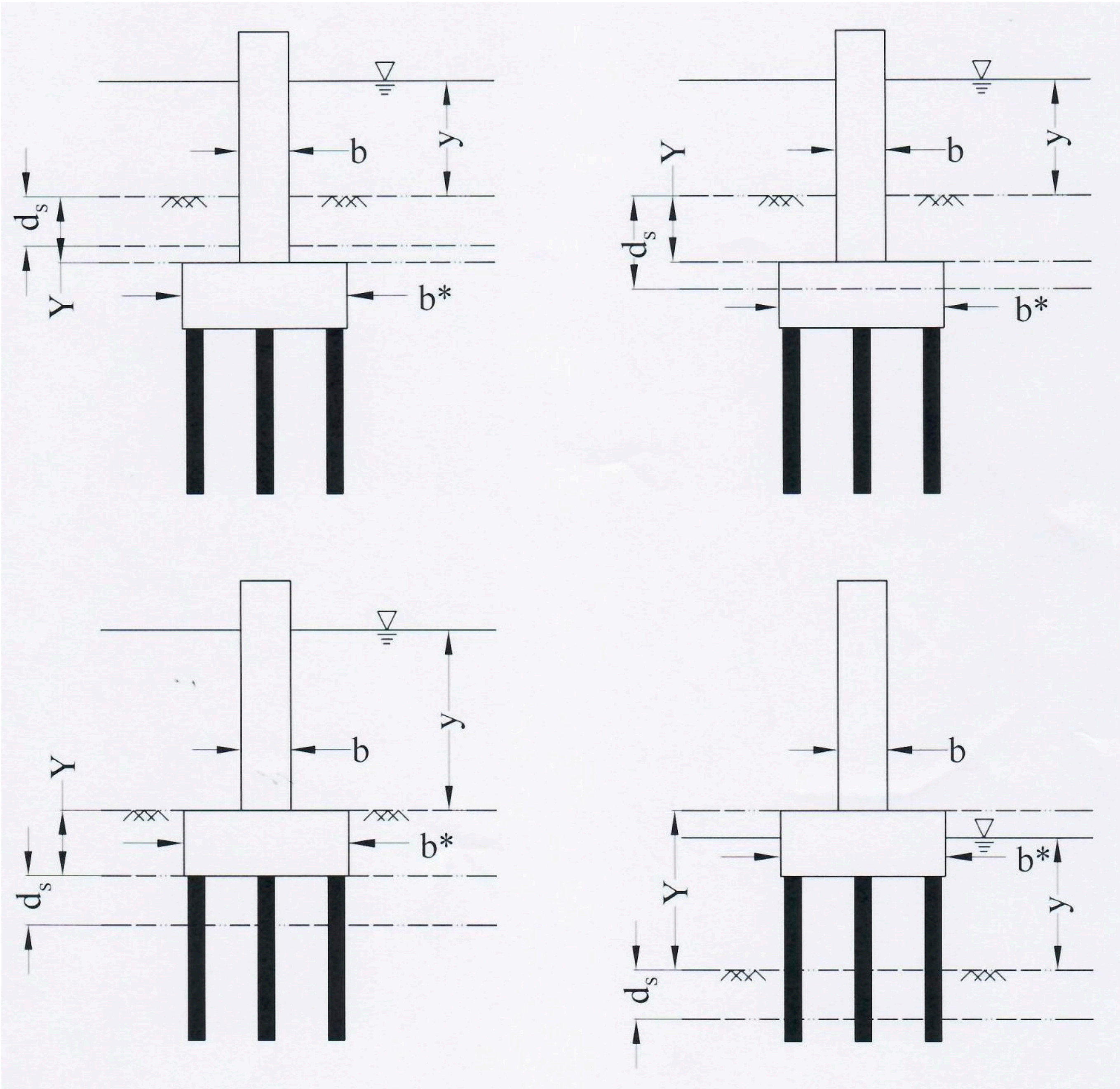


**Figure 1.** Different pier configurations considered: Case I (**top-left**), case II (**top-right**), case III (**bottom-left**), and case IV (**bottom-right**).

Laursen [16] suggested the following equation for clear-water scour estimation at the threshold condition:

$$\frac{d_{sc}}{b} = 1.34\left(\frac{y}{b}\right)^{0.5} \tag{4}$$

where, $d_{sc}$ is the scour depth below the riverbed for clear-water conditions.

Breusers [17] suggested the following equation for estimation of local scour:

$$d_{se} = 1.4b \tag{5}$$

where, $d_{se}$ is the scour depth below the riverbed for sediment transporting conditions.

Neill [18] also suggested an equation for estimation of local scour:

$$d_{se} = Kb \tag{6}$$

where, $K$ is a pier shape factor. The value of $K$ is 1.5 for round-nosed and circular piers, and 2.0 for rectangular piers.

Jain and Fischer [19] suggested the following equation for clear-water scour estimation at the threshold condition:

$$\frac{d_{sc}}{b} = 1.86\left(\frac{y}{b}\right)^{0.5} \tag{7}$$

It can be seen from Equations (4) and (7) that the two equations are the same in format, the only difference is in one coefficient. Thus, Equation (7) would always result in a higher scour than Equation (4). The Equation (7) was later modified by Jain [22] as:

$$\frac{d_{sc}}{b} = 1.84\left(\frac{y}{b}\right)^{0.3} \tag{8}$$

Chitale [20] suggested the following equation:

$$\frac{d_{sc}}{b} = 2.5 \tag{9}$$

Melville and Coleman [6] indicated that when the ratio of the depth of flow to pier width is greater than 2.4, the scour depth does not depend on the depth of flow; however, for a smaller ratio, the depth of flow affects the scour depth. They provided the following equation for estimation of local scour:

$$\frac{d_{sc}}{b} = \begin{cases} 2.4, & \frac{b}{y} < 0.7 \\ 2\left(\frac{y}{b}\right)^{0.5}, & 0.7 < \frac{b}{y} < 5 \\ 4.5\left(\frac{y}{b}\right), & \frac{b}{y} > 5 \end{cases} \tag{10}$$

Another equation, known as the Colorado State University equation [21], which is incorporated in the Hydrologic Engineering Center—River Analysis System (HEC-RAS) model, was also used. This equation includes the impact of flow velocity on local scour in the form of Froude Number ($Fr$) and is given as:

$$\frac{d_{se}}{b} = 2\left(\frac{y}{b}\right)^{0.35}(Fr)^{0.43} \tag{11}$$

#### 2.2.3. Simulation of Hydraulic Parameters

To estimate the local scour, flow parameters such as depth of flow and velocity of flow at design hydraulic conditions are needed. Measured field data at such design conditions are mostly not available even in developed countries. Therefore, numerical models are generally used to estimate those parameters.

In this study, the design hydraulic parameters are estimated using a widely used, one-dimensional hydrodynamic model HEC-RAS, developed by the US Army Corps of Engineers [23]. Mondal et al. [4,24,25] have used the HEC-RAS model for the GBM river system as well as for other rivers of Bangladesh. Either a steady or an unsteady flow simulation, depending on the available hydrologic data, was carried out with the model. For a steady flow simulation, discharge was used as the upstream boundary, and water level or normal depth as the downstream boundary. In the absence of an energy gradient, the hydraulic gradient of a river in a dimensionless form determined from two nearby gage stations of a bridge site was used as the normal depth. For an unsteady flow simulation, discharge was used as the upstream boundary and water level as the downstream boundary. Each model setup covered a river reach of 4 km to 60 km depending on the size of the river and the complexity of the river network. The model was calibrated for one major flood year such as 1988 and validated for another major flood year such as 1998. In addition, primary water level, velocity, and discharge measurements were carried out for the Feni river in the Feni district, the Dhanu river in the Kishoreganj district, the Dhaleswari river in the Manikganj district, the Bishkhali river in the Barguna district and the Panguchhi River in the Bagerhat district to use in further calibration and validation of the hydrodynamic model. Manning's roughness coefficients ($n$) for the main river and adjacent floodplains were the main calibrations and validation parameters. The $n$ value for the main channel was found to vary from 0.02 to 0.035 and that for the floodplain from 0.03 to 0.06 depending on the size of the river, depth of flow, obstruction to flow in the floodplain, etc. Further details on calibration and validation of the model can be found in Mondal et al. [3,26] and the 239 numbers of individual hydro-morphological study reports prepared on 239 bridge sites.

Design discharge and water level at a bridge site were estimated either from flood frequency analysis or from HEC-RAS model simulation. The long-term data available at different gage stations of BWDB were subjected to flood frequency analysis. Five probability distribution functions namely two-and three-parameter log-normal, Pearson and log-Pearson type III, and Gumbel extreme value distributions were used. Then a goodness-of-fit test was conducted on the five distributions using the highest probability plot correlation coefficient as the selection criterion. A 20-, 50-, or 100-year return period was selected as the design return period based on the economic importance of a bridge, the width and navigational importance of the river, morphological condition of the site, etc. Where gage data were not available, locally surveyed flood level was used to correlate with nearby gage data and the HEC-RAS model was used to estimate the design flood.

### *2.3. Data*

This study required both primary and secondary data. The available secondary data on river water level and discharge were collected from the Hydrology Directorate of BWDB in Dhaka. BWDB is the major government organization responsible for the collection, processing, and storage of hydrological data. It has local offices and hydrological gage networks all over the country. The data were generally available at a daily time scale since 1985. The primary data on river bathymetry, bankline, and floodplain topography were collected by using standard survey equipment, such as eco-sounder, RTK devices, and level machine. For each site, the survey generally covered a reach of about 6 km of the river—3 km in upstream and 3 km in downstream of the bridge centerline. Thus, the total primary survey made was 6 × 239 = 1434 km of rivers. The survey sections are spaced from 50 m to 500 m depending on locations with respect to the proposed bridge centerline. The survey was conducted with a proper benchmark connection to the locally available national benchmarks maintained by the Survey of Bangladesh. The bank-to-bank widths of the rivers, lowest bed levels, etc., were estimated from the digital survey AutoCAD files.

Bed soil samples (two from each site making the total number to be 2 × 239 = 478) were collected to find out the grain size distribution of the bed materials of the rivers. Other data required, such as design flood discharge, depth of flow, velocity, and Froude no., were obtained from flood frequency analysis and hydrodynamic model simulation. Pier and pile cap dimensions, pier spacing, and pile dimensions and spacing of each bridge were decided in consultation with the bridge design experts at LGED and RHD and also based on contemporary bridge construction practices in Bangladesh. At least one field visit was made to each site to observe the site condition and collect relevant data from local people making the total field visits to a number of more than 239. The data were collected during 2018–2020.

## 3. Results

### 3.1. Variation of Hydraulic Parameters in Bangladesh Rivers

The design scour depth at a complex bridge pier depends on river hydraulic depth, flow velocity, pier width, pile cap width, and vertical position of the pile cap. The variations of these factors in the Bangladesh rivers were studied. The variation of design hydraulic depth is given in Figure 2. The average hydraulic depth in the Bangladesh rivers is found to be 6.66 m with a standard deviation of 2.42 m. Among the studied rivers, the highest hydraulic depth of 16.99 m was found in the Ghorautra river in the Kishoreganj district and the lowest depth of 1.45 m in the Arial Kha river in the Gournadi sub-district of Barishal district. The notable deep rivers are the Ghorautra at Kishoreganj, Cholti at Sunamganj, Panguchi at Bagerhat, Khairabad at Barishal, Halda at Raozan, Kalni at Kishoreganj, and Karkhana at Barishal with a depth of 13 m or more.

The average design discharge of the Bangladesh rivers is found to be 1546 $m^3/s$ with a standard deviation of 1736 $m^3/s$. This means that the discharge is highly variable across the rivers. The variation of average channel velocity in the Bangladesh rivers is given in Figure 3. The average channel velocity is found to be 1.03 m/s with a standard deviation of 0.46 m/s at the design discharge condition. Thus, the velocity in the Bangladesh rivers is generally low. This is due to the flat terrain of the country and the low hydraulic gradient of the rivers.

The average length suggested for bridges over the Bangladesh rivers is 348 m with a standard deviation of 308 m. The average length suggested for the central span of the bridges is 51 m with a standard deviation of 23 m. The span length depends on the horizontal navigational requirement of a river based on its navigational class as determined by the Bangladesh Inland Water Transport Authority (BIWTA). There are four navigational classes in Bangladesh—Class I, II, III, and IV with minimum horizontal clearance requirements of 76.22 m, 76.22 m, 30.48 m, and 20.00 m, respectively. The variation of pier width used in this study is given in Figure 4. The pier width is varied from 1.0 m to 3.0 m depending on the river, navigational class, bridge span, etc. The pile cap width depends on the pier width—the larger the pier width, the larger the cap width. The pile cap width is varied from 5.6 m to 10.0 m.

Figure 5 shows the distribution of the average grain size of bed sediment of the rivers. As seen, the average bed material size is less than 0.25 mm in the Bangladesh rivers and there is a wide variation in bed sediment size. The size usually reduces from the north to the southwest and south-center of the country due to abrasion and sorting.

### 3.2. Local Scour in Bangladesh Rivers

Using the above hydraulic and geometric parameters and empirical equations, the local scour depths in the Bangladesh rivers were estimated. Different equations provided different scour depths, and the highest depth was generally considered to be the design scour depth. The estimated local scour depths in the Bangladesh rivers are given in Figure 6. It is seen from the figure that the estimated local scour depths are usually less than or equal to 13 m below the riverbed level. The scour depths are found to be more than 13 m for only 7 cases—the Dhanu, Ghora Utra, and Kalni rivers in Kishoreganj, the Old Brahmaputra river in Mymensingh, the Teesta river in Nilphamari, and the Meghna Branch river in Chandpur. The average scour depth in the Bangladesh rivers is found to be 8.28 m with a standard deviation of 2.31 m. This means that about two-thirds of the rivers have local scour depths between 5.97 m and 10.59 m.

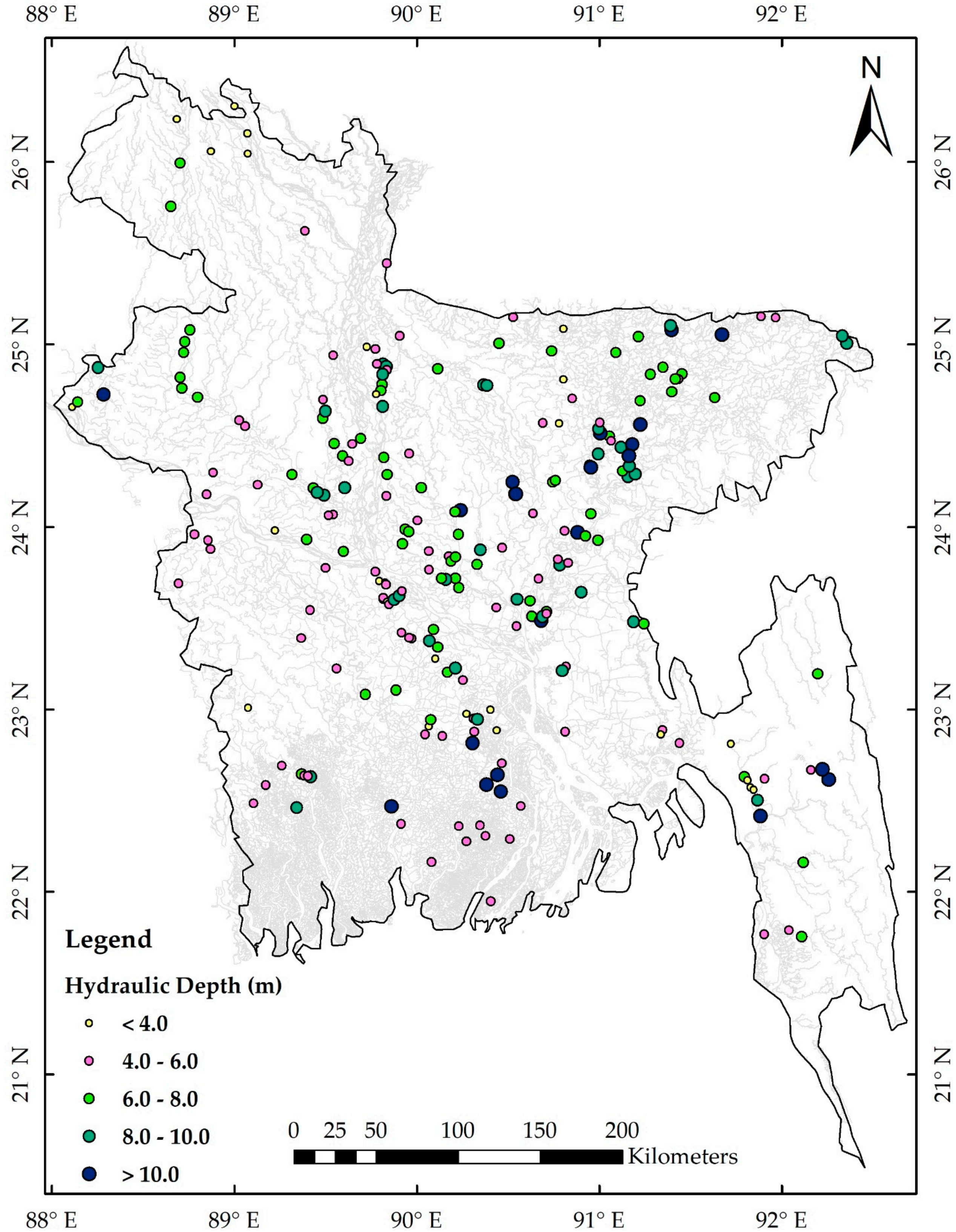


**Figure 2.** Variation of the hydraulic depths in the Bangladesh rivers.

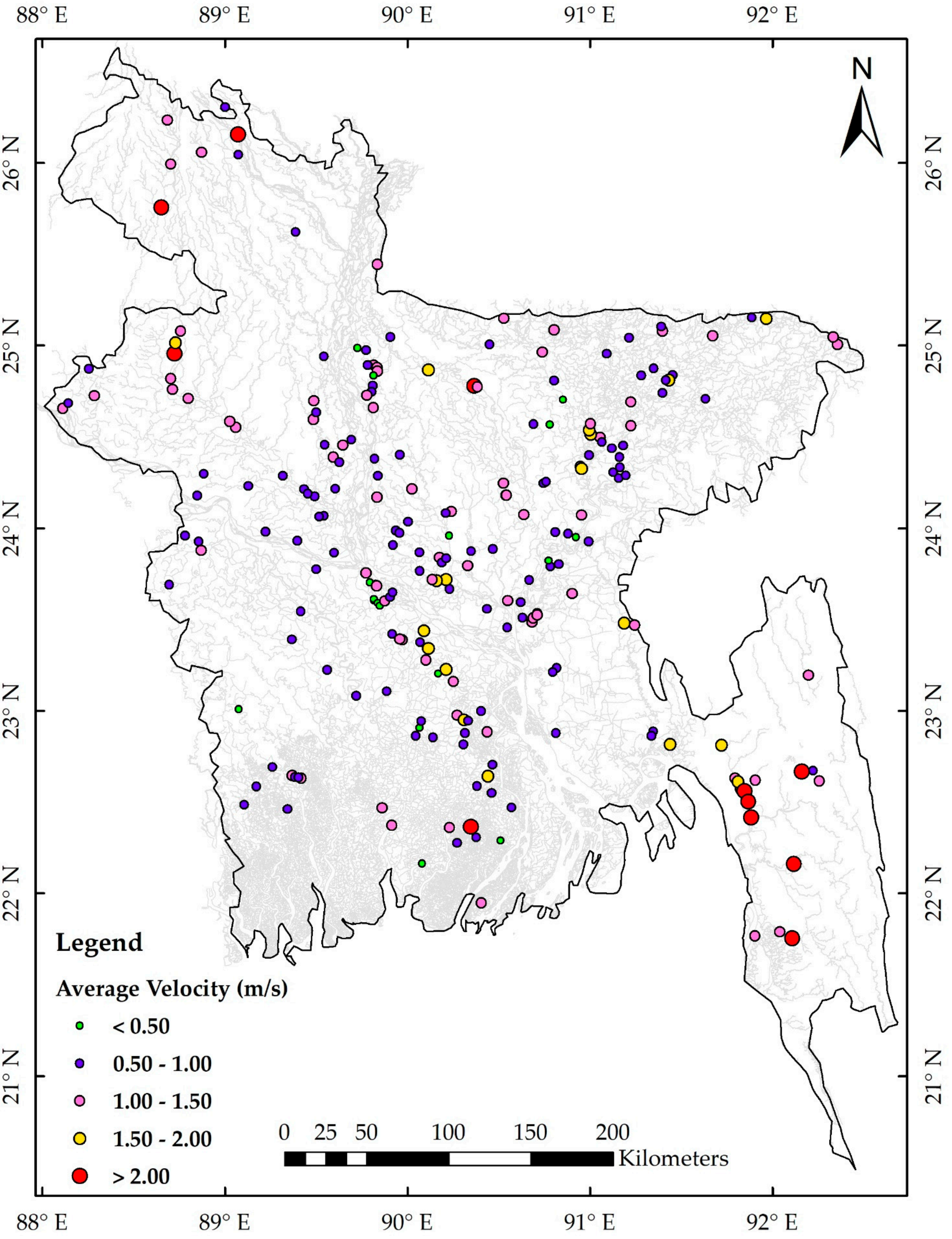


**Figure 3.** Variation of the average velocities in the Bangladesh rivers.

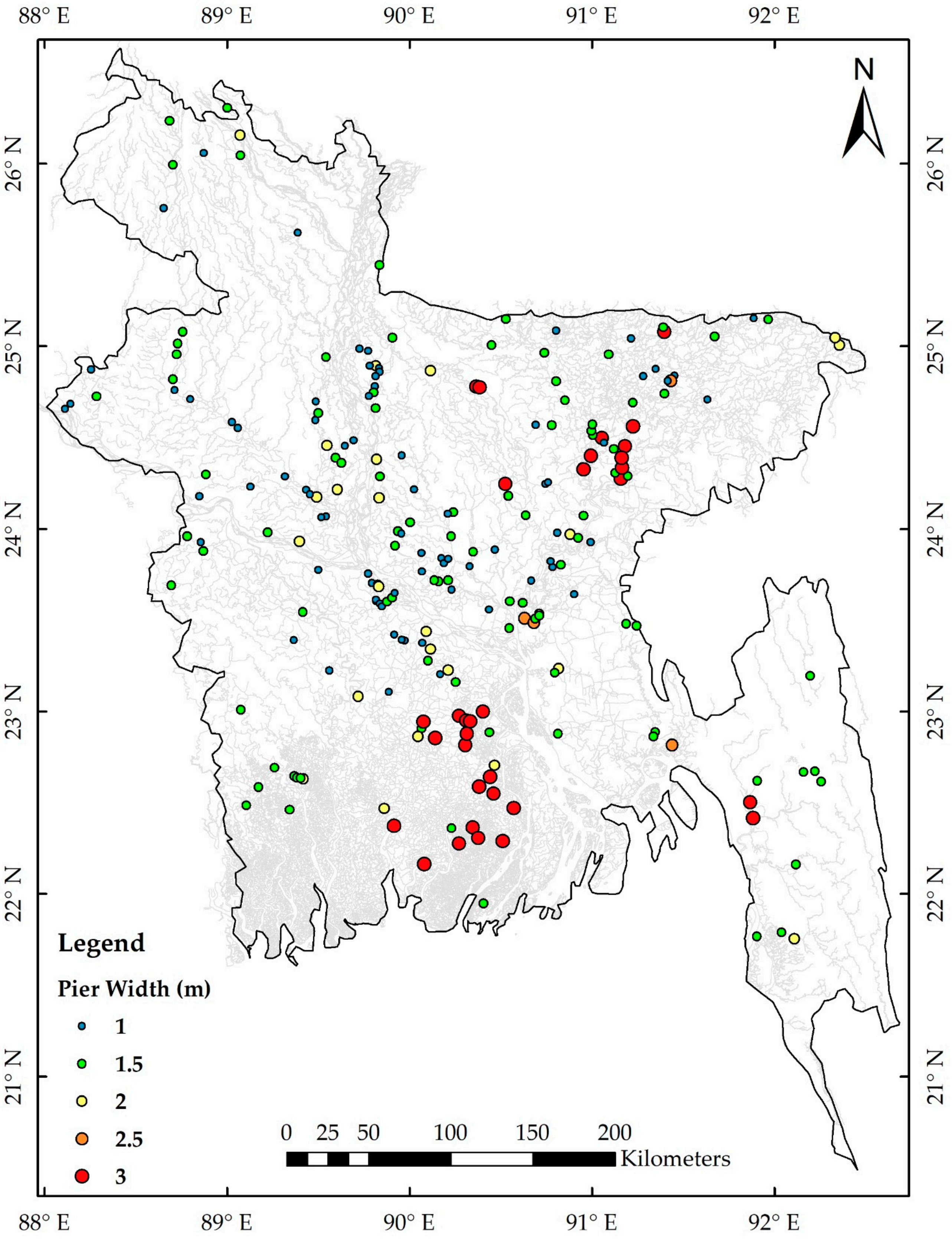


**Figure 4.** Variation of the pier widths of the study bridges over the Bangladesh rivers.

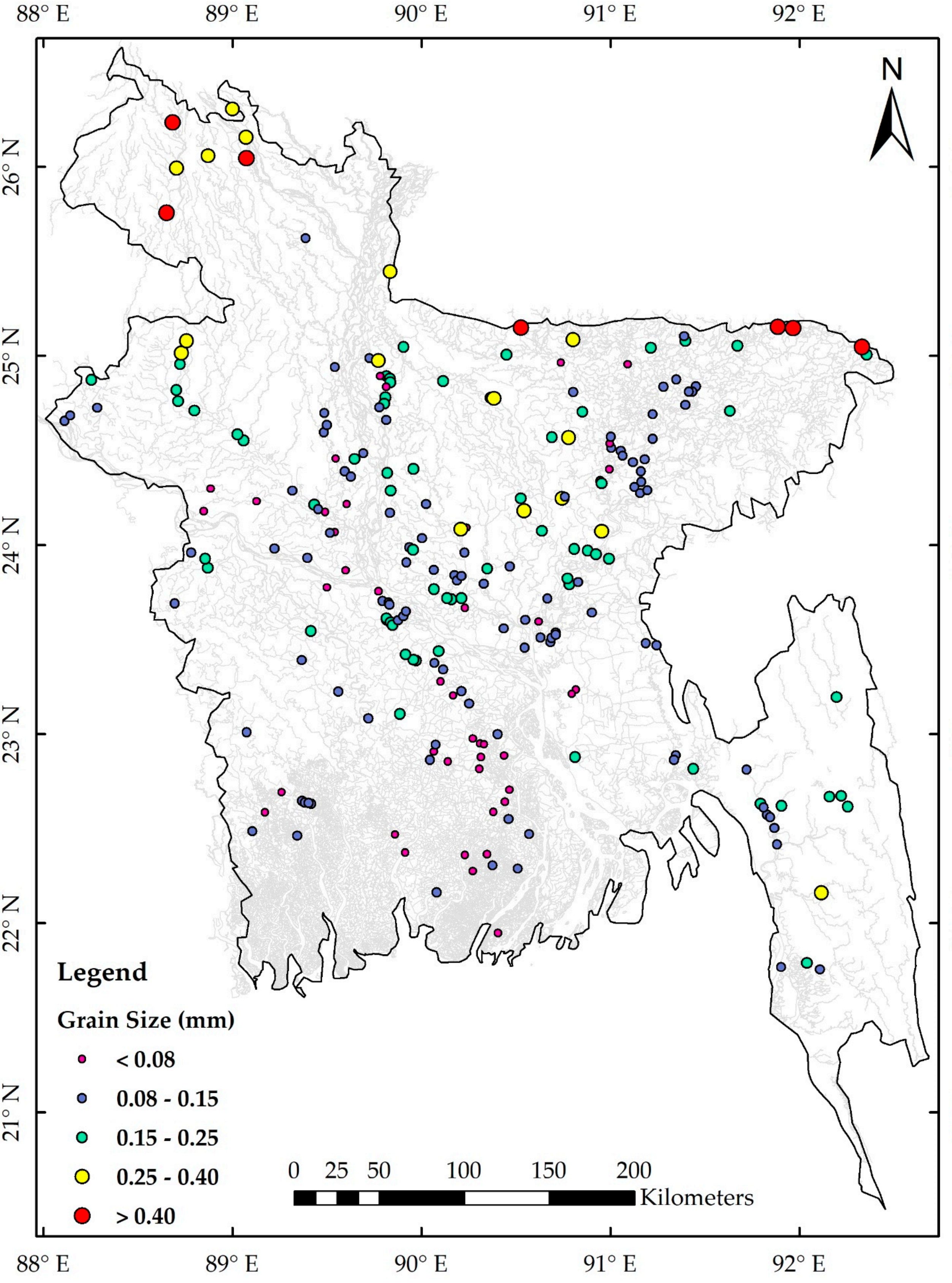


**Figure 5.** Grain size distribution of the bed materials of the Bangladesh rivers.

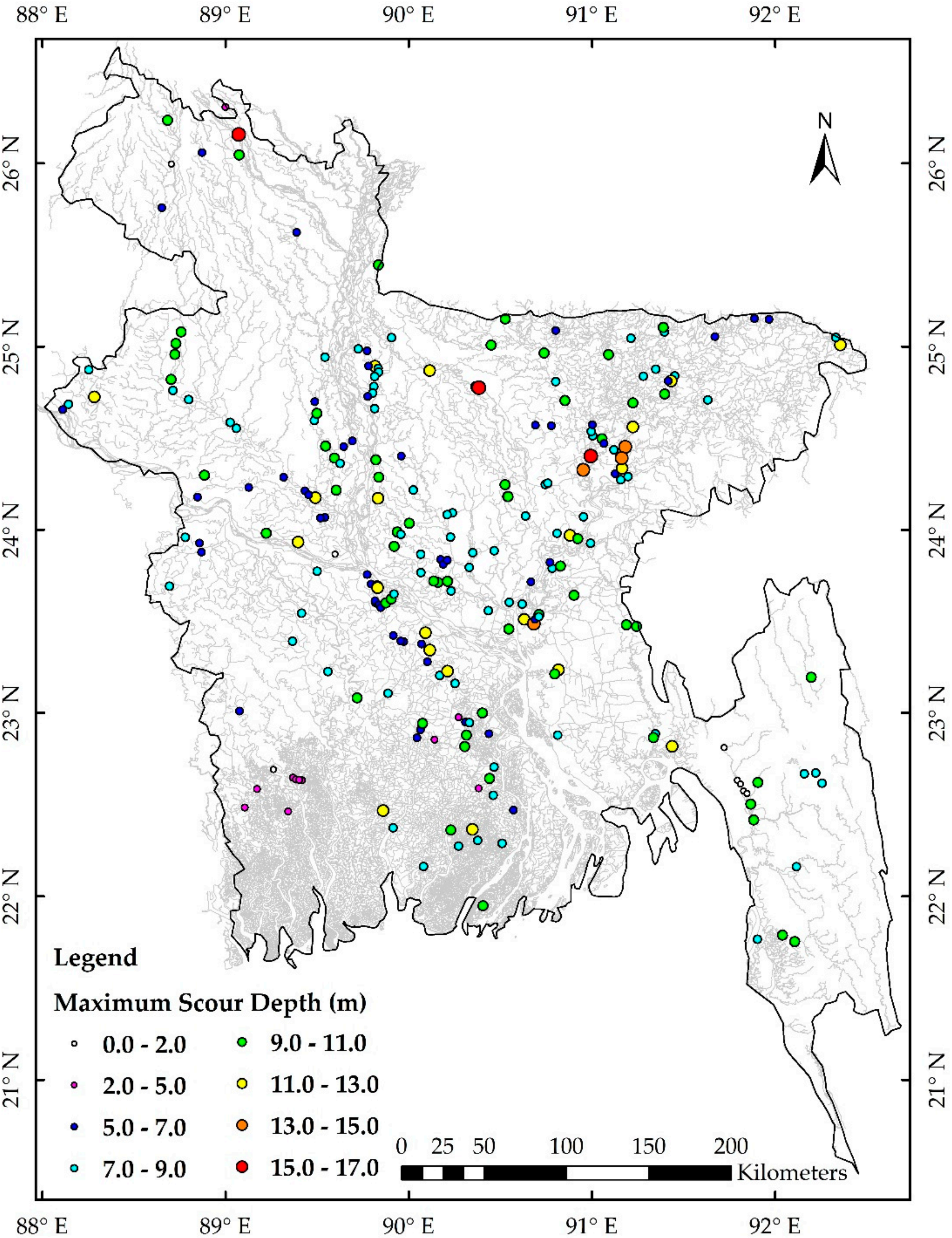


**Figure 6.** Variation of the local scour depths in the Bangladesh rivers.

In this study, scour depth at the pier was estimated at 231 potential bridges, out of 239. Other bridges, such as those on the Halda river in the Chattogram district, had a single span without any pier. Table 1 provides a summary of the equations which provided the design scour depths. As seen, the equation of Chitale [20] provides the maximum scour depth in about 37% of the bridges. The equation of Jain and Fischer [19] dictates the scour depth in about 34% of the bridges. The third and fourth highest numbers of bridges result from the equations of Richardson [21], and Melville and Coleman [6], respectively. The equations of Breusers [17] and Laursen [16] guide the scour depth in relatively few cases. It is to be noted that the equation of Melville and Coleman [6] becomes critical when the equation of Chitale [20] is not used, and the equation of Laursen [16] becomes critical when the equation of Jain and Fischer [19] is not used. The equation of Breusers [17] is selected in some cases not due to providing the highest scour by the equation, but due to some other considerations, such as tidal river and non-representativeness of the values from other equations. To sum up, the equations of Melville and Coleman [6], Jain and Fischer [14], and Richardson [16] appear to be dominating in estimating local scour depth at bridge piers.

**Table 1.** Summary information on the equations guiding the design scour depths.

| Equation | No. of Bridges in Which the Equation Guided the Estimation of Scour Depth | Percent of Bridges in Which the Equation Guided the Estimation of Scour Depth |
|---|---|---|
| Chitale [20] | 85 | 36.8 |
| Jain and Fischer [19] | 79 | 34.2 |
| Richardson [21] | 26 | 11.2 |
| Melville and Coleman [6] | 23 | 10.0 |
| Breusers [17] | 10 | 4.3 |
| Laursen [16] | 8 | 3.5 |
| Total | 231 | 100 |

## 4. Discussion and Future Direction

Local scour is estimated at a large number of potential bridge sites, distributed all over Bangladesh. A complex pier configuration is used in estimating the scour. The use of complex pier configuration in scour estimation is relatively recent. In the already constructed large bridges over the mighty GBM rivers, the complex pier configuration was not used though the pier configuration is of complex type. The role of pile cap and piles below in increasing the obstruction to flow and hence in increasing the local scour was not considered. In other words, the effective pier size was not considered in the previous studies on large bridges. Therefore, the estimated local scour at these bridges was low and there is a potential risk of foundation failure at these bridges. The Meghna bridge has already experienced such an issue and needed huge repair and protection works to solve the problem. Therefore, it is suggested that a complex pier configuration be considered while estimating local scour at large bridges.

In Bangladesh, scour estimation practices are not uniform across different organizations. IWFM uses Laursen, Breusers, Neill, Jain and Fischer, Chitale, Melville and Coleman, and Richardson in the estimation of local scour at bridge piers (see, for example, [26,27]). It does not use Lacey [28], Shen et al. [29], and Kothyari et al. [30]. Also, it does not consider the general scour while estimating the total scour. However, the organization considers the riverbed lowering due to potential dune formation in scour estimates. In recent years, the organization has considered the complex pier formulation in its scour estimates, though it did not practice such formulation a few years back. It has also been suggested to locate the pile cap below the riverbed to create less interference with the river flow. It is found that the implementing agencies in Bangladesh, such as LGED, RHD, and BBA, are gradually embracing this suggestion. The organization also did not suggest any pier protection in any bridge it studied, except for one bridge on the Dakatia River in Chandpur [27] due to soft sub-soil and river confluence at the bridge crossing. The Institute of Water Modeling (IWM) uses Laursen, Breusers, and Richardson in estimating local scour at bridge piers (see, for example, [31,32]). In contrast to IWFM, it considers the general scour in estimating the total scour. It also uses the complex pier configuration while estimating scour. However, it does not consider the dune effect in the estimation. There are concerns regarding the reliability of its scour values as the estimated values do not appear to be reasonable. The

Department of Water Resources Engineering (DWRE) uses the equations of Laursen, Breusers, Neill, Melville, and Coleman, and Richardson [33]. Recently, it has also included the equation of Froelich [34], but it was never found to provide the highest scour (see, for example, [35–37]). It also considers general scour in some studies [36], but does not consider the influence of dune and a complex pier configuration in any study. A few other organizations, such as Dev Consultants Limited et al. [38], carried out some hydro-morphological studies and provided scour depths at bridge piers, but did not report the methodology of estimation. It thus appears that different organizations in Bangladesh follow different methodologies for estimation of local scour at bridge piers without a thorough review of global literature and practices.

A number of design manuals, handbooks, and standards have been prepared by different government agencies in Bangladesh to estimate scour depth at bridge piers. RHD [39] has prepared a bridge design standard, but the document does not provide any guidelines on scour depth estimation. LGED [40] has suggested an equation like the Indian Road Congress (IRC) [41] in its design manual, but the organization itself hardly uses this. BUET and IWM [42] have suggested the equations of Lacey, Richardson, Laursen, Breusers, and Melville, and Coleman for estimation of local scour at the pier. The last three equations are widely used in Bangladesh, but the use of the first two equations is not common. Again, it appears that different techniques are suggested for scour estimation in different organizational documents, which do not adhere to global practices. Thus, it is necessary to develop a national standard to guide and make the practices uniform following global practices. Moreover, there are no design guidelines on how to consider general and constriction scours in total scour estimation. It is to be noted that a few countries, such as the USA, UK, New Zealand, China, and India, have already developed guidelines and established dominant practices on local scour estimation [43].

The rivers in Bangladesh are gradually being silted up and many rivers are already dead or at the potential risk of dying. As a consequence, capital and maintenance dredging are needed in most of the rivers. The dredging operation is mainly conducted by BWDB and BIWTA. Sometimes, these organizations face difficulties in dredging operations due to the presence of a bridge, its shallow foundation, and the pile cap above the riverbed level. The implementing agencies, such as LGED, RHD, and BBA, also face difficulties in that there is no clear guideline to follow on the level of dredging depending on the river class. Such guideline is urgently needed to facilitate infrastructural development as well as to maintain the navigability of the rivers.

The present study has some limitations. One potential limitation is the use of a few selected equations. There are a number of other equations, such as Lacey [28], Shen et al. [29], and Kothyari et al. [30], which could also be used in the study. We did not use the equation of Lacey [28] due to the criticism that it overpredicts local scour at bridge piers [43], provides combined scour including constriction scour [11], and under-performs than Melville and Coleman, and Laursen [7]. However, we checked two equations – Lacey [28] and IRC [41], the latter being also suggested in Rakshit [44] and Victor [45] – if these provide a more conservative estimate of local scour in the case of the Meghna River [46]. Though IRC [41] was found to provide a higher scour depth than most other equations, it provided a lower scour than the equations of Chitale [20] and Melville and Coleman [6]. However, Islam [47] found the highest scour with Lacey's equation using a simple pier configuration for a bridge on the Kaliganga River in the Manikganj district. However, Lacey's equation provided less scour compared to the equations of Jain and Fischer, Chitale, and Melville and Coleman, when a complex pier configuration was used for the same bridge. Thus, Lacey's equation does not always over-estimate local scour when compared with other equations. Hence, Lacey's equation is still popular in the Indian sub-continent and widely used in scour estimation [48–51] for bridges.

Another potential limitation of the present study is the choice of equations. The study did not use the equation of Shen et al. [29], which is based on a vortex strength model and incorporates the Reynolds number in its formulation [11]. The formulation is available for both clear-water and live-bed scours and provides a conservative scour estimate. Though it has a form similar to Richardson [21], its applicability was not tested. Also, another equation due to Kothyari et al. [30], which is based on the formation of a horse-shoe vortex on the upstream side of a pier and laboratory data, was not used in this study. Again, the formulation is available for both clear-water and live-bed scours as well as for uniform and non-uniform sediments [43].

A third limitation of the study is the lack of field data. Only five sets of field data were available during the pre-monsoon, monsoon, and post-monsoon seasons at the Kaliganga bridge. The performance of different equations was evaluated with these measured data. The equation of Richardson was found to better match the observed scour at the bridge [47,52]. This is in agreement with the findings of Mohamed et al. [53] on some selected rivers from Pakistan, India, and Canada. However, Shen et al. [29] and Kothyari et al. [30] were not evaluated in either of these studies. Using a global dataset of 441 laboratory experiments, Sheppard et al. [54] evaluated the performance of different commonly used scour prediction formulas and found the Richardson formula among the top performers. Again, Kothyari et al. [30] were not included in the study, and a complex pier configuration was not used.

Finally, we conclude this section by highlighting the potential difficulties in using the empirical equations and how we overcame these. We did a hydro-morphological study for the construction of a bridge on the Feni river in southeast Bangladesh [25]. We came up with a local scour of 12.74 m below the riverbed level using different empirical formulae and the HEC-RAS model, for a pier width of 2.5 m and a pile cap width of 7.0 m [55]. However, in actual structural design, due to seismic factors, wind speed, storm surge effect, and traffic load, the pier width was suggested to be 6 m and the pile cap width to be 14.6 m. Using the same methodology, the scour depth came out to be 30.0 m. However, given the subsoil investigation report of the river, the degree of suitability of the different empirical equations in the particular context, scour depth provided in other bridges in the region, and potential cost escalation due to a deeper foundation, the 30 m scour depth was judged to be high. Finally, a 17.5 m scour depth was suggested for the bridge pier. This indicates that considerable experience and good professional judgment are required in deciding on the level of scour at a bridge foundation, particularly for wide piers and pile caps. Also, close interaction between river engineers, structural engineers, and geotechnical experts is a prerequisite to making a sound decision. Ettema et al. [56] also emphasized physical and numerical modeling for a better understanding of the flow-field around a pier and hence estimation of the design scour depth. Furthermore, they suggested scour monitoring for complex site conditions and inspection of bridge piers of all categories as the existing design equations do not apply well to complex pier types and are subject to many uncertainties. Their concerns are also linked to the difficulty of using a single method or set of equations to provide reliable estimates of pier design scour depth. In this context, it would be useful to estimate the effective pier size by different methods [6,12,57] and compare the resulting scours. The US Department of Transportation [57] has provided a guideline on the estimation of local scour at the complex pier in relation to the use of the equation of Richardson [21]. That guideline can also be tested with the other equations suggested in this manuscript and the results can be compared.

## 5. Conclusions

The studied Bangladesh rivers have an average design discharge of 1546 $m^3/s$, a velocity of 1.03 m/s, and a hydraulic depth of 6.66 m. The proposed bridges on the rivers have an average bridge length of 349 m and a central span length of 51 m. The average scour depth in the Bangladesh rivers considering a complex pier configuration is estimated to be 8.28 m with a standard deviation of 2.31 m. The scour depths were found to be more than 13 m for a few bridges in the northeast, north-center, and northwest of the country. The equations of Melville and Coleman, Jain and Fischer, and Richardson appear to be dominating in estimating the design local scour depth at the complex bridge piers. The equation of Richardson matched best to the measured scour at a bridge on the

Kaliganga River. The equations of Kothyari et al., Shen et al., and Lacey are suggested to be included for local scour estimation at bridge piers. Thus, this study clearly indicates the empirical equations to be used in conjunction with a complex pier configuration while assessing the design local scours at bridge piers. Different organizations in Bangladesh use different methods to estimate scours at bridge piers. Even there is no coherence between different available organizational guidelines and standards. A common unified national standard is suggested to be developed by reviewing global literature and practices. This is necessary as even the large bridges on the globally known GBM rivers were constructed without adequate consideration of local scour. The scale of the present study is unique, and the findings would be useful in other riverine countries in local scour assessment and guideline development.

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