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Some hydrotechnical features of Padma River, Bangladesh

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ABSTRACT: The 100-km long Padma River in central Bangladesh carries the combined flows of the Brahmaputra that enters Bangladesh from the north and the Ganges that enters from the west. With a mean flow of around 30,000 m^3/s, a bankfull flow of about 75,000 m^3/s and a 100-year flood flow of around 130,000 m^3/s, in terms of flow it is one of the largest rivers in the world. The boundary materials are mainly fine sand and silt with occasional clay mostly in the upper banks, and the planform and cross-sections are highly unstable over much of the length. Cross-sections are highly irregular in shape, often showing multiple sub-channels, and the gradient is only about 5 cm per km. The overall roughness coefficient (n) declines from around 0.04 at low stage to 0.015 or less at bankfull stage, associated with flattening and wash-out of dunes to an essentially plane-bed condition at high stages. A final note mentions representation of the river bed behaviour in a physical model study designed to investigate bridge pier scour.

Keywords: alluvial rivers; Bangladesh; sand beds; roughness; bed-forms

1. INTRODUCTION

The 100-km long Padma River in central Bangladesh is formed by the junction of two of the world's large rivers, the meandering Ganges and the braided Brahmaputra, both entering Bangladesh from different parts of India as shown in Figure 1. (The greater part of the Brahmaputra in Bangladesh is known locally as the Jamuna, for reasons explained below.) A major road/rail bridge was planned to replace an existing ferry crossing at Mawa, about 60 km downstream from the head of the Padma and about 50 km south of Dhaka, the country's capital. This first bridge over the Padma would provide a reliable link between the central and southwest regions of the country.

The paper is based mainly on a design study for river training works associated with the bridge, conducted from 2009 to 2011 by Northwest Hydraulic Consultants as subconsultants to AECOM on behalf of the Bangladesh Bridge Authority. Earlier pre-feasibility and feasibility studies for the bridge (Rendel Palmer and Tritton et al. 2000; Nippon Koei et al. 2004) included analyses of river characteristics as well as tentative schemes for river training works.

Several previous river crossing projects in Bangladesh have involved extensive river studies. A multipurpose bridge over the Jamuna was constructed in the 1990s about 80 km upstream of the Padma site (Tappin et al. 1998). Other major crossings include a power line crossing of the Jamuna (Hinch et al.

1984), and road bridges over the Ganges (Parsons Brinckerhoff et al. 1999) and the upper Meghna (Collins et al. 2003). An extensive account of fluvial processes in the Padma's major tributary, the Brahmaputra or Jamuna, was published by Coleman (1969).

2. SOURCES AND SETTING OF PADMA RIVER

Both principal tributaries, the Jamuna (or Brahmaputra) and the Ganges, have their principal sources in the mountain ranges of the Himalaya and Hindu Kush. Local flow contributions from within Bangladesh are relatively negligible.

The Padma River (Figure 1) flows southeast for approximately 100 km from the Jamuna-Ganges confluence to join the Upper Meghna River flowing from the northeast. The combined river, known as the Lower Meghna, discharges through delta channels into the Bay of Bengal. The land traversed by the Padma is a deltaic plain built up over many millennia, characterized by intensive agricultural settlement and fine-grained alluvial soils extending to considerable depths. Over most of its length the Padma is tidally affected under lower flow conditions.

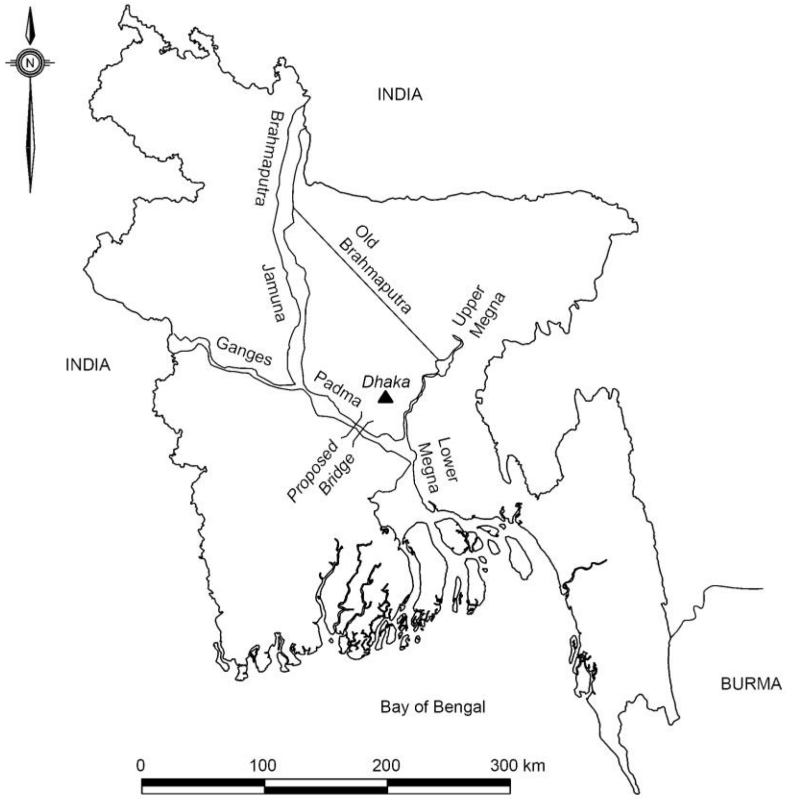

Figure 1. Major rivers of Bangladesh

The Padma River and its surroundings are subject to earthquakes. In the 18th century the Brahmaputra was diverted by an earthquake up to 100 km westward into the present Jamuna River course, leaving the former channel (now called the Old Brahmaputra) as a relatively small distributary connecting to the Upper Meghna (Figure 1). Landslides resulting from a severe earthquake in 1950 along the Brahmaputra valley in Assam (India) produced large quantities of additional bed sediment. These moved downstream to the Lower Meghna over a period of about 60 years and in passing temporarily changed some features of the Padma River.

3. HYDROLOGIC AND MORPHOLOGIC CHARACTERISTICS

3.1. Key water levels and discharges

The annual water level and discharge patterns of the Padma River are typical of monsoon climates, with an average high season in August-September and a low season in February-March (Figure 2). The stage-discharge relationship at the bridge site (Figure 3) shows a fairly wide scatter, probably mainly because of changes in hydraulic resistance resulting from changing river-bed configurations. A frequency distribution of maximum annual discharges at the bridge site, based on a 35-year record, is shown in Figure 4.

Key water levels and discharges in the river itself, discounting wide overbank flows, are approximately as shown in Table 1.

Table 1**.** Key discharges and water levels near bridge site based on historic record.

Condition	Discharge (m^3/s)	Water level (m PWD*****)
Average low water	15 000	1.5
Overall mean	30 000	3.8
Bankfull	75 000	5.5
2- year maximum	91 000	6.0
10-year maximum	110 000	6.5
100-year maximum	128 000	7.0

* The Public Works Datum (PWD) is approximately 0.5 m below present mean sea level

Recorded discharges at the head of the Padma River are 5% to 20% larger than the above bridge-site values, depending on return period. The apparent loss between the head of the river and the bridge site is accounted for by one major distributary about 15 km upstream of the bridge site and by overbank flow not included in gauge determinations. The distribution of flow over the floodplain was estimated using 2-D numerical modeling.

Assessments were made of potential discharge increases due to climate change. Allowing for climate change over a 100-year design life, two key discharges were adopted for the bridge project: a "design flood" (100-year) discharge of 148 000 m^3/s, and for certain purposes a "check flood" (500-year) discharge of 160 000 m^3/s.

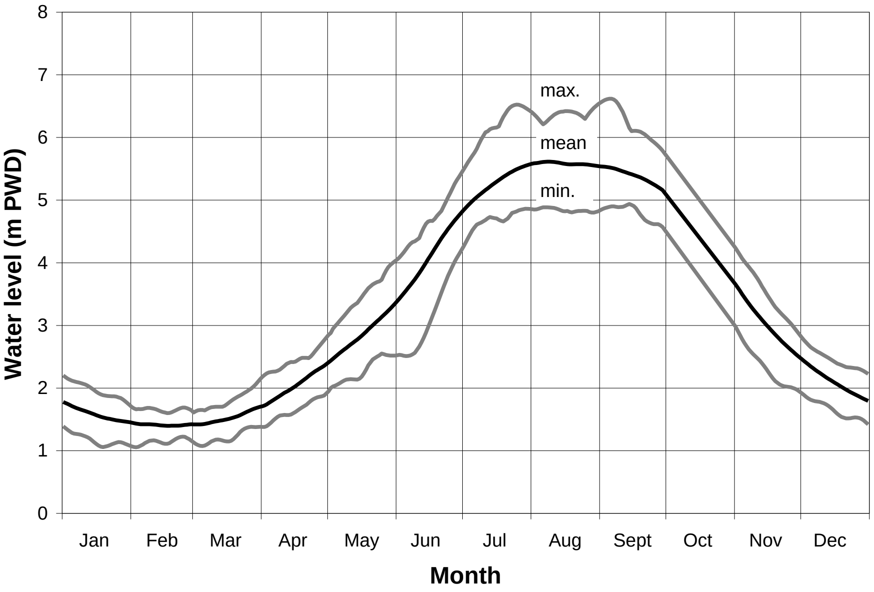

Figure 2. Seasonal variation of water levels, Padma River at bridge site

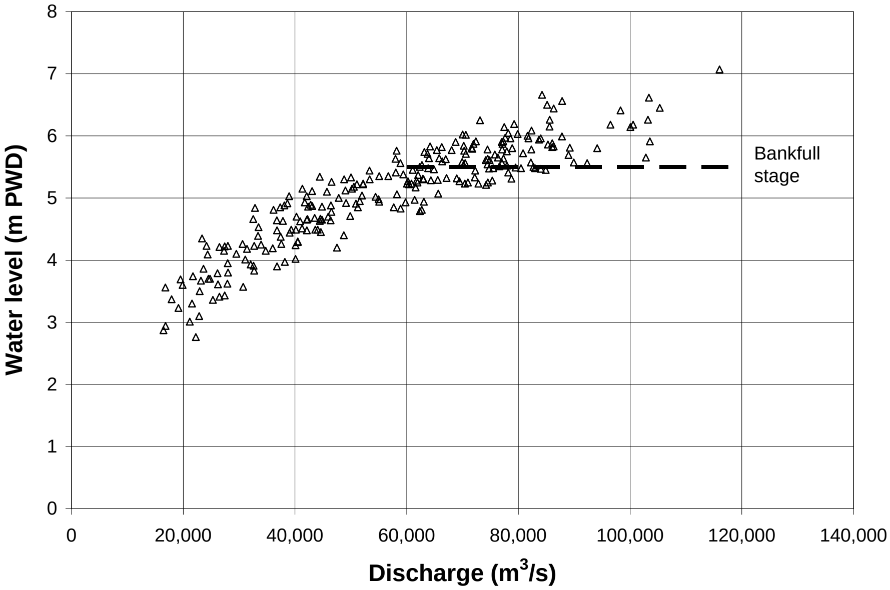

Figure 3. Stage-discharge relationship at bridge site

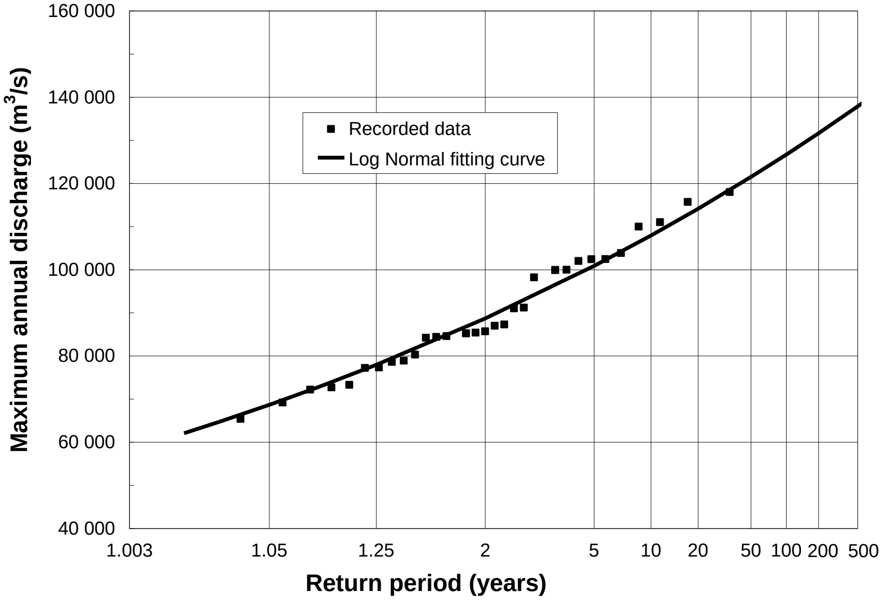

Figure 4. Frequency distribution of annual maximum discharges at bridge site

3.2. Morphologic features

The overall course of the Padma (Figure 5) is fairly straight, and exhibits an alternation of single-channel and multi-channel reaches with occasional meanders. Single-channel reaches are generally controlled by nodal points where the banks contain cohesive or semi-cohesive soils that are relatively resistant to erosion. Elsewhere, especially along the right bank, the main channel is generally bounded by loose, very fine, non-cohesive sands that are easily eroded, so that the channel boundaries can shift extensively in response to large flow events and in the course of more gradual morphologic changes.

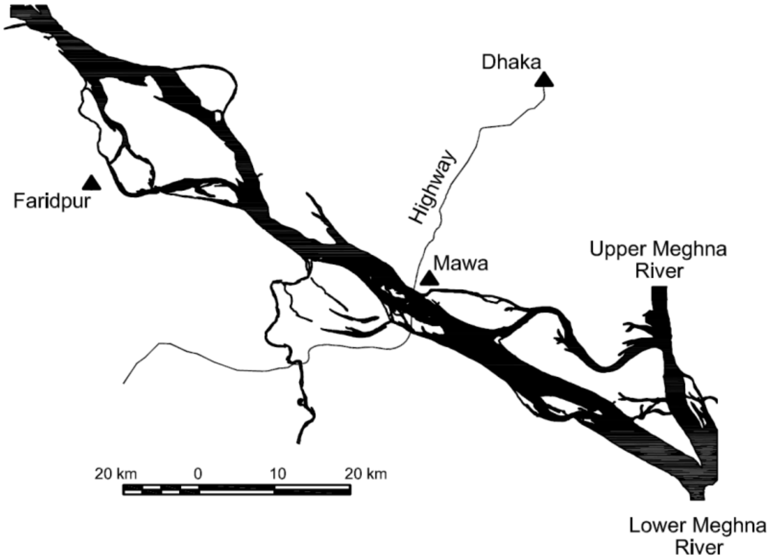

Figure 5. Plan of Padma River as of 2009

Typical river cross-sections (Figure 6) have a fairly well-defined bankfull stage corresponding to floodplain levels on both sides, but bed profiles change greatly over periods of years or decades. Local bank-to-bank widths in the general vicinity of the bridge site range widely, from about 2 to 10 km or more with an average of about 6 km. If the dominant discharge is taken as the bankfull value of 75 000 m^3/s, this average width is more than four times the "regime" width for stable alluvial channels as formulated by Lacey (1929-30). This large difference reflects the unstable and essentially multi-channel character of the river.

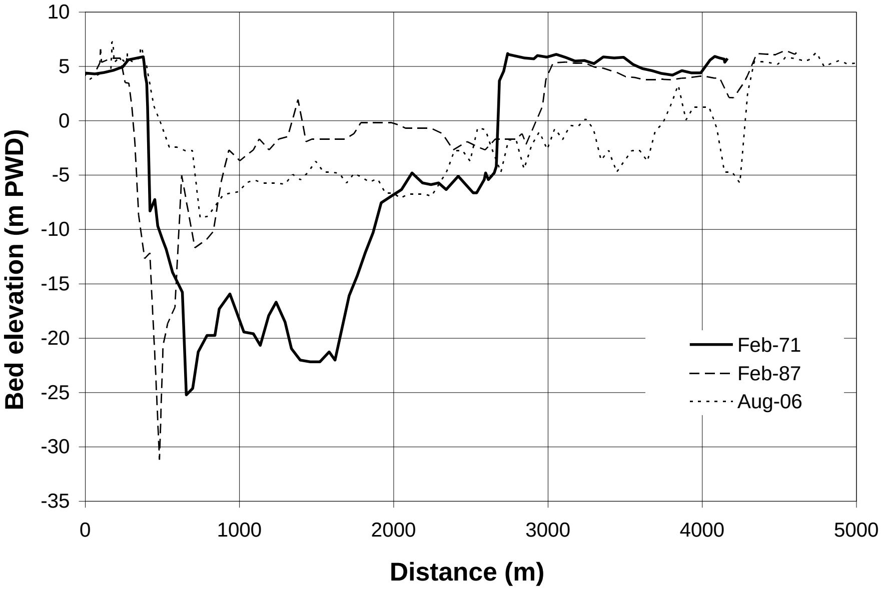

Figure 6. Typical cross-section near bridge site showing long-term variability

Water depths tend to be very unevenly distributed across the section. Under low-water conditions there is often a single deep channel with a shifting location, and several shallower channels separated by temporary sediment bars or islands. Width-averaged depth below bankfull stage is about 10 m, but maximum scoured depths can be up to 50 m or more below bankfull. These maximum depths are usually found in narrow sections, or opposite alternating bars, or where the main flow impinges on a resistant bank.

The bed material generally consists of very fine, non-cohesive sand with a median diameter of about 0.12 mm, containing widely varying percentages of mica. The bed material can be mobilized under relatively low flow conditions to create large-scale bed-forms, as discussed further below. Bank materials are mostly similar, but in certain locations consist of cohesive silt-clay at certain elevations. The overall gradient of the river is very flat, averaging about 0.00005 (5 cm/km).

The river planform is subject to major and sometimes rapid shifts in location (Figure 7). A length of about 25 km immediately upstream of the bridge site has alternated historically between a relatively straight course with a direct approach to the bridge (as in 1980 and 2009), and a pronounced meander loop with a very oblique approach (as in 1967 and 1996). This large-scale instability involved shifts in the right bank of up to 8 km over periods of only a few years and posed considerable difficulties in developing a feasible scheme of river training and bank protection.

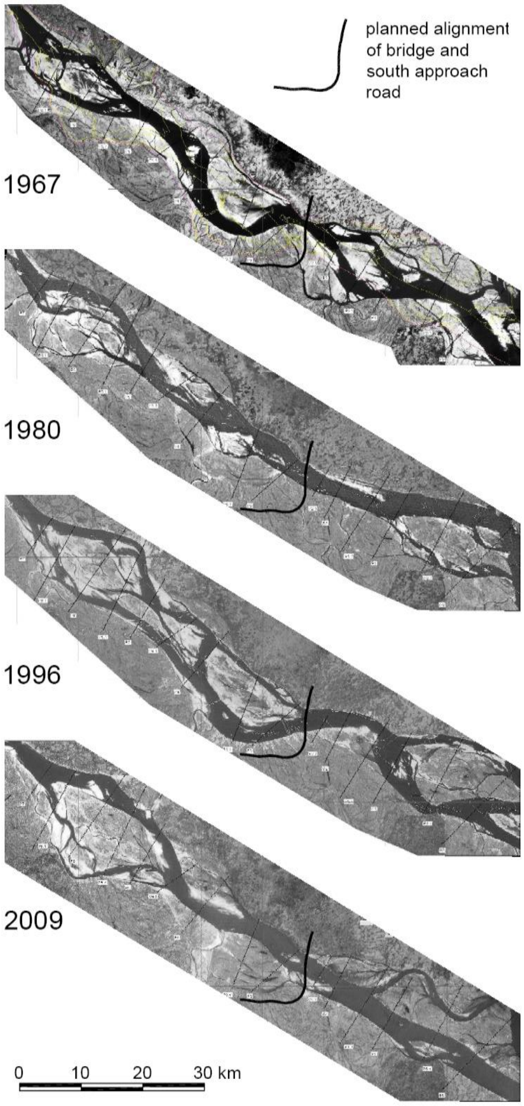

Figure 7. Evolution of Padma River from 1967 to 2009

3.3. Hydraulic characteristics

3.3.1 Velocities

River velocities were measured in August 2009 at eight cross-sections covering a channel length of about 10 km including the bridge site, at around the bankfull condition. Cross-sectional averages ranged from 1.2 to 1.6 m/s, and maximum vertically-averaged values from 2.1 to 2.7 m/s. A typical transverse distribution of vertically-averaged velocities is shown in Figure 8. For the bridge section, those bankfull data were extended to higher flows by numerical modelling, giving maximum vertically-averaged velocities of about 4.0 m/s for the historical 100-year flood and 4.4 m/s as adjusted for climate change.

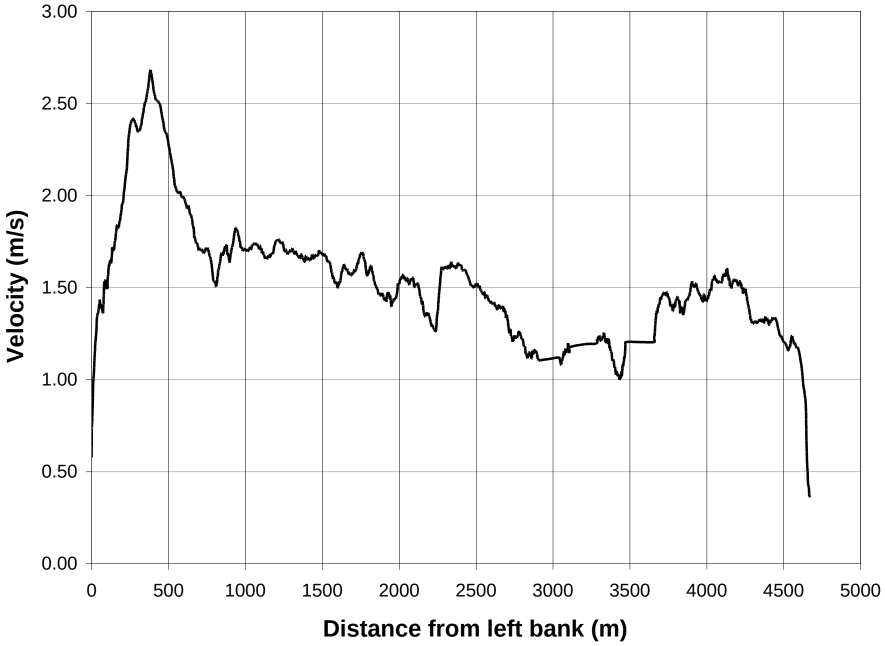

Figure 8. Transverse distribution of vertically-averaged velocities near bridge site, August 2009

3.3.2 Hydraulic roughness

The most striking feature of Padma hydraulics is an unusually large and systematic variation in overall hydraulic roughness as a function of stage or discharge, as calculated from measured cross-sectional dimensions and velocities and average longitudinal slope. A plot of Manning *n* against discharge, based on measurements in a 60-km length extending upstream the bridge site, was published by Stevens and Simons (1973) and republished by Simons and Senturk (1977). A similar correlation based on 2009-2010 measurements in a 40-km reach straddling the bridge site shows a reasonably close correspondence (Figure 9). The later data show *n* reducing systematically from a maximum of around 0.04 at a discharge of about 14 000 m^3/s to around 0.013 at the bankfull discharge of about 75 000 m^3/s. The available data do not extend much above bankfull.

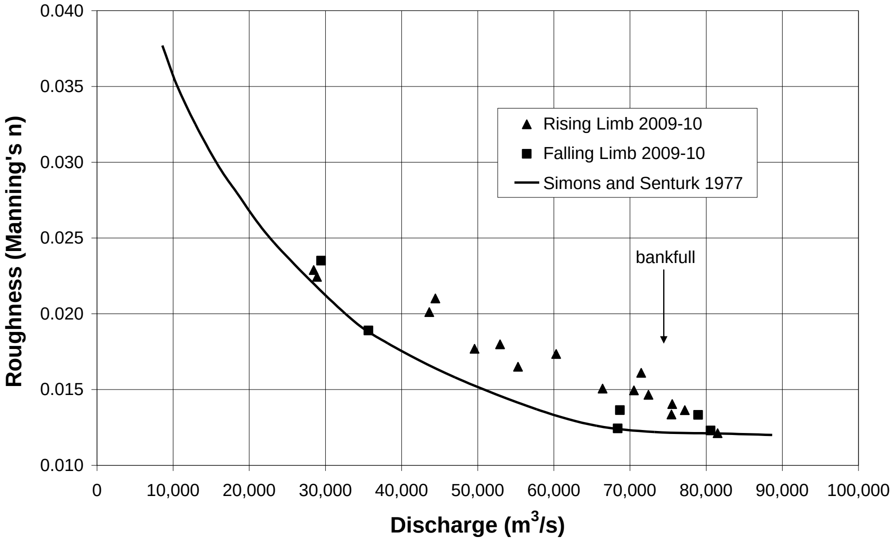

Figure 9. Variation in overall hydraulic roughness with discharge

A major factor in the this large decline in roughness with increasing discharge is almost certainly the changing geometry of bed-forms, as surmised by Stevens and Simons (1973) and as documented to some extent below. It appears that relatively large bed-forms under low to moderate flow conditions diminish with increasing discharge until they wash out to nearly plane bed conditions at around bankfull stage. Another aspect is that for a given discharge, roughness tends to be higher on rising than on falling discharges (Figure 10). This suggests a time lag between a given flow condition and associated equilibrium bed-forms.

Another factor causing very low roughness at higher discharges may be the effect of dense concentrations of suspended sediment near the bed in damping vertical turbulent exchange. It has long been noted that the effective roughness of channels with sandy beds is reduced when there is a high concentration of suspended sediment (Vanoni 1946; Blench 1957).

The large variation of roughness with discharge in the Padma has implications for numerical modeling of fine-grained alluvial rivers, where single values of the Manning roughness coefficient are sometimes adopted on the basis of calibration at moderate flows. Such assumptions may lead to serious under-estimation of flood velocities and corresponding over-estimation of flood levels.

An earlier analysis of overall hydraulic resistance in the Jamuna River (Government of Bangladesh et al. 1996) and its variation with discharge or stage was expressed in terms of the Chezy coefficient C, and so is difficult to compare directly with the Padma data presented herein. No specific relationship to bed-form geometry was postulated.

4. BED-FORMS

Available information from the recent bridge studies provides some glimpses of bed-form geometries. Longitudinal profiles over a length of several km, showing bed-forms in the general vicinity of the bridge site, were obtained under various flow conditions in the high-flow season of 2009, in depths ranging from about 10 to 25 m. A profile of 14 August at a discharge of about 55 000 m^3/s shows well-defined dune forms with average lengths of around 200 m and heights of around 5 m (Figure 10). On 28 August with an increased discharge of about 75 000 m^3/s, maximum dune dimensions had diminished to about 50 m x 1 m and many lengths were almost flat. On 9 September with discharge reduced to about 65 000 m^3/s, dune dimensions had increased again to about the same as on 14 August. These limited data suggest a fairly quick response to flow changes and a tendency to approach plane bed conditions at around bankfull discharge. The bed-forms present at any given time probably reflect not only the prevailing discharge and depth but also the preceding sequence of those parameters, and presumably they vary considerably at different places along and across the channel.

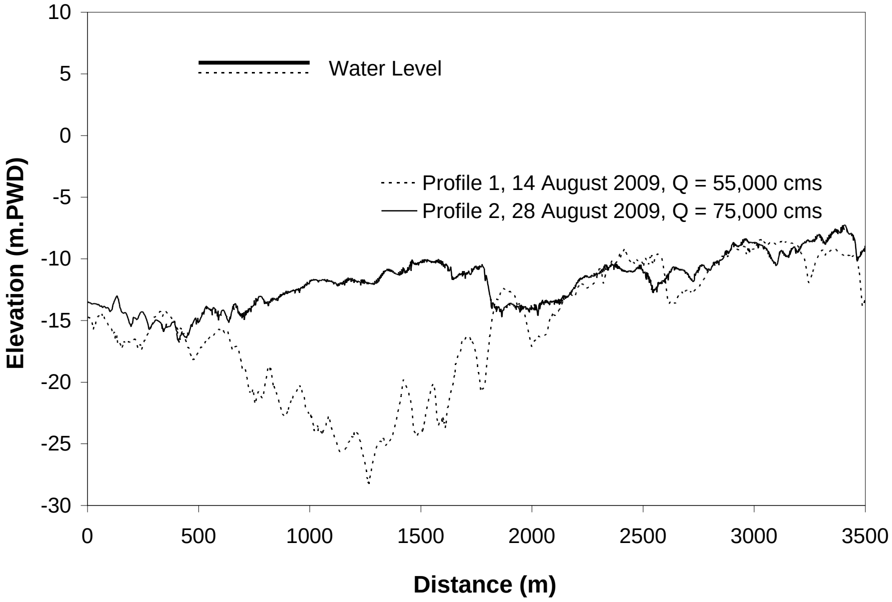

Figure 10. Bed-form profiles in Padma River, 14 and 28 August 2009

Charts by various investigators that use various hydraulic and sediment parameters to discriminate between different types of bed-forms are reproduced by Garcia (2007). The hydraulic and sediment criteria proposed for occurrence of ripples, dunes, plane bed and anti-dunes vary widely among authors - a situation that does not inspire much confidence in their universal applicability. Nevertheless, using calculated values of appropriate parameters for several charts, the Padma River at bankfull discharge conditions seems to plot within zones designated as "plane bed".

Information on bed-forms in the Jamuna River (the Padma's major tributary, with slightly coarser bed sand) is available from earlier studies (Klaassen et al. 1988, Government of Bangladesh et al. 1996). In the latter reference, observed dunes ranged up to about 400 m long and 5.5 m high, but the majority were less than 100 m long and 2 m high. Over a range of flow depths from 2 to 20 m, maximum dune heights were generally about one-third of flow depth, but no clear correlation was apparent between maximum lengths and flow depth. The data indicated fairly rapid response of dune dimensions to changes in flow velocity, but dunes appeared to be present over a wide range of flows with few indications of plane-bed conditions. Estimated dune migration rates at high flows ranged widely from about 1 to 17 m/hr.

It is not clear to what extent the recent Padma observations are compatible with these earlier observations in the Jamuna River. It is evident from these and numerous other field and laboratory studies that relationships between bed-form geometry and hydraulic characteristics are extremely complex, as illustrated in the review by Garcia (2007). It appears fairly evident, however, that the strong negative correlation of hydraulic roughness with discharge in the Padma River (Figure 9) is mainly determined by the changing scale of bed-forms. The overall *n* value of around 0.013 at bankfull conditions seems indicative of a mainly plane-bed condition.

5. SEDIMENT TRANSPORT

Not much information on sediment transport is available from the recent bridge studies. Sporadic sampling in August 2009, with discharge rising from about 30 000 to 75 000 m^3/s, produced suspended sediment concentrations in the range of 400 to 1200 mg/L and corresponding loads of up to about 6 million t/day. No data on bed loads are available.

Note on bed behaviour in model study of bridge pier scour

As part of the Padma bridge studies, a physical hydraulic model was operated in a straight laboratory flume in order to estimate depths of local scour around bridge pier foundations. The geometric scale was 1:80 and the flume represented a partial river width equivalent to one bridge span. In order to achieve sufficient bed mobility without distorting the Froudian velocity scale of 1:8.9, the fine bed sand of the Padma River was represented by crushed walnut shell of 0.2 mm grainsize with a submerged relative density of about 0.3 as against 1.6 for sand. The incipient-motion velocity in the model was approximately 0.095 m/s, which scales up to a river velocity of about 0.85 m/s. Accurate reproduction of bed-material transport under high flow conditions was considered neither practicable nor necessary, since the deepest local scour near piers is usually associated with relatively low bed transport.

Bed-forms that developed in the model at a scaled-up velocity of 2.6 m/s and a scaled-up flow depth of around 25 m appeared to scale reasonably with maximum prototype dunes observed in the 2009 high-flow season. At higher velocities the model bed transformed to a plane condition, also corresponding reasonably to field observations and inferences from roughness determinations. It was therefore concluded that for the purposes of the model, the 0.2 mm walnut shell reproduced Padma River bed-forms and roughness characteristics to an acceptable degree. The greater part of the bed-material transport in the model occurred in suspension, as is believed to be the case in the Padma River.

6. SUMMARY OF KEY POINTS

The relatively short Padma River, carrying the combined the flows of the Jamuna (or Brahmaputra) and Ganges rivers in central Bangladesh, is one of the world's largest in terms of discharges. Studies for river training works associated with a planned major bridge have extended previous hydrotechnical information about the river.

The river planform is mostly straight overall, but exhibits multiple channels that are liable to extensive and rapid shifting between a few stable nodal points. The average bank-to-bank width of about 6 km is several times greater than the "Lacey" width for a stable alluvial channel of equivalent discharges. Depths can range up to 50 m or more at certain locations. The bed material is very fine sand, and the average gradient is only about 5 cm/km.

The pattern of flow variations is of monsoon type, with wet-season maxima in August-September and dry-season minima in February-March. The frequency curve of annual maxima is quite flat, with a ratio of only 1.4 between 100-year and 2-year values. Under bankfull flow conditions the overall cross-sectional average velocity is around 1.5 m/s. Vertically-averaged local velocities in the deeper parts of the cross-sections can be up to 4 m/s or more under 100-year flood conditions.

The average boundary roughness in terms of Manning *n* declines systematically from around 0.040 at relatively low flows to around 0.013 at bankfull conditions. This decline appears to be associated with progressive flattening of dune-type bed-forms and the attainment of virtually plane-bed conditions around the bankfull condition.

In a scale model study of local scour around bridge pier foundations, the bed behaviour of the Padma appeared to be reproduced acceptably using low-density crushed walnut shell of similar grainsize to represent the river sand.

7. ACKNOWLEDGEMENTS

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