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APPLICABILITY OF ALLUVIAL ROUGHNESS PREDICTORS FOR GANGES RIVER

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ABSTRACT: The applicability of thirteen alluvial roughness predictors, five based on overall roughness and eight based on division of roughness, for the river Ganges utilizing data for the stations Hardinge Bridge and Baruria, has been investigated. The predictors have been evaluated on the basis of Manning's n, Chezy's C and Darcy-Weisbach friction factor f and, where possible, on the basis of depth and/or velocity. The predicted grain roughness has been compared with the grain roughness calculated by using the Strickler formula. Only the Shen (1962) method seems to predict roughness parameters for the river Ganges satisfactorily. The Shen method shows a good agreement with the computed values of Manning's n, Chezy's C and friction factor f even at low discharges when the roughness parameters change sharply. The predicted grain roughness by the Shen method also shows a very good agreement with the grain roughness computed by the Strickler formula. The bed form of the river Ganges seems to remain in the lower flow regime, i.e. ripple and dune throughout the year. The Manning's n and the Darcy-Weisbach friction factor f for the river Ganges increase with decreasing discharge and attain maximum value during March and minimum value during August-September. However, the variation of Chezy's C is reverse to that of Manning's n and Darcy-Weisbach friction factor f, i.e. it increases with increasing discharge. The variation of form roughness with discharge is similar to that of total roughness, but the variation of grain roughness with discharge is reverse to that of the total roughness.

INTRODUCTION

Flow in a river is generally variable in time and space, i.e. it is unsteady and non-uniform. For practical applications, however, the variation may be considered so slow that a quasi-steady and quasi-uniform flow situation can be assumed.

In rigid boundary open channels, the resistance to flow is due to grain roughness only, i.e. the roughness of the material forming the channel boundary. Therefore, it is common for the engineers to think of a rigid boundary open channel as having a single roughness value for all discharges. However, the problem of predicting the resistance to flow in alluvial rivers with mobile boundary is complicated by the fact that the configuration of the bed changes with change in flow conditions. This changing bed condition makes it impossible to describe the resistance to flow in an alluvial channel by a single-valued resistance coefficient.

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The resistance to flow in a channel carrying clear water with fixed boundaries was studied extensively and could be predicted with a satisfactory degree of certainty. However, when a stream has a movable bed and sediment is being transported, the problem of determining the resistance is much more complicated.

The prediction of flow resistance in alluvial channels is needed for two major purposes: (i) the estimation of stage-discharge relationship, and (ii) the estimation of sediment transport from the hydraulic characteristics of the channel by means of transport formula. Moreover, knowledge of the resistance characteristics of alluvial streams is of great value when dealing with the location of bridges, training works, flood control works, navigation and channel improvement, backwater computation due to confluences and barrages, mathematical and physical modelling of flow, prediction of aggradation and degradation due to presence of hydraulic structures and so on.

Attempts to determine resistance factors for alluvial channels have been based on modifications of existing fixed bed equations. The Einstein and Barbarossa (1952) approach was the first attempt to predict the stage-discharge relationship for natural streams with an alluvial bed. This approach was based on the hypothesis that the resistance of an alluvial bed can be separated into grain resistance due to the presence of grains and the form resistance offered by the bed undulations.

Since the pioneering work of Einstein and Barbarossa (1952) in the field of alluvial roughness prediction, a large number of roughness predictors have been developed for predicting the roughness of alluvial rivers. The existing resistance relationships of alluvial channels follow two different approaches:

(i) Separate estimate of grain roughness and form drag on basis of grain size distribution of the bed material and the anticipated bed forms. The total roughness is found by adding both roughnesses together.

(ii) Integral methods in which simultaneously the continuity and the Chezy or Manning equations are solved and the total roughness is found. These methods are based on overall flow parameters such as depth of water and depth-averaged flow velocity.

In Bangladesh most of the river courses are of alluvial nature. Due to their great tendency to change course, large rivers have been subject to investigation and studies. Minor rivers, however, have only been studied while formulating water resources projects involving these rivers. The roughness coefficient of some rivers of Bangladesh was determined by Khan (1975). Later on Khan (1979) developed the relationship between discharge, mean velocity of flow and depth of scour for 1966-67 flood period of Brahmaputra river. Stage-discharge relationship for the river Jamuna at Bahadurabad was studied by Chowdhury (1996). The River Survey Project (FAP-24)(Delft Hydraulics/DHI, 1996) reported that bed form roughness is the main component of the overall resistance in the river Jamuna. The validity of the Soil Conservation Service (SCS) method (French, 1986) for estimating roughness coefficients was also investigated by the River Survey Project (FAP-24).

In this study, an attempt has been made to investigate the applicability of some alluvial roughness predictors for the river Ganges. The specific objectives of the proposed study are, (i) to determine the applicability and limitations of 13 different methods for predicting the roughness characteristics of the river Ganges at the stations Hardinge Bridge and Baruria, and (ii) to determine the roughness characteristics of the Ganges. Out of these thirteen roughness predictors, five are based on overall roughness and the rest eight are based on division of roughness.

PARAMETERS FOR DESCRIBING RESISTANCE TO FLOW

The three most common parameters describing the resistance to flow in alluvial channels are the Manning's roughness coefficient n, the Chezy's resistance factor C and the Darcy-Weisbach friction factor f. Assuming that the river flow is quasi-steady and quasi-uniform, these coefficients are obtained by applying the Manning, the Chezy and the Darcy-Weisbach formulas as (Chow, 1959; Chaudhry, 1993)

$$n = \frac{R^{\frac{2}{3}} S^{\frac{1}{2}}}{U} = \frac{A R^{\frac{2}{3}} S^{\frac{1}{2}}}{Q} \tag{1}$$

$$C = \frac{U}{R^{\frac{1}{2}} S^{\frac{1}{2}}} = \frac{Q}{A R^{\frac{1}{2}} S^{\frac{1}{2}}} \tag{2}$$

$$f = \frac{8gRS}{U^2} \tag{3}$$

where U is the mean velocity of flow (m/s), R is the hydraulic radius (m), S is the slope of the energy line, Q is the discharge (m^3/s), A is the cross-sectional area (m^2) and g is the acceleration due to gravity (m/s^2).

According to Einstein and Barbarossa (1952), total bed shear stress ($\bullet_b$) is the sum of bed shear stress related to grain roughness ($\bullet'_b$) and bed shear stress related to grain roughness ($\bullet''_b$). It is assumed that $\bullet_b$, $\bullet'_b$ and $\bullet''_b$ are caused by the same flow velocity U. Then,

$$\bullet_b = \bullet'_b + \bullet''_b \tag{4}$$

$$Ux^2 \rho = Ux'^2 \rho + Ux''^2 \rho \, (Ux = \sqrt{\frac{\tau_b}{\rho}} \tag{5}$$

$$Ux^2 \rho = Ux'^2 \rho + Ux''^2 \tag{6}$$

$$RS = (RS)' + (RS)'' \; (U\times = C\sqrt{RS}) \quad (7)$$

where • is the density of water and U. is the shear or friction velocity.

The Chezy's formula can be rearranged as

$$\frac{U^2}{C^2} = RS = (RS)' + (RS)'' \quad (8)$$

or

$$\frac{1}{C^2} = \frac{(RS)'}{U^2} + \frac{(RS)''}{U^2} + \left(\frac{1}{C'}\right)^2 + \left(\frac{1}{C''}\right)^2 \quad (9)$$

Taylor and Brooks (1962) suggested that the Darcy-Weisbach friction factor f be divided into two parts, that due to grain roughness

$$f' = \frac{8gR'S}{U^2} \quad (10)$$

and that due to form roughness

$$f'' = \frac{8gR''S}{U^2} \quad (11)$$

In this case, the total friction factor

$$f = f' + f'' \quad (12)$$

According to the Bajorunas (1952), the Manning's roughness coefficient n is composed of two parts and can be determined by the relationship

$$n = n' + n'' \quad (13)$$

where n' is due to the grain roughness and n'' is due to form roughness.

The Strickler formula (Strickler, 1923) which relates grain roughness to Manning's n is (Chang, 1988)

$$n' = \frac{D_{50}^{\frac{1}{6}}}{21.1} \quad (14)$$

where D_{50} is the diameter of the bed material than which 50% of the material by weight is smaller.

THE RIVER GANGES

The river Ganges rises west of the Nanda Devi Range west of Nepal. It has a length of about 2,200 kilometers and drainage area of 978,000 square kilometers. The Ganges is an international river with its basin area spreading over China, Nepal, India and Bangladesh. After travelling through several states of India, the Ganges enters Bangladesh at Lalgola, 18 kilometers downstream of Farakka. In Bangladesh it is called the river Ganges up to and including its confluence with the Brahmaputra (Jamuna) river near Aricha. Downstream of Aricha the combined Ganges and Jamuna flows are carried by the Padma river. The Padma river is 120 kilometers long and joins the Upper Meghna near Chandpur, after which it is called the Lower Meghna, which debouches into the Bay of Bengal at some 150 kilometers from the confluence. The main river system of Bangladesh is shown in Fig. 1.

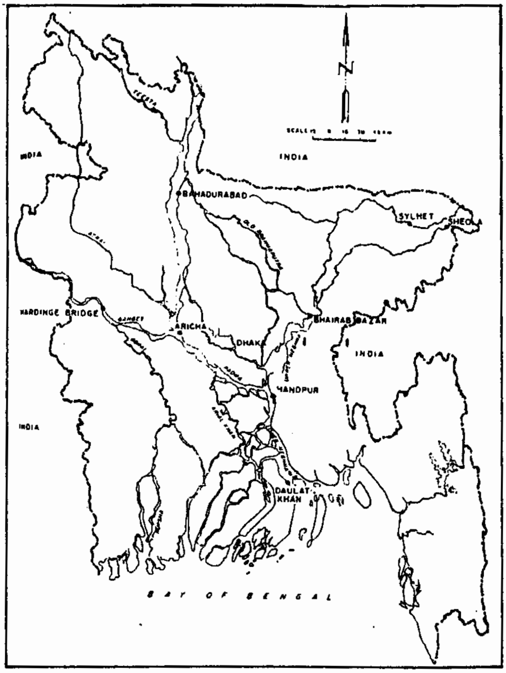

Fig 1. The main river system of Bangladesh

The Ganges is a wide meandering river. Its width may at places be as large as 5 kilometers. The shape of the cross-section is quite variable. The meander belt of the river varies from 5 to 15 kilometers with eroding outer bends and depositing inner bends. From the Indo-Bangladesh border to the confluence located at Aricha, there are four distinct and wide bends (Hossain, 1989).

Hardinge Bridge and Baruria are two measuring stations of Bangladesh Water Development Board (BWDB) located on the river Ganges. Hardinge Bridge is a very old primary measuring station of BWDB which is located in a constricted river bend where the main river width of 3.8 kilometers has been reduced to 1.6 kilometers. The meander migration of the Ganges at Hardinge Bridge had stopped since the construction of railway bridge in 1910.

Baruria gauging station is located downstream of the Ganges/Jamuna confluence and 6 kilometers downstream of Aricha. The river has more or less stable banks at Baruria.

ROUGHNESS PREDICTORS CONSIDERED

In this study, the applicability of 13 roughness predictors for the river Ganges has been investigated. Out of these, 5 predictors are based on overall roughness and the rest 8 are based on division of roughness. The selected overall roughness predictors are Simons and Richardson (1966), Garde and Ranga Raju (1970), Brownlie (1983), White et al. (1987) and Karim (1995). The selected predictors based on division of roughness are Einstein and Barbarossa (1952), Shen (1962), Engelund and Hansen (1967), Vanoni and Hwang (1967), Alam and Kennedy (1969), Haque and Mahmood (1983), Shen (1990) and Van Rijn (1993). A brief description of the methods is available in Alam (1998).

Out of 13 roughness predictors considered in this study the Engelund and Hansen (1967), the Brownlie (1983) and the Karim (1995) methods predict both depth and velocity. The Einstein and Barbarossa (1952), the Shen (1962) and the Van Rijn (1993) methods predict only depth. The Simons and Richardson (1966), the Garde and Ranga Raju (1970) and the White et al. (1987) methods predict only velocity. The Vanoni and Hwang (1967), the Alam and Kennedy (1969), the Haque and Mahmood (1983) and the Shen (1990) methods neither predict depth nor predict velocity, but they predict the roughness parameters directly.

In recent times, attention is being focussed on predicting dimensions of bed forms and then predicting roughness values by using these bed form dimensions. In this study, the bed form dimensions are predicted by using the Allen (1963), the Vajda (1990) and the Yalin (1992) methods. A brief description of the methods is also available in Alam (1998).

DATA REQUIREMENTS, DATA COLLECTION AND DATA ANALYSIS

Data required for this study are: discharge Q, energy line slope S, top width B, cross-sectional area A and particle sizes D_{16}, D_{35}, D_{50}, D_{65}, D_{84} and D_{90}. Since the energy line slope is not available, the water surface slope is taken equal to the energy line slope.

Among the data required to carry out the proposed study, the cross-sectional area, discharge and water width data for the stations Hardinge Bridge and Baruria are collected from the Hydrology Division, Bangladesh Water Development Board (BWDB). Discharge, cross-sectional area and top width data for the station Hardinge Bridge are available since 1970 with missing years of 1971 to 1973, 1977, 1978 and 1982. Discharge, cross-sectional area and top width data for the station Baruria are available since 1968 with missing years of 1970 to 1973 and 1975 to 1981. The Hydrology Division of BWDB measures discharge weekly during the monsoon season and fortnightly during the rest of the year. BWDB uses the area-velocity method for discharge measurements.

The different grain sizes of the bed material and the overall water surface slopes for the stations Hardinge Bridge and Baruria are collected from the River Survey Project (FAP-24) (Delft Hydraulics/DHI, 1996) and are shown in Table 1.

Table 1: Grain size of bed material and water surface slope of the Ganges at Hardinge Bridge and Baruria

Station	Grain size of bed material in mm					Slope
	D_{16}	D_{35}	D_{50}	D_{84}	D_{90}	
Hardinge Bridge	0.100	0.120	0.150	0.180	0.210	$5.5\text{x}10^{-5}$
Baruria	0.100	0.124	0.140	0.185	0.220	$4.0\text{x}10^{-5}$

River Survey Project (FAP-24) provides, from size analysis of bed material samples, the sizes of D_{16}, D_{35}, D_{50}, D_{84} and D_{90} for the station Hardinge Bridge and Baruria. But D_{65} is not available from size analysis. Some roughness predictors express roughness of the grain as Nikuradse roughness value K_s having value equal to D_{65}. From analysis of S curve for grain size distribution, the value of D_{65} is approximated as 0.165 mm both for Hardinge Bridge and Baruria.

Computer programs, written in FORTRAN, have been developed to predict the roughness coefficients by all the selected 13 roughness predictors.

The Manning, the Chezy and the Darcy-Weisbach formulas give only the total roughness, and hence, comparison with these formulae can only be made on the basis of total roughness. The roughness parameters predicted by different methods are compared with the values obtained by direct calculation using the Manning, the Chezy and the Darcy-Weisbach formulas. For brevity, the comparison is made on the basis of Manning's n only. The numerical values of n, C and f obtained by different methods indicate that if the Manning's n is compatible, then the Chezy and the Darcy-Weisbach formulas also give compatible results. That is why detailed comparisons on the basis of Manning's n have been done. The Chezy's C and the Darcy-Weisbach friction factor f have not been compared for all the cases.

The reliability of the predicted roughness coefficients by using the selected methods have been tested on the basis of

1. percentage of predicted depth, velocity and Manning's roughness value n that lies within ±10%, ±20% and ±30% error ranges,
2. Mean Normalised Error (MNE) of the predicted roughness coefficients, depth and velocity, and
3. graphical variation of measured and predicted Manning's n obtained by different methods.

The accuracy of prediction measured by the mean normalized error (MNE) in predicted depths or velocities expressed in percent is defined as (Karim, 1995)

$$MNE = \frac{100}{N} \sum_{i=1}^{N} \frac{|X_{ci} - X_{mi}|}{X_{mi}} \qquad (15)$$

where, X_{ci} = predicted depth (or velocity or roughness parameter) for ith flow

X_{mi} = measured/calculated depth (or velocity or roughness parameter) for ith flow

N = total number of data of a station.

RESULTS AND DISCUSSIONS

At Hardinge Bridge, altogether 923 data sets having discharges equal to or greater than 1,200 m^3/s have been selected. At Baruria all available 577 data sets have been used. Using these data depths and velocities are calculated and are hereafter termed as computed depths and computed velocities, respectively. Applying the roughness predictors, depth of flow and/or velocity are then predicted and compared with computed values on the basis of percentage of error in the ±10%, ±20% and ±30% error ranges. The mean normalized error (MNE) for predicted depth and/or velocity are also calculated.

Almost all the overall roughness predictors seem to predict Manning's n accurately in the moderate range of discharges both at Hardinge Bridge and Baruria. A few of them, however, seem to predict Manning's n accurately in the moderate as well as high discharges. But none of the methods seem to predict Manning's n accurately at low discharges.

The MNE for predicted Manning's n and percentages of predicted Manning's n lying within some specified error ranges by different roughness predictors both at Hardinge Bridge and Baruria are given in Table 2. On the basis of the percentage of predicted values of Manning n in the error ranges, at Hardinge Bridge the Shen (1962), the Van Rijn (1993) and the Haque and Mahmood (1983) (bed form by Vajda) methods rank 1, 2 and 3, respectively (Fig. 2). At Baruria the Shen (1962), the Karim (1995) and the Van Rijn (1993) methods rank 1, 2 and 3, respectively (Fig. 3). On the basis of the MNE for Manning's roughness value n, at Hardinge Bridge the Shen (1962), the Haque and Mahmood (1983) (bed form by Vajda) and the Vanoni and Hwang (1967)(bed form by Vajda) methods rank 1, 2 and 3, respectively (Fig. 4). At Baruria the Shen (1962), the Karim (1995) and the Engelund and Hansen (1967) methods rank 1, 2 and 3, respectively (Fig. 5).

The Shen (1962) method ranks 1 in predicting depth at Hardinge Bridge. It also ranks 1 for predicting Manning's roughness coefficient n both at Hardinge Bridge and Baruria. However, it seems to be less accurate than the Karim (1995) and the Engelund and Hansen (1967) methods for predicting depth at Baruria. The Shen method does not predict velocity and bed form dimensions.

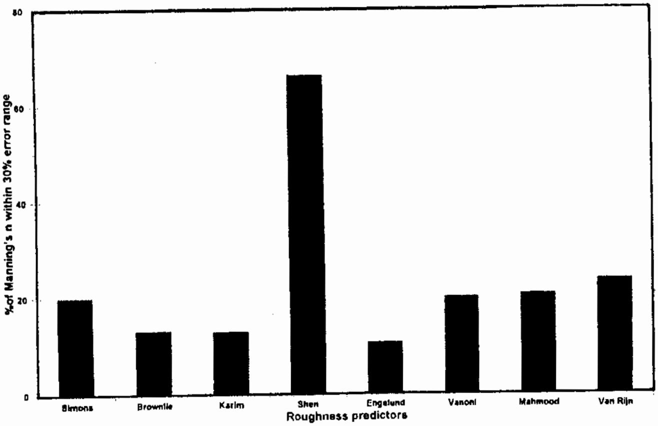

Fig 2. Percentage of Manning's n lying within ±30% error ranges predicted by different roughness predictors at Hardinge Bridge

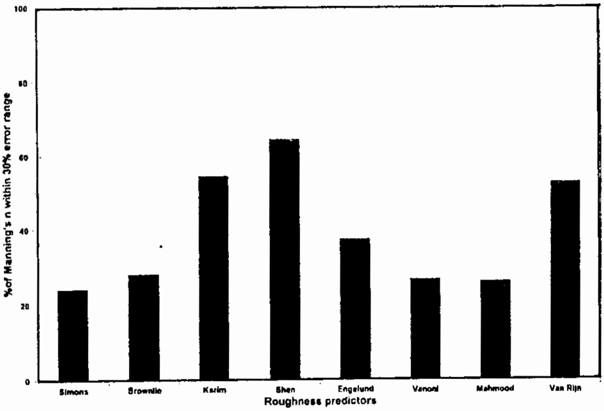

Fig 3. Percentage of Manning's n lying within ±30% error ranges predicted by different roughness predictors at Baruria

The Karim (1995) method ranks 2 in predicting depth at Hardinge Bridge and ranks 1 in predicting depth at Baruria. In predicting velocity, it ranks 1 at Baruria, but less accurate than Brownlie (1983) and Engelund and Hansen (1967) methods at Hardinge Bridge. In predicting Manning's roughness value n, the Karim method ranks 2 at Baruria, but at Hardinge Bridge it seems to be one of the least accurate methods for predicting the roughness parameters.

Table 2: **Percentages of predicted Manning's n lying within specified error ranges by different roughness predictors**

Name of roughness predictor		MNE for Manning's n (%)		Percentages of Manning's n lying within specified error ranges					
		H.Bridge	Baruria	Hardinge Bridge			Baruria		
				±10%	±20%	±30%	±10%	±20%	±30%
Simons & Richardson (1966)		57.57	45.01	5.09	10.51	19.93	4.16	11.09	24.96
Garde & Ranga Raju (1970)		61.14	49.27	4.66	9.10	13.76	8.49	19.07	27.21
Brownlie (1983)		65.45	63.36	3.35	7.47	12.89	13.00	19.58	27.90
White et al. (1987)		62.26	58.90	3.79	8.23	13.97	11.09	18.89	27.90
Karim (1995)		59.00	28.77	5.30	9.10	12.56	20.62	39.51	54.25
Einstein & Barbarossa(1952)		68.49	40.19	4.76	10.07	15.06	13.86	27.90	38.30
Shen (1962)		20.74	25.49	30.23	46.81	66.20	28.60	49.05	64.48
Engelund-Hansen (1967)		61.52	36.73	3.15	6.73	10.31	13.35	23.40	37.27
Vanoni & Hwang (1967)	Vajda(1990)	58.25	151.63	5.85	11.70	19.82	2.60	5.20	11.10
	Yalin(1992)	61.25	82.34	5.85	10.51	15.28	8.14	16.29	26.51
Haque & Mahmood (1983)	Vajda(1990)	56.23	163.44	5.75	13.77	20.49	3.47	6.24	10.92
	Yalin(1992)	59.63	77.22	6.07	10.84	15.17	6.59	15.77	25.99
Shen et al. (1990)	Allen(1962)	59.15	47.61	5.31	9.22	13.88	14.04	23.04	32.08
	Vajda(1990)	56.60	76.95	4.87	10.62	18.10	5.20	11.78	17.84
	Yalin(1992)	61.90	46.25	4.87	9.85	14.18	7.28	14.56	27.39
Van Rijn (1990)		59.07	50.18	8.45	16.14	23.61	16.30	34.32	52.69

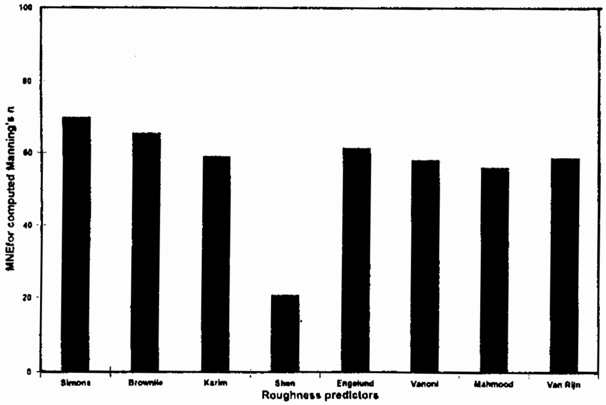

Fig 4. The MNE for predicted Manning's n by different roughness predictors at Hardinge Bridge

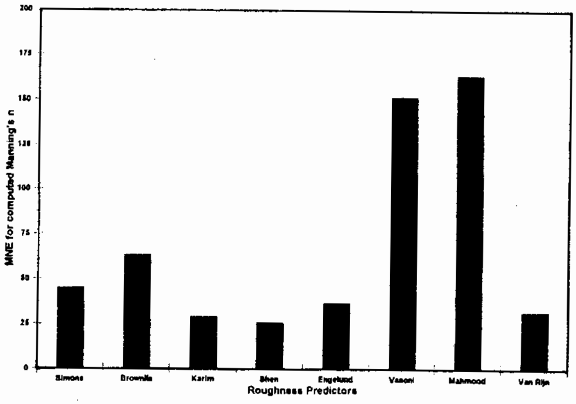

Fig 5. The MNE for predicted Manning's n by different roughness predictors at Baruria

In predicting depth, velocity and Manning's roughness value n, the Engelund and Hansen (1967) method is less accurate than the Shen and the Karim methods. Out of selected 6 methods, for predicting depth at Hardinge Bridge, the Engelund and Hansen method ranks 3 on the basis of the MNE and ranks 4 on the basis of predicted depths lying within ±30% error range. At Baruria this method ranks 2 in predicting depth. The Engelund and Hansen method ranks 2 on the basis of the predicted velocities lying within ±30% error ranges both at Hardinge Bridge and Baruria. However, on the basis of the MNE of the predicted velocity, this method ranks 1 and 2 at Hardinge Bridge and Baruria, respectively. This method seems to fail to predict the roughness parameters accurately both at Hardinge Bridge and Baruria.

The accuracy of predicted depths by the Van Rijn (1993) method seems to be very poor. But the accuracy of predicted Manning's n seems to be more accurate. In predicting Manning's n, the Van Rijn method ranks 2 at Hardinge Bridge and ranks 3 at Baruria on the basis of the computed values lying within ±30 error ranges. On the basis of the MNE at Hardinge Bridge and Baruria, it ranks 6 and 2, respectively.

In predicting depth, the Brownlie (1983) method ranks 3 and 4 at Hardinge Bridge and 4 and 3 at Baruria on the basis of the computed values lying within ±30% error ranges and the MNE, respectively. In predicting velocity at Hardinge bridge, it ranks 1 and 3 on the basis of computed velues lying within ±30% error range and the MNE. At Baruria it ranks 3 in both respects. It is among the least accurate methods for predicting roughness.

At Hardinge Bridge the Shen (1962) method ranks 1 and the Karim method ranks 2 in predicting depth. The variation of depth predicted by the Shen and the Karim methods with the discharge for the station Hardinge Bridge is shown in Fig. 6. The Shen method predicts depth better than the Karim method both at low and high discharges. The Karim method predicts depth better than the Shen method only when the discharge ranges between 25,000 and 40,000 m^3/s. Since the Shen method does not predict velocity, the two methods can not be compared on the basis of velocity. On the basis of the accuracy of the predicted Manning's n, the Shen method ranks 1, the Van Rijn method ranks 2 and the Karim method is among the least accurate methods. The variation of Manning's n predicted by different methods with discharges at Hardinge Bridge is shown in Fig. 7. Among the roughness predictors selected for this study, only the Shen method shows a good agreement with the measured roughness at all discharges. Even at low discharges when the roughness parameters change sharply, the Shen method seems to predict the roughness parameters satisfactorily.

At Hardinge Bridge the MNE is 28.83% for depth, 20.74% for Manning's n, 21.10% for Chezy C and 28.82% for Darcy-Weisbach friction factor f by the Shen (1962) method.

According to Strickler formula the grain roughness n• ranges between 0.0109 and 0.0147 at Hardinge Bridge. The predicted grain roughness by Shen method ranges between 0.0099 and 0.0149, which shows a very good agreement with the grain roughness computed by the Strickler formula.

Thus, it may be concluded that, for predicting grain roughness, form roughness and total roughness, the Shen (1962) method seems to be the best for Hardinge Bridge.

At Baruria the Karim method ranks 1, the Engelund-Hansen method ranks 2 and the Shen method ranks 3 in predicting the depth. At low discharges neither the Karim method nor the Shen method predicts the depth very well (Fig. 8). The predicted depths by the Karim method shows a good agreement with the computed depths when the flows are 45,000 m^3/s or above. When the discharges lie between 25,000 and 45,000 m^3/s, the depths predicted by the Karim method seems to be reasonable. However, when the discharges are below 25,000 m^3/s, the accuracy of this method for predicting depths are very low. The Shen method shows very good agreement in predicting depth for discharges between 40,000 and 70,000 m^3/s. But at low and high discharges this method does not produce very good accuracy.

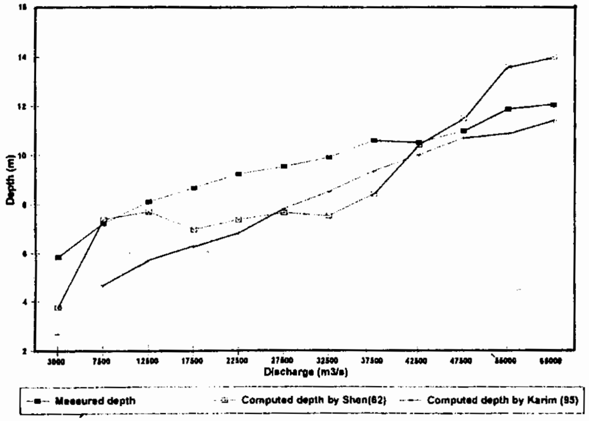

Fig 6. Variation of depth predicted by Shen (1962) and Karim (1995) methods with discharges at Hardinge Bridge

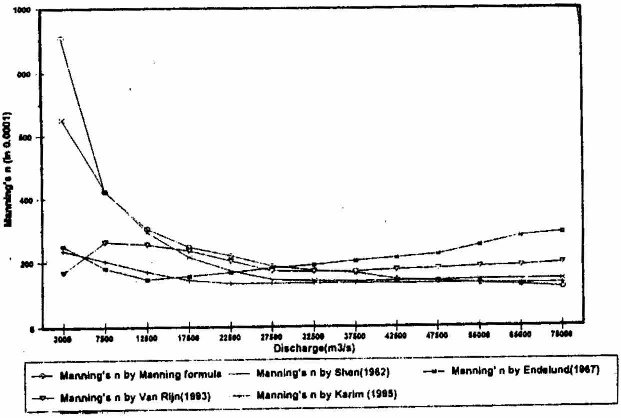

Fig 7. Comparison between computed Manning's n value and predicted Manning's n value using different roughness predictors at Hardinge Bridge

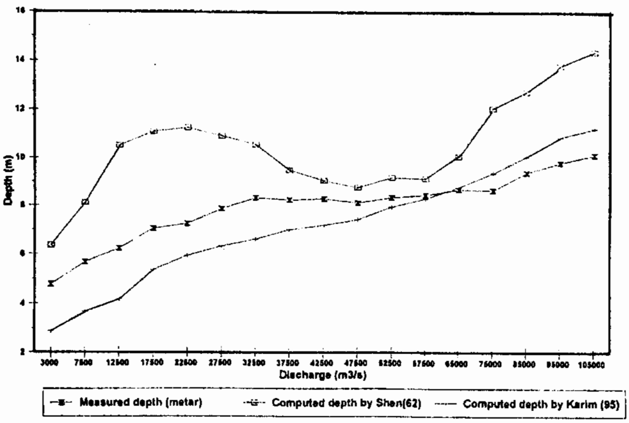

Fig 8. Variation of depth predicted by Shen (1962) and Karim (1995) methods with discharges at Baruria

On the basis of predicted Manning's roughness value n at Baruria, the Shen method ranks 1 and the Karim method ranks 2. The variation of Manning's n predicted by different methods with discharges at Baruria is shown in Fig. 9. Only the Manning's n predicted by the Shen method shows good agreement with the computed values at all discharges. The Karim method ranks 2 in predicting Manning's n. The values of Manning's n predicted by the Karim method are almost constant and show a little variation with change in discharge. The Karim method is slightly better than the Shen method in predicting Manning's n when the discharge is more than 65,000 m^3/s.

At Baruria the MNE by Shen method is 42.10% for depth, 25.55% for Manning's n, 14.36% for Chezy C and 42.11% for Darcy-Weisbach friction factor f.

According to Strickler formula the grain roughness n• ranges between 0.0108 and 0.148 at Baruria. The predicted grain roughness by Shen method lie between 0.0109 and 0.0150 and is almost same as that computed by the Strickler formula.

Thus, it may concluded that, for predicting grain, form and total roughnesses, the Shen (1962) method seems to be the best for Baruria also.

RESISTANCE CHARACTERISTICS OF THE RIVER GANGES

It may be observed from the present study that for the river Ganges, the bed undulations remain for most of the period of the year when discharge is small. During flood flow the bed undulations are due to erosion and during low flow the bed undulations are due to siltation or non-erosion of the existing bed forms. Surveys over dunes in some major rivers of Bangladesh by the River Survey Project (FAP-24)(Delft

Hydraulics/DHI, 1996) confirmed that over 40% of the beds are always occupied by dunes at any flow stages. Julien and Klaassen (1995) showed that mean dune steepness does not always decrease at high transport stages in large rivers and that large bed forms may exist even at high transport stages.

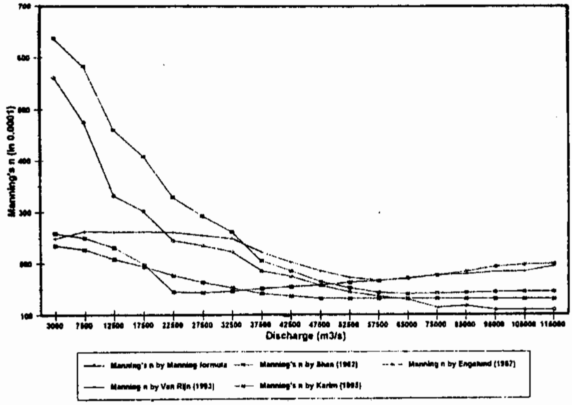

Fig 9. Comparison between computed Manning's n value and predicted Manning's n value using different roughness predictors at Baruria

The bed forms in alluvial channels have been classified based on different parameters. According to Yalin (1992), the bed forms may be in the lower flow regime or upper flow regime depending on the Froude number of the flow. Lower flow regime occurs when the Froude number is less than 0.60. Upper flow regime occurs when Froude numbers are 0.6 and above. In the lower flow regime, the bed forms may be plane bed without sediment movement, ripples and dunes (Simons and Richardson, 1966). The river bed is plane at low discharges when the bed material does not move. Then the ripples form at relatively high discharges. With further increase of discharge, the bed form changes to dune and washed-out dune. From analysis of available data for the river Ganges, the Froude number ranges from 0.021 to 0.331 at Hardinge Bridge and from 0.029 to 0.315 at Baruria. Thus, considering the Froude number as the classification parameter, it may be concluded that the bed forms of the river Ganges both at Hardinge Bridge and Baruria seems to remain in the lower flow regime, i.e. ripples or dunes for most of the period of the year when the discharge is small.

At Hardinge Bridge the Manning's n ranges from 0.0109 to 0.1589, the Darcy-Weisbach friction factor f ranges from 0.0042 to 0.996 and Chezy's C ranges from 8.88 $m^{1/2}/s$ to 136.03 $m^{1/2}/s$ for discharges ranging from 1,200 m^3/s to 76,000 m^3/s. At Baruria the Manning's n ranges from 0.0092 to 0.0907, the Darcy-Weisbach friction factor f ranges from 0.0032 to 0.3794 and the Chezy's C ranges from 14.38

$m^{1/2}$/s to 156.10 $m^{1/2}$/s for discharges ranging from 2,680 m^3/s to 130,000 m^3/s.

The mean monthly variation of Manning's n since 1970 at Hardinge Bridge and Baruria is shown in Fig. 10. For the station Hardinge Bridge, the Manning's n decreases during the flood season and increases during the dry season. At Hardinge Bridge the variation of Manning n is very large. It attains its mean monthly maximum value in April and minimum value in September. During flood flow, from July to October, the variation is mild. From October-November it again starts increasing and reaches its maximum value in April. At Hardinge Bridge the form roughness is more responsive to the discharge and its non-linear variation with discharge is the dominant factor in the variation of total roughness.

The variation of grain roughness n•, form roughness n• and total roughness in terms of n, C and f with discharge at Hardinge Bridge is shown in Fig. 11. The value of form roughness n• is maximum at low discharges and decreases with increasing discharge. The grain roughness n• is less responsive to discharge, linear in nature and increases slightly with increasing discharge. The values of grain roughness n• at Hardinge Bridge ranges from 0.0099 to 0.0149 and at Baruria ranges from 0.0109 to 0.0150. The variation of Darcy-Weisbach friction factor f with discharge is similar to Manning's n. But it varies more than Manning's n with discharge. The variation of Chezy's C with discharge is reverse to that of Manning's n and Darcy-Weisbach f, i.e. it increases with increasing discharge.

The mean monthly resistance to flow at Baruria decreases during flood season and increases during the dry season. The variation of Manning's n at Baruria is not as wide as that at Hardinge Bridge. It attains its mean monthly maximum value in March and minimum in August. After March the value of n starts decreasing. From July to September its value remains almost constant. From October the value of n again increases and attains its maximum value in March.

The variation of grain roughness n•, form roughness n• and total roughness in terms of n, C and f with discharge at Baruria is shown in Fig. 12. The grain roughness n• is less responsive to discharge and increases with increasing discharge. The maximum to minimum ratio of grain roughness is 1.5. The form roughness n• that is more responsive to discharge is the dominant factor in the variation of total roughness. The value of form roughness is maximum at low discharges and decreases with increasing discharge. The form roughness becomes zero at high discharges. The variation of Darcy-Weisbach friction factor f with discharge is similar to that of Manning's n, but the variation of Chezy's C with discharge is opposite to those of Manning's n and Darcy-Weisbach friction factor f.

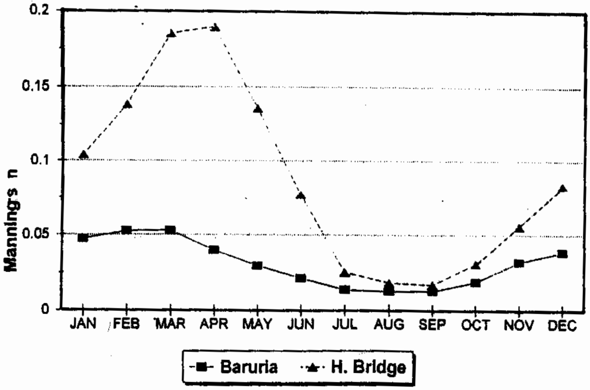

Fig 10. Mean monthly variation of Manning's n at Hardinge Bridge and Baruria

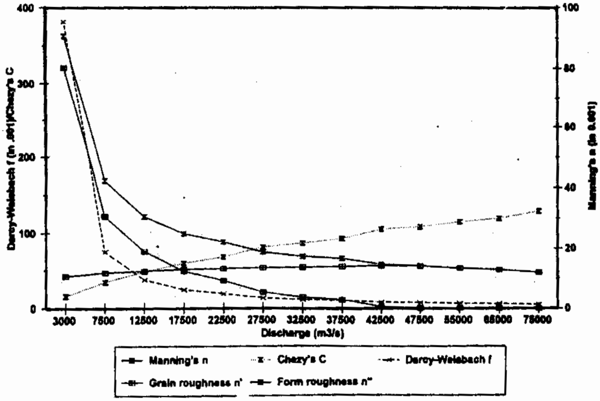

Fig 11. Variation of different roughness parameters with discharge at Hardinge Bridge

CONCLUSIONS

Among the various roughness predictors considered, the Shen (1962) method seems to predict the resistance characteristics of the river Ganges satisfactory. It shows a close compliance with the measured depth and the measured roughness. It also seems to predict the grain roughness quite satisfactory.

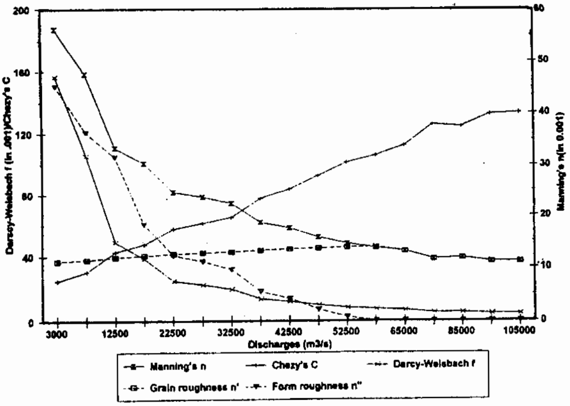

Fig 12. Variation of different roughness parameters with discharge at Baruria

The roughness parameters n and f are maximum during the dry season when the discharge is minimum. These values are minimum during flood season when the discharge is maximum. For the river Ganges at Hardinge Bridge the value of Manning's n ranges from 0.0109 to 0.1589, Darcy-Weisbach friction factor ranges from 0.0042 to 0.9960 and Chezy's C ranges from 8.88 $m^{1/2}/s$ to 136.02 $m^{1/2}$ for discharges ranging from 1,200 to 76,000 m^3/s. At Baruria the values of Manning's n ranges from 0.0092 to 0.0907, Darcy-Weisbach friction factor f ranges from 0.0032 to 0.3794 and Chezy's C ranges from 14.38 $m^{1/2}$ to 156.10 $m^{1/2}$ for discharges ranging from 2,860 to 130,000 m^3/s.

The Manning's n for the river Ganges increases with decreasing discharge, attains its maximum value during March, then decreases gradually with increasing discharge and attains its minimum value during August and September. The Darcy-Weisbach friction factor f also shows a similar variation over the year. The variation of Chezy's C is reverse to that of Manning's n and Darcy-Weisbach friction factor f. The Chezy's C increases with increasing discharge and decreases with decreasing discharge.

For the river Ganges the Manning's grain roughness increases slightly with increasing discharge. At low discharges the grain roughness is the minor part of the total roughness. At high discharges the grain roughness alone is either equal to or close to the total roughness.

Like the total roughness, the form roughness decreases with increasing discharge. It is more responsive to discharge than the grain roughness. At high discharges, the form roughness is either zero or very close to zero and its influence is negligible. At low discharges the influence of the form roughness is prominent and becomes the major constituent of the total roughness.

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