SYNTHESIZED FLUIVIAL STAGE-DISCHARE AND SEDIMENT RATING OF JAMUNA RIVER AT BAHADURABAD

Md A Matin*[1], Maliha B Islam[2] and Anika N Mowrin[3]

[1] *Ex. Professor, Bangladesh Univ. of Engg. and Tech., Bangladesh, e-mail: mamatin@wre.buet.ac.bd*
[2] *Graduate, Bangladesh Univ. of Engg. and Tech., Bangladesh, e-mail: 1716021@wre.buet.ac.bd*
[3] *Assistant Professor, Stamford University Bangladesh, e-mail: anikanowshin@stamforduniversity.edu.bd*

***Corresponding Author**

ABSTRACT

This paper deals with the development of a synthesized fluvial stage-discharge rating curve for Jamuna River at Bahadurabad based on combined application of sediment transport and resistance equation. Cross-sectional survey data of the Jamuna River reach between Jamalpur and Sirajganj districts from 2018 to 2021 were used in this study. In particular, river cross-sections in the vicinity of Bahaduarad station have been used to generate the flow data corresponding to the given water level. Two flow resistance equations e.g. the White-Bettess-Paris equation and Manning's equation and two sediment transport equations e.g. the Ackers-White formula and the Engelund-Hansen method were used in the present computational procedure. The flow resistance equations facilitate the calculation of mean velocity through the channel sections in conjunction with the sediment transport equation. These equations were also applied to predict the sediment concentration of the different sections for generating the sediment data for the rated discharge. Based on the findings of the study, it was found that the combination of the Ackers-White Formula transport and the White-Bettess-Paris resistance equation produces more accurate prediction of discharge values and deviates only 2.83% when compared with that of observed values. Moreover, the combination of the Engelund-Hansen method and the White-Bettess-Paris equation deviates 6.31% from observed values which implies that this method complies relatively less in predicting discharge values. It is expected that the procedure suggested will be helpful to generate the discharge and sediment data of river, where flow measurements are scarce for setting up a hyrdo-morphological model for the reach under study.

Keywords: *Fluvial, Stage-discharge, Sediment, Resistance equation, Jamuna River*

1. INTRODUCTION

In Bangladesh, most rivers have the alluvial characteristics and are subject to frequent course changes. The variability of flow, sediment transport, and channel configuration in the major rivers and their tributaries and distributaries poses unique challenges. Stage, discharge, and sediment transport exhibit daily and seasonal changes, continuously influencing scour and fill patterns and hydraulic resistance. The stage discharge curve is a graphical representation of the relationship between the stage (water level) and discharge of a river. The sediment rating curve, on the other hand, relates the sediment concentration or load to the discharge of the river. In many areas, particularly in developing countries, absence of gauging stations and stream flow data makes it challenging to evaluate the hydraulic behavior of alluvial rivers. In such cases, the establishment of synthetic stage discharge and sediment rating curves can offer an useful relatioship for the design of river hydraulic structures and flood management.

Many studies have been conducted worldwide on stage-discharge prediction techniques. Brownlie (1983) worked on sand bed river and compared various stage-discharge predictors using data from Rio-Grande conveyance channels and the Mississippi River. Alhamid and Matin (2000) studied the Wadi Hanifa main channel to explore the application of flow resistance equations in developing a fluvial stage-discharge rating curve. They modified the Garde and Ranga Raju (1966) predictor to a simplified form for easy application in alluvial channels. Garde and Ranga Raju (1980) reported a study on the computation of degradation and aggradation in alluvial rivers. They presented semi-empirical methods for calculating bed and water surface profiles in common cases of aggradation, mainly based on work carried out in India. James P. et. al (2000) investigated the correlations between suspended sediment load rating parameters, river basin morphology, and climate. They aimed to develop predictive equations for sediment rating parameters using long-term time-averaged discharge, suspended load, flow duration, flow peak, precipitation, temperature, range in temperature, drainage area, and basin relief data from 59 gauging stations. Based on the above context, this study aims to explore the application of well known sediment transport and flow resistance equations to develop a stage-discharge rating curve. More recently, Badhan and Matin (2018) reported similar type of the work named "Fluvial stage and sediment discharge rating with possible maximum scour depth prediction of a selected reach of the Jamuna River".

2. METHODOLOGY

An alluvial channel can adjust its width, depth, and slope to achieve a stable condition in which it can transport a certain amount of water and sediment. Thus, it has three degrees of freedom and the problem is to establish relationships which determine these three quantities i.e. width, depth, and slope. By using the Ackers and White (1973) equations, Engelund and Hansen (1967) sediment transport equations and the White-Bettess-Paris (1980) equations, the Manning equation for flow resistance equation, the geometric and hydraulic parameters of a stable channel can be obtained for a wide range of practical applications.

The present study reach is located within the district of Jamalpur and Sirajganj, covering approximately 47 km of the Jamuna River. The coordinates for Jamalpur, Bangladesh are approximately 24.9375°N latitude and 89.9372°E longitude. The coordinates for Sirajganj, Bangladesh are approximately 24.4550°N latitude and 89.7086°E longitude. Six cross-section stations have been selected for analysis. The reach length was chosen due to its nearly straight topography in most cross-sections, facilitating simplified analysis. The location of the study area is shown in Figure 1.

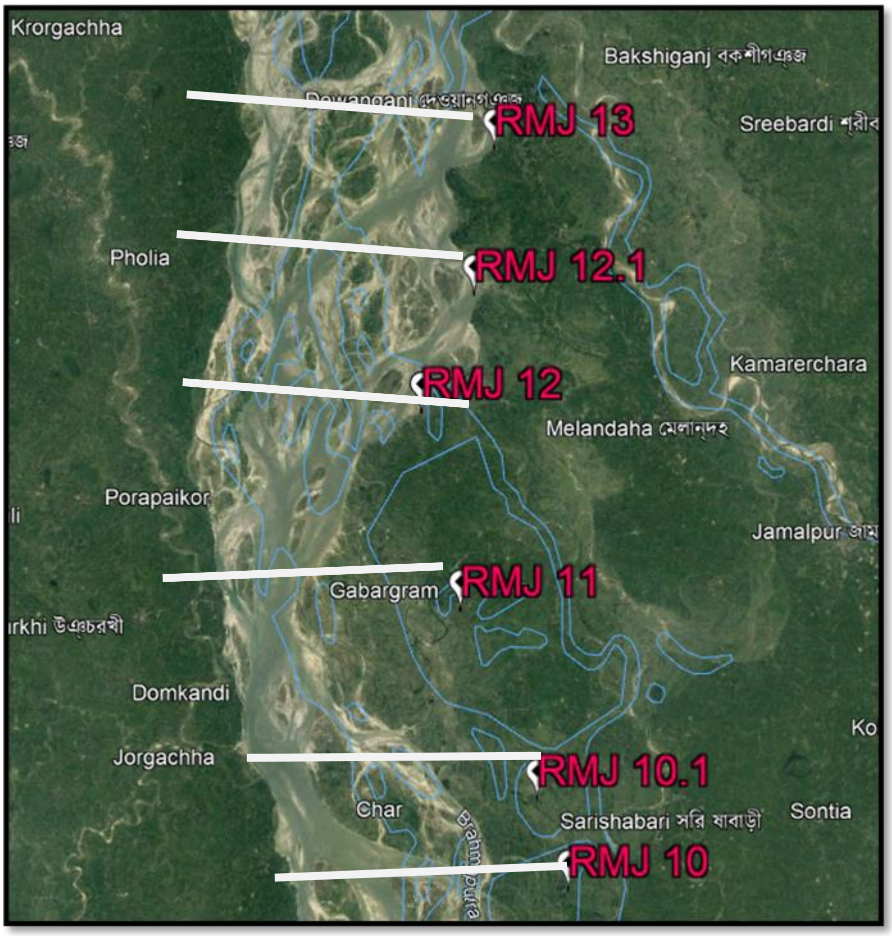

Figure 1: Locations of Cross-section of the Jamuna river Study area

2.1 Approach

This study follows a variational principle based on the assumption that an alluvial channel adjusts its geometric characteristics and gradient in such a way that the sediment transporting capacity is maximized. By using this variational principle together with the Ackers and White equations for sediment transport and the White-Bettess-Paris equations for flow resistance, the geometric and hydraulic parameters of a stable channel can be obtained for a wide range of practical applications.

In this sysnthesied approach the flow resistance equations facilitate the calculation of mean velocity through the channel sections in conjunction with the sediment transport equation White-Bettess-Paris equation resistance equation and Manning's equation and two sediment transport equations e.g. the Ackers-White formula and the Engelund-Hansen method were used in the present computational procedure. These equations were also applied to predict the sediment concentration of the different sections for generating the sediment data for the rated discharge.

Three aproaches have been analysed in the sudy; these are i) Ackers-White formula, White-Bettess-Paris equation ii) Englund-Hansen formula, White-Bettess-Paris equation and iii) The Mannings equation only.

2.2 Data

Table 1 shows the summary of data collected from Bangladesh Water Development Board (BWDB) of the river Brahmaputra in the vicinity of Bahadurabad.

Table 1: Summary of Data Collection (Source: BWDB)

Data Type	Station No.	Data Collection	
		From	**To**
Cross-Section	RMJ13	01 Jan, 2018	27 Dec, 2021
	RMJ12.1	01 Jan, 2018	31 Dec, 2021
	RMJ12	01 Jan,, 2018	31 Dec, 2021
	RMJ11	01 Jan., 2018	21 Jan, 2022
	RMJ10.1	01 Jan,, 2018	31 Dec, 2021
	RMJ10	01 Jan, 2018	15 Jan, 2022
Water Level	(SW46.9L)	01 Jan, 2018	31 Dec, 2022
Discharge	(SW46.9L)	01 Jan, 2018	31 Oct, 2022
Sediment	(SW46.9L)	01 Jan, 2018	23 May, 2022

Water level gauges were installed along the right bank of the Jamuna River for the purpose of conducting the bathymetry survey. From 06:00 to 18:00 hours, water levels were recorded at three-hour intervals on a daily basis. To establish a consistent reference, the gauges were connected to the Public Works Department (PWD) datum using direct fly leveling techniques,

The values of bed material sizes, namely D_{50} (median grain size) and D_{90} (mean grain size), are crucial for calculating fluvial discharge capacity, shear stress differences, and fluvial sediment concentration using the equations obtained from the FAP21 (1994) study. These bed material size values specific to the Brahmaputra-Jamuna River are considered as D50=0.20 mm to D_{90} =0.34 mm.

The maximum and minimum values of observed reduced levels, distance between consecutive stations and top width/bank full width of selected six stations for the year 2020 are given below:

Table 2: Dimension of Selected Cross-Sections along Jamuna Reach from Bahadurabad

Station No.	Bankful width (m)	Distance from Bahdurabad (m)	Minimum Bed Level (m PWD)	Maximum Bed level (m PWD)
RMJ13	10985	0	-10.02	23.81
RMJ12.1	10987	8926	1.92	20.45
RMJ12	12544	7811	2.35	20.38

RMJ11	7260	12310	-5.68	18.41
RMJ10.1	11480	12310	1.68	16.15
RMJ10	11473	5823	-2.20	17.76

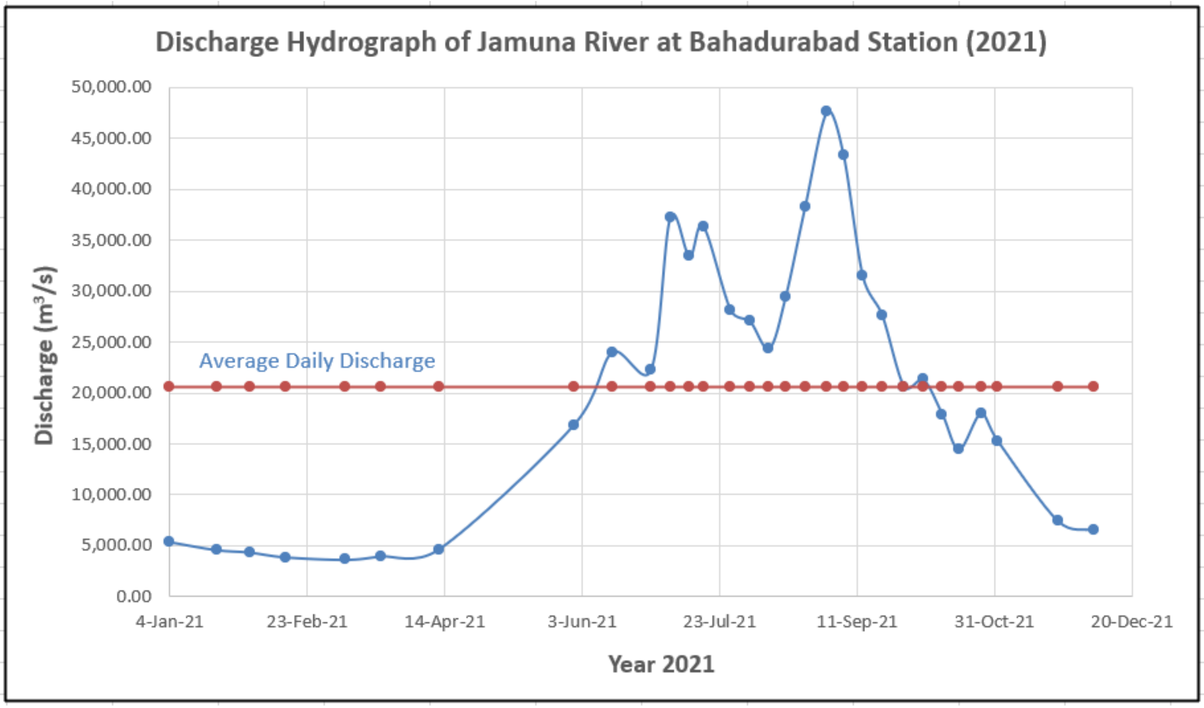

Figure 1: Monthly discharge hydrograph for the year 2021

To evaluate the applicability of predicted discharge and sediment transport capacity, stream flow data, water level data, total sediment concentration data from the year 2021 of Bahadurabad station are used. The maximum and minimum values of observed water level data at Bahadurabad Station for the year 2021 are 20.13 m and 12.21 m. In year 2021, the lowest monthly discharge of 3631.58 m^3/s is found during March whereas the highest discharge of 47574.6 m^3/s is seen during the month of August. Monthly discharge hydrograph (2021) is shown in Figure 1.

2.3.0 Equations

The Ackers and White equations (1973) have been used to calculate the sediment concentration. Ackers and White described the movement of sediment in terms of three dimensionless groups: (1) Particle Mobility, F_{gr} (2) sediment transport, G_{gr} and (3) dimensionless particle size, $D_{gr.}$ The particle mobility is the ratio of shear forces and immersed weight. For coarse sediments, transport is considered to be a bed process and the particle mobility is expressed in terms of the net grain resistance. A fine sediment is considered to be transported in the main body of the flow where it is suspended by turbulence. As the intensity of the turbulence is dependent on the total energy degradation, for fine sediments the particle mobility is expressed in terms of the total shear stress. The general definition of the particle mobility is –

$$F_{gr} = \frac{V_*^n}{\sqrt{gD(s-1)}} \left(\frac{V}{\sqrt{32 \log\left(\frac{10d}{D}\right)}} \right)^{1-n} \quad (1))$$

For coarse sediments, n = 0, while for fine sediments, n = 1. For intermediate or transitional sizes of sediment, n may take a value between 0 and 1 depending on the value of D_{gr}.
Fine and coarse material are defined in terms of D_{gr} (Dimensionless Particle Size) in which

$$D_{gr} = D \left[\frac{g(s-1)}{\nu^2} \right]^{1/3} \quad (2)$$

where g is acceleration due to gravity, s is specific gravity of the sediment, v is the kinematic viscosity and D is the sediment diameter. The right-hand term involves the cube root of the ratio of immersed weight to viscous forces. An extensive analysis of flume data led to the definition of $D_{gr} > 60$ for coarse sediments and $D_{gr} < 1$ for fine sediments. Sizes transitional between these two can exhibit both fine and coarse sediment behavior.

The expression for sediment transport is based on the stream power concept. By combining the efficiency of transport with the mobility number, a transport parameter is defined as

$$G_{gr} = \frac{Xd}{sD} \left(\frac{V_*}{V} \right)^n \quad (3)$$

$$G_{gr} = C \left(\frac{F_{gr}}{A} - 1 \right)^m \quad (4)$$

A general transport equation is then obtained in the formmin which C and m are coefficients depending on D_{gr} and A = the initial motion parameter, that is, the value of F_{gr}, at the threshold of movement. The coefficients are determined from best-fit curves of about 1000 sets of laboratory data with sediment size greater than 0.04 mm and Froude number less than 0.8.

Values of these coefficients are considered For application in the Jamuna river reach, the calculated values of coefficients from Table 3.1 for Jamuna river are C = 0.02298, n = 0.419, A = 0.209, and m = 2.225 In Eq. (3.), X is the total sediment concentration by weight and it is expressed in ppm by multiplying the calculated value with 10^6.

White-Bettess-Paris Resistance Equation**:** By utilizing the same basic parameters as in the Ackers and White sediment transport theory, White, Bettess and Paris,(1980) found that a linear relationship between mobilities related to the total shear stress, F_{fg}, in which

$$F_{fg} = \frac{V_*}{\sqrt{gD(s-1)}} \quad (5)$$

and the mobility, related to the effective shear stress, F_{gr}, existed with coefficients depending on D_{gr}. An extensive correlation exercise for a wide range of sediment sizes (0.04 mm to 10 mm) gave the equation.

$$\frac{F_{gr} - A}{F_{fg} - A} = 1.0 - 0.76\left[1 - \frac{1}{\exp{(\log D_{gr})^{1.7}}}\right] \tag{6}$$

This method has been favorably compared with the traditional methods of Einstein and Barbarossa, Engelund, and Raudkivi showed good agreement with data for sediment sizes in the range of 0.04 mm to 68 mm.

3. ILLUSTRATIONS

3.1 Fluvial Stage-Discharge Rating Curve for Selected Reach of Jamuna River

In order to generate stage-discharge data for each cross-section, the predicted mean velocity equation was utilized. This equation allows for the estimation of discharge based on the water level of the flow. The obtained and computed data was used to predict the discharge and stage-discharge curves were generated accounting temporal variation. Discharge has also been computed using Manning's equation. Figure 2 displays the stage-discharge curves for the upstream station RMJ 13.

3.2 Comparison between White-Bettess-Paris Equation; Ackers-White Formula and Manning's Equation

Manning's equation and the White-Bettess-Paris equation; Ackers-White formula are two commonly used formulas for calculating flow velocity or discharge in open channels. In terms of application, Manning's equation is more commonly used and has a longer history of use in engineering practice. It is widely implemented in hydraulic calculations, such as flood modeling, river flow analysis, and channel design. In Figure 2, stage discharge rating curve for both the methods for the upstream cross-section, RMJ 13, has been illustrated. As in both methods, the graph shows good correlation and follow a very close trend line. It is safe to say that White-Bettess-Paris equation; Ackers-White formula can be used for developing stage-discharge relationship for the study reach.

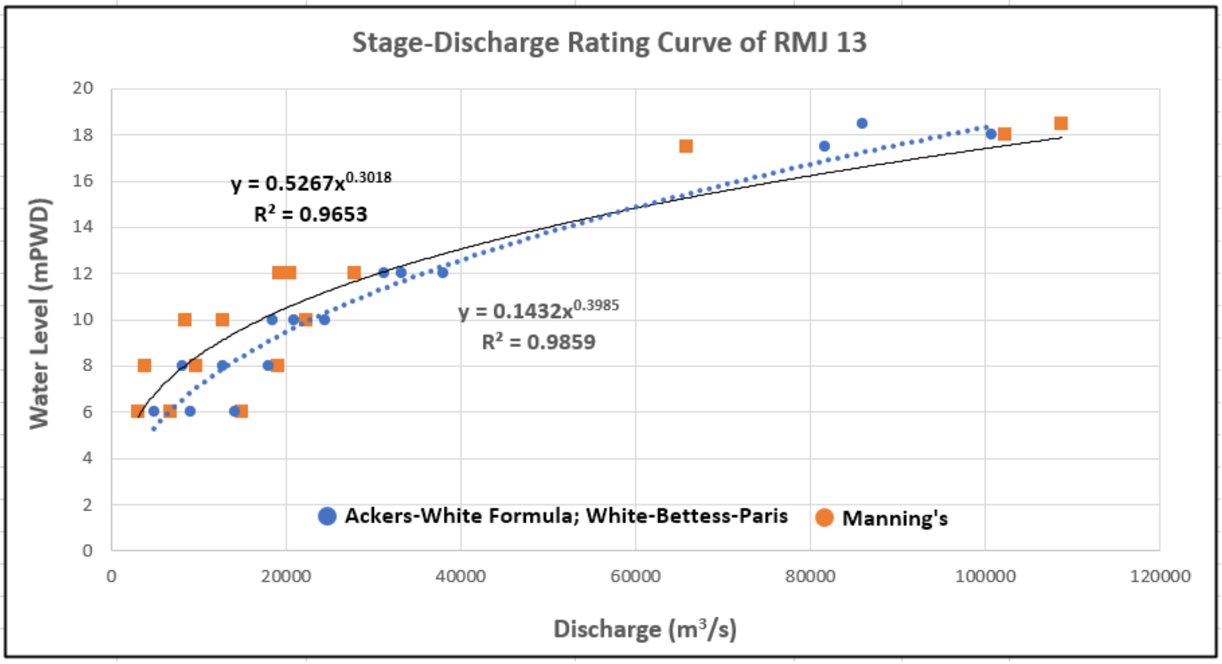

Figure 2: Predicted versus Observed Rating for Various Approaches

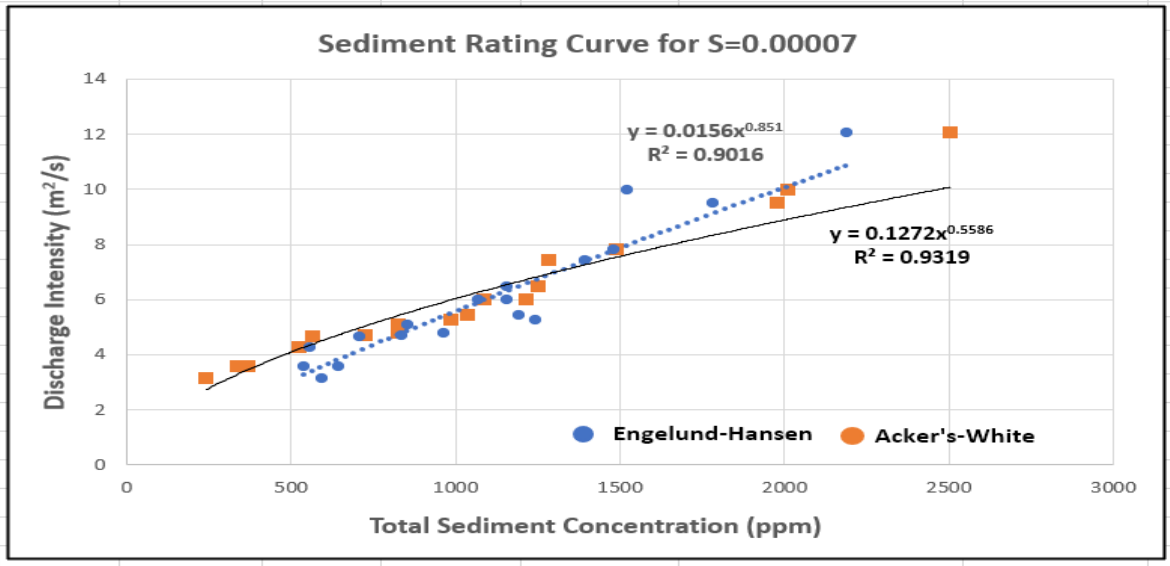

Figure 3: Sediment Rating Curve for from 2018 to 2020

Acker's-White formula and the Engelund-Hansen method are both commonly used in hydraulic engineering to estimate sediment transport in rivers. Acker's-White formula provides reasonably accurate results for practical applications whereas Engelund-Hansen method provides a more refined estimation by considering the critical shear stress and sediment concentration. In Figure 3, sediment rating curve for both the methods for longitudinal slope, S=0.0007, has been illustrated. In both methods, the graph shows great correlation and follow a very similar trend line.

Before utilizing the obtained results, it is important to validate the accuracy of the predicted values by comparing it with observed flow data. To verify the analysis, comparison is done using the available data from Bahadurabad station, located upstream of the study reach.

Figure 4 displays the observed stage-discharge rating curve of Bahadurabad station, along with the computed discharge values for various water levels. The computed values through Ackers-White

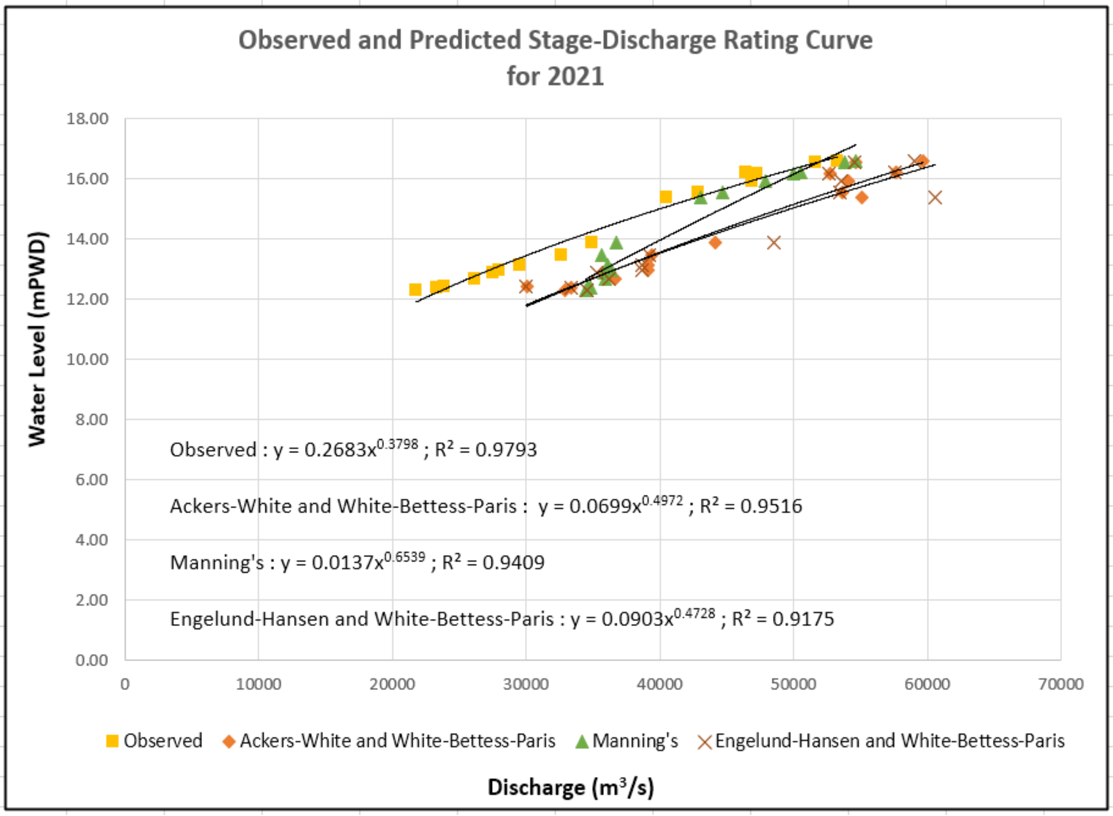

Figure 4: Observed and Predicted Stage-Discharge Rating Curve at RMJ 13

Formula and White-Bettess-Paris equation deviates 2.83% from observed data whereas values from Manning's equation deviates 3.92% and in case of Engelund-Hansen method and White-Bettess-Paris equation, the deviation is around 6.31.% It implies the combination of Ackers-White Formula and White-Bettess-Paris equation predicts discharge values more accurately than the other two methods. Comparison among the observed data and predicted values from all three methods for Bahadurabad Station for the year 2021 shows that the discrepency ratio synthesized approach using the combination of Ackers-White sediment transport and White-Bettess-Paris resistance equation is found to be 1.1 to 1.5.

4. CONCLUSIONS

Synthesized fluvial stage-discharge rating curve has been established based on combined analyses of sediment transport and resistance equation. The analyses reveal that the computed values of flow rating obtained by using the Ackers-White formula and White-Bettess-Paris equation exhibit a strong fit to the graph, with a fitting percentage of 97.17%. Similarly, the values derived from Manning's equation show a fitting percentage of 96.08%. In contrast, the combination of the Englund-Hansen method and White-Bettess-Paris equation demonstrates a slightly lower fitting percentage of 93.69% compared to that of observed data. These findings suggest that the Ackers-White formula and White-Bettess-Paris equation i.e. Approach-(i) provides a more accurate prediction when compared with observed rating values compared to the other methods considered in the study. It is hoped that the procedure can be adopted to obtain Q vs. WL rating values for the similar ungauged cross-sections of Jamuna River.

ACKNOWLEDGEMENTS

Authors gratefully acknowledge the cooperation exerted by hydrology division BWDB for providing the necessary data to carry out this work.

REFERENCES

Abdulaziz A. A. and Matin M.A. (2000). Fluvial Stage-discharge Rating of Wadi Hanifa Main Channel, *Journal of King Saud University, Engineering Sciences*: 12(1); 45-63.

Ackers, P. and White, W.R. (1973). Sediment Transport: A New Approach and Analysis. *Journal of Hydraulic Division, ASCE, 99 No. HY l*, 2041-2060.

Badhan, M.Z, and Matin, M.A. (2018). "Fluvial stage and sediment discharge rating with possible maximum scour depth prediction of a selected reach of the Jamuna River." Proceedings ICCESD-2018, KUET, Bangladesh,

Brownlie, W. R (1983). Flow Depth in Sand Bed Channels. *Journal ofHydraulic Engineering,* ASCE, 109, No. HY7,.959-990

Engelund, F and Hansen, E. (1967). *A Nomo graph on Sediment Transports in alluvial stream, Publication and Sale:* TEKNISK FORLAG, Denmark.

FAP 21, (1994), "River Training studies of the Brahmaputra river", Master Plan Report, Annex 4, Design and Construction, BWDB.

Garde, R.J. and Ranga Raju, K.G. (1966). Resistance Relationships for Alluvial Channel Flow. *Journal Hydraulic Division, ASCE, 92, HY4*, 77-100.

Garde, R.J. and Ranga Raju, K.G.(1980) *Mechanics of sediment transportation of alluvial channel problems,* Wiley Eastern, New Delhi, P. 483.

James, P. Syvitski, Mark D. Morehead, David B. Bahr, and Thierry Mulder, (2000). Estimating fluvial sediment transport: The rating parameters, *Water Resources Research, VOL. 36, NO. 9,* pp. 2747-276,

White, W.R., Paris, E. and Bettess, R. (1980). "The Frictional Characteristics of Alluvial Streams: A New Approach". Proc. ICE, 69, No.1, pp.737-750.

Brownlie, W. R. "Flow Depth in Sand Bed Channels". Journal ofHydraulic Engineering, ASCE, 109, No. HY7, (July, 1983), .959-990,.