

Development and validation of a rating curve for the Ganga River at the Varanasi bend

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ABSTRACT

This research paper focuses on the development and validation of a rating curve for the River Ganga at Varanasi. Traditional methods of measuring gauges and calculating discharge face challenges during floods, necessitating innovative approaches. This study employs acoustic Doppler current profilers (ADCP) and remote measurement techniques, addressing the limitations of conventional methods. The methodology involves a two-step procedure: establishing the stage–discharge relationship and measuring the stage for discharge determination. The results highlight the importance of the proposed rating curve equation as a valuable tool to predict river discharge during flood conditions at the Varanasi bend. Ongoing checks are emphasized due to evolving stream channels, affirming the equation's reliability for practical applications. This study contributes to advancing river discharge estimation techniques, particularly in challenging environments like floods. The proposed rating curve equation proves effective and reliable, showcasing its potential for broader applications in hydrological studies and river management.

Key words: acoustic Doppler current profilers, discharge estimation, rating curve, River Ganga, stage–discharge relationship, Varanasi

HIGHLIGHTS

- Utilizes acoustic Doppler current profilers and remote measurement technologies to overcome limitations of traditional gauge, and discharge measurement methods during floods.
- Develops a stage–discharge relationship and measures the stage to determine discharge, ensuring accurate river flow data even under challenging conditions.
- Provides high-resolution velocity profiles and discharge measurements, improving the precision of flood prediction and hydrological modelling.

INTRODUCTION

The most important basic technique to determine discharge in an open channel flow (like a river) is to measure the gauge followed by the calculation of discharge using an empirically generated gauge discharge rating curve (Abhash *et al.* 2023). This oldest approach has been in practice since 1890 to gauge the Rio Grand at Embudo, New Mexico. The creation of an empirical rating curve for a river involves the joint assessment of gauge and discharge measurements. Flow velocity is directly measured at multiple vertical positions beneath the water surface across various subsections of the channel. The measurements are conducted using either current metres (Rantz 1982) or more modern techniques like acoustic Doppler current profilers (Zhou *et al.* 1994). Discharge for a specific section is determined by summing the products of subsection areas and their corresponding estimated average velocities (Rantz 1982; Naeimi *et al.* 2019). Although this approach is known for its accuracy, it has some limitations. First, direct flow velocity measurements are very difficult or impossible during floods with the help of current metres or ADCPs (Chauhan *et al.* 2014). Second, the development and maintenance of the rating curve of any river is quite expensive and difficult due to the need for very huge skilled manpower (Medisetty *et al.* 2020; Srivastava *et al.* 2023). Third, for measurement convenience and safety, gauge sites are often located at geographically difficult sites, which include bridges, narrow sections suitable for cableways, and wide sections suitable for wading (Ahmadi *et al.* 2020). Due to the characteristics of these sites, they often are vulnerable to erosion and deposition, which requires extra flow

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measurements to define stage-dependent or post-flood shifts to the rating curves (Omar *et al.* 2021). Newly developed techniques for computing velocity and shear stress fields in streams and rivers, particularly for sediment transport and geomorphic applications, offer potential solutions to address certain challenges in the existing methods (Gaur *et al.* 2023). In the last few decades, efforts have been made to improve conventional gauging methods. The improved methods emphasized developing techniques to measure gauge and discharge remotely. The advantage of these techniques is that there is no loss of human life and no damage to measuring instruments.

It is worth noting that surface velocity measurements obtained remotely from the river's edge using Doppler radar have been utilized to estimate discharge at a specific cross-section (Gupta *et al.* 2022a). In this approach, a ground-penetrating radar, suspended from a cableway, is employed for the remote measurement of cross-sectional geometry (Spicer *et al.* 1997; Costa *et al.* 2000; Cheng *et al.* 2004; Chauhan *et al.* 2013). However, this method involves expensive equipment and is particularly well-suited for measuring discharge in channels with unstable beds. Another alternative involves surface velocities measured remotely through video cameras and particle image velocimetry algorithms, which have been successfully employed for discharge determination (Bradley *et al.* 2002; Creutin *et al.* 2003). The advantage of this technique lies in its relative cost-effectiveness and portability. Nevertheless, it requires clearly identifiable tracers in the flow. If such tracers are not naturally present in the form of foam or floating debris, they must be introduced artificially (Shekhar *et al.* 2021). Additionally, similar to the Doppler radar method, the determination of cross-sectional geometry must be conducted independently. It is widely recognized that currently available streamflow routing packages, such as Hydrologic Engineering Center-River Analysis System (HEC-RAS) (U.S. Army Corps of Engineers 2002; User's manual 'HEC-RAS' 2010), may not be suitable for achieving the goal of extending or developing a rating curve at a site under the mentioned circumstances. This limitation arises from their demanding requirements for detailed channel cross-section information and roughness data at close intervals. However, approximate flood routing techniques could prove more effective for this purpose, given their ability to handle sparse spatial details (Chauhan *et al.* 2015). Considering that the rating curve sites seeking extension or development are typically situated on mainstems, the chosen approximate routing technique should also be capable of routing flows in compound channels, which include both a main channel and an adjoining floodplain channel (Gupta *et al.* 2022b). This type of investigation requires a deep knowledge of the work related to the topic of concern.

The main aim of this study is to measure the flow properties of the Ganga River at Varanasi bend using the latest technology (ADCP) and to generate the rating curve for the Ganga River with the measured flow properties of the river. For this, 14 cross-sections of the Ganga from Ramnagar (upstream) to Rajghat (downstream) have been identified and prepared.

This research focuses on addressing the limitations of traditional gauge-discharge measurement methods during flood conditions, particularly at the Varanasi bend of the River Ganga. By incorporating ADCP and innovative remote-sensing techniques, this study establishes a robust stage-discharge relationship tailored to dynamic and challenging environments. Unlike the existing literature, which often struggles with evolving stream channels and extreme hydrological events, this work proposes and validates a novel rating curve equation, providing a reliable tool for real-time discharge prediction. The study's emphasis on continuous monitoring and adaptability ensures practical utility for river management and hydrological modelling.

Study area

The study area, Varanasi (25° 20' N and 83° 07' E), is situated in the middle Ganga valley of North India, specifically in the eastern part of the state of Uttar Pradesh. The left crescent-shaped bank of the Ganga at Varanasi spans an average elevation between 50 feet (15 m) and 70 feet (21 m) above the river (Mohanty 1993). Varanasi is renowned as the oldest city located on the convex bank of the holy River Ganga, considered the longest river in India with a total length of 2,525 km from Gangotri to Ganga Sagar. The 'Varanasi Urban Agglomeration' comprising seven urban sub-units covers an area of 112.26 km². Being positioned in the Indo-Gangetic Plains of North India, the region benefits from fertile land due to regular low-level floods in the Ganga, which continually replenish the soil (Singh *et al.* 2023). Varanasi is often described as being located between two confluences: one of the Ganga and Varuna and the other of the Ganga and Assi. However, it's important to note that the latter is more accurately characterized as a rivulet rather than a full-fledged river. The distance between these two confluences is approximately 4.0 km. A notable religious practice for Hindus is the Pancha-kroshi Yatra, a round trip covering 8.3 km between these two places, culminating in a visit to a Sakshi Vinayak Temple, considered a sacred ritual.

The climate in Varanasi, reflective of Northern India in general, is tropical in nature, featuring extremes of temperature. Winter temperatures can drop to a minimum of 3 °C, while summer temperatures can soar to a maximum of 47 °C. The

annual rainfall in the region ranges from 680 to 1,500 mm, with a significant portion occurring during the monsoon season, typically spanning from July to September.

The city's topography is predominantly flat with a gentle slope towards the River Ganga. Varanasi is situated on the northern bank of the river, characterized by an elevated terrain that prevents flooding in most areas. The region is part of the Indo-Gangetic Plain, with an altitude ranging from 70 to 80 m above sea level. Notable features include natural levees and riverine terraces, contributing to its unique landscape. The topography supports urban development and agriculture while influencing drainage patterns and water resource management. Varanasi primarily features alluvial soil, formed by the deposition of sediments from the River Ganga and its tributaries. The soil is fertile, with a high concentration of clay, silt, and fine sand, making it suitable for agriculture. The pH levels range from neutral to slightly alkaline, with moderate organic content. The soil exhibits good water retention but can be prone to waterlogging in low-lying areas.

The present research work is done in an arc-type shape, which is shown in Figure 1. The length of the arc is about 7.5 km and the average radius of curvature is about 4.672 km and the arc angle is about 91.71° for the main Varanasi region from the Pontoon Bridge of Ramnagar to about 200 m downstream from the Rajghat Bridge. The total number of cross-sections is 14, as shown in Figure 2, at each cross-section latitude, and longitude are listed in Table 1.

METHODOLOGY FOR THE DEVELOPMENT OF RATING CURVE

In this study, a rating curve is developed for the river gauge at the M-1 cross-section with the help of data collected from November 2012 to March 2013, which is obtained with the help of ADCP and is validated with the help of the remaining 28 days of data taken during the same time of cross-section investigation. For the generation of the rating curve for the river gauge, the M-1 profile is selected as a suitable cross-section. It is located downstream at Rajghat Bridge, Varanasi (India).

As previously discussed, the direct method of measuring discharge entails a two-step process. The initial step of paramount significance involves establishing the stage–discharge relationship (G – Q). Once this relationship is determined, the subsequent step is to measure the stage (G) in order to obtain the corresponding discharge (Q) using the established (G – Q) relationship. The latter part of this process is considered a routine operation. Ultimately, the objective of all direct-discharge measurements, including those with current meters, is to establish a stage–discharge relationship for the specific channel

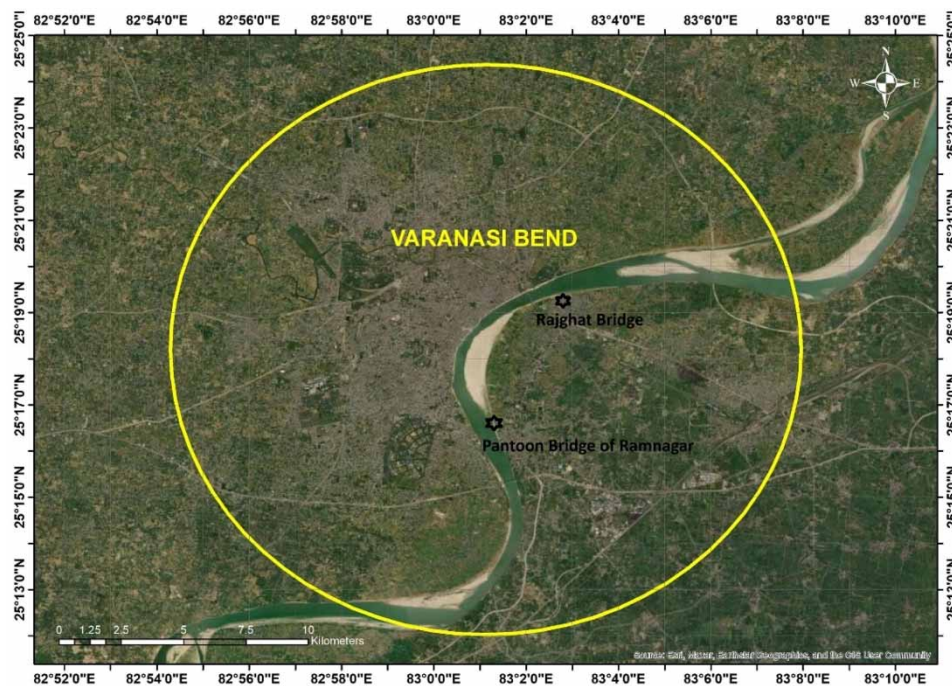


Figure 1 | Location of the study area.

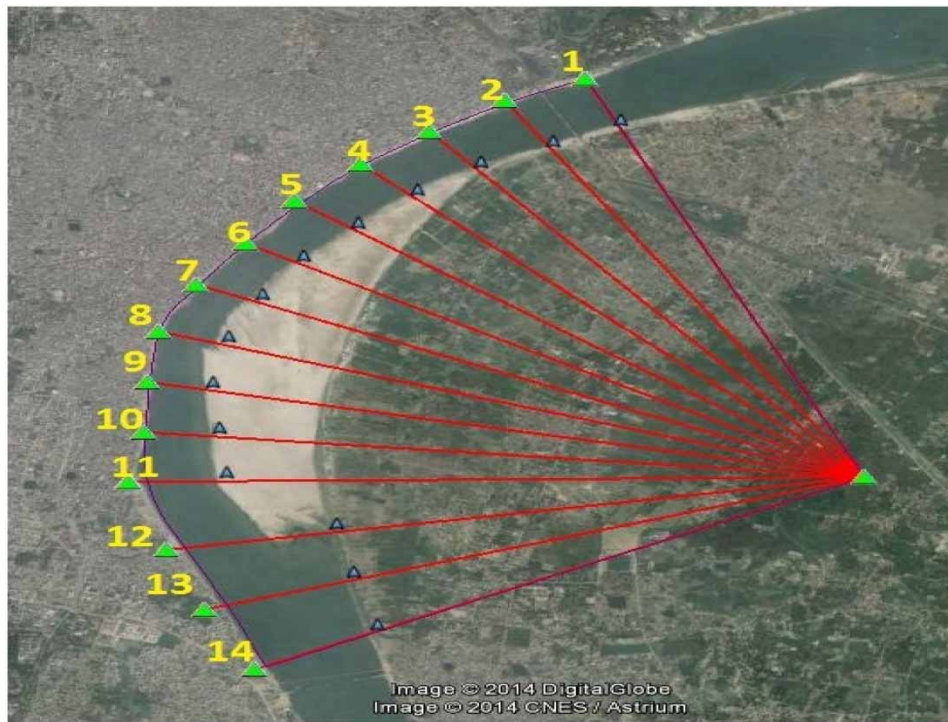


Figure 2 | Showing all 14 cross-sections on the River Ganga.

Table 1 | Location of each cross-section with coordinates

S. No.	N-reading (Concave Bank)	E-reading (Concave Bank)	N-reading (Convex Bank)	E-reading (Convex Bank)
1	25° 19.530'	83° 02.175'	25° 19.285'	83° 02.302'
2	25° 19.410'	83° 01.849'	25° 19.147'	83° 02.042'
3	25° 19.243'	83° 01.552'	25° 19.0203'	83° 01.76'
4	25° 19.065'	83° 01.284'	25° 18.878'	83° 01.50'
5	25° 18.868'	83° 01.021'	25° 18.7123'	83° 01.263'
6	25° 18.640'	83° 00.828'	25° 18.532'	83° 01.042'
7	25° 18.420'	83° 00.631'	25° 18.336'	83° 0.847'
8	25° 18.166'	83° 00.486'	25° 18.0944'	83° 0.750'
9	25° 17.896'	83° 00.437'	25° 17.8415'	83° 0.744'
10	25° 17.627'	83° 00.424'	25° 17.598'	83° 0.769'
11	25° 17.361'	83° 00.662'	25° 17.365'	83° 0.769'
12	25° 17.024'	83° 00.572'	25° 17.054'	83° 0.936'
13	25° 16.696'	83° 00.731'	25° 16.808	83° 01.164'
14	25° 16.367'	83° 00.899'	25° 16.546'	83° 01.313'

gauging section. This relationship, commonly known as the rating curve, is crucial for hydrological analysis. The plotted values of measured discharge against the corresponding stage provide a representation that integrates the influence of various channels and flow parameters. This integrated effect is termed 'control.' If the ($G-Q$) relationship for a gauging section remains constant and does not undergo changes over time, it is described as having permanent control. However, if the relationship changes with time, it is referred to as shifting control.

Stage–discharge relationship: permanent control

The majority of streams and rivers, particularly those that are non-alluvial, typically exhibit a condition known as permanent control. In such instances, the correlation between the stage and discharge is characterized by a singular and constant relationship, expressed as a single-valued function (Subramanya 2017).

$$Q = C_r(G - a)^\beta \quad (1)$$

where Q is the stream discharge, G is the gauge height (stage), a is the constant which represents the gauge reading corresponding to zero discharge, and C_r and β are the rating curve constants.

This relationship can be expressed graphically by plotting the observed relative stage ($G - a$) against the corresponding discharge values in an arithmetic (Figure 3) or logarithmic plot (Figure 4). Logarithmic plotting is advantageous as Equation (1) plots a straight line in logarithmic coordinates.

In plots (arithmetic or logarithmic), discharge is plotted in the abscissa, and gauge height or stage is plotted, as the ordinate. Discharge measurements are numbered sequentially in chronological order to facilitate the identification of time trends. Significant exercise is done based on various factors such as knowledge of the river and the quality and magnitude of each measurement to consider the best curve.

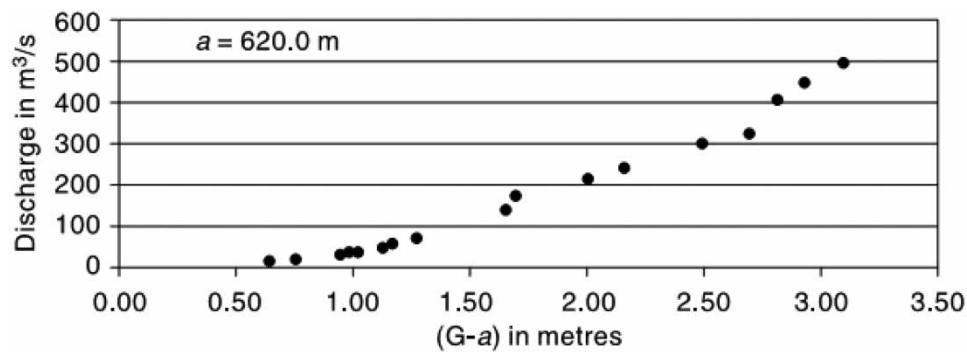


Figure 3 | Graphical representation (arithmetic plot) of the relationship between discharge and gauge height (After Subramanya 2009).

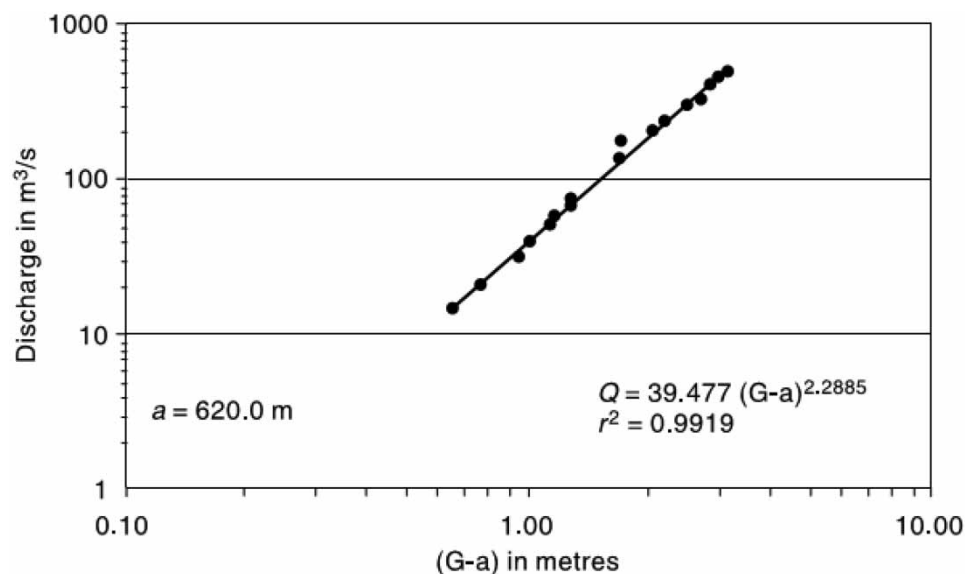


Figure 4 | A logarithmic plot between discharge and gauge height (after Subramanya 2009).

In Figure 4, a straight line is drawn to effectively depict the data plotted in the form of Q vs. $(G - a)$. It is not necessary for the coefficients C_r and β to remain constant across the entire range of stages. The optimal values of C_r and β in Equation (1) within a specific stage range are determined using the least-square-error method. This involves taking logarithms of Equation (1) to obtain the most accurate representation.

$$\text{Log } Q = \beta \log (G - a) + \log C_r \quad (2)$$

$$\text{Or } Y = \beta X + b$$

where dependent variable Y ; $Y = \log Q$; independent variable X ; $X = \log (G - a)$; and $b = \log C_r$.

For the best-fit line of N observations of X and Y , by regression.

$$r = \frac{N(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[N(\sum X^2) - (\sum X)^2][N(\sum Y^2) - (\sum Y)^2]}}$$

$$\beta = \frac{N(\sum XY) - (\sum X)(\sum Y)}{N(\sum X^2) - (\sum X)^2}$$

$$b = \frac{\sum Y - \beta(\sum X)}{N}$$

In this context, the variable ' r ' indicates the degree of linearity between the two sets of data. A perfect correlation is denoted by ' $r = 1.0$.' A correlation between 0.6 and 1.0 is generally considered good. It is important to highlight that, in the current scenario, where discharge Q increases with $(G - a)$, the variables Y and X are positively correlated, resulting in a positive value for ' r '.

Calculation of stage for zero discharge (theoretically)

In Equation (1), the constant ' a ' signifies the stage (gauge height) for zero discharge in the stream. The zero discharge constant in a stage–discharge curve adjusts the stage (water level) measurement to account for the point where the discharge (flow) is zero. This correction is necessary because river gauges may not measure directly from the riverbed or because some flow may exist even at low water levels. By applying this constant, the stage – discharge relationship aligns with the true starting point of zero flow, improving the curve's accuracy. This parameter is hypothetical and cannot be directly measured in the field, introducing certain challenges in its determination. Several alternative methods exist for estimating ' a ':

1. Create a plot of Q vs. G on arithmetic graph paper and draw a best-fit curve. Extrapolate the curve visually to identify ' a ' as the G value corresponding to $Q = 0$. Using this value of ' a ', generate a plot of $\log Q$ vs. $\log (G - a)$ and assess whether the data form a straight line. If not, select another value in the vicinity of the initially assumed value and iteratively determine an acceptable ' a ' value that results in a linear plot of $\log Q$ vs. $\log (G - a)$.
2. A graphical method in which the Q vs. G data is plotted to an arithmetic scale and a smooth curve through the plotted points is drawn (Wisler & Brater 1959). Three points A, B, and C are selected on the curve in such a way that their discharges are in geometric progression (Figure 5), i.e.

$$\frac{Q_A}{Q_B} = \frac{Q_B}{Q_C}$$

At points A and B, vertical lines are established, followed by the drawing of horizontal lines at points B and C, resulting in the intersection of points D and E with the vertical lines. Connecting these points, two straight lines, ED and BA, are formed, intersecting at point F. The ordinate at F represents the desired value of ' a ', the gauge height corresponding to zero discharge. This technique assumes the lower section of the stage – discharge curve to take the form of a parabola.

3. Alternatively, plot Q vs. G on an arithmetic scale and sketch a well-fitted curve based on visual judgement. Choose three discharge values, Q_1 , Q_2 , and Q_3 , such that the ratio Q_1/Q_2 is equal to Q_2/Q_3 . Record the corresponding gauge readings,

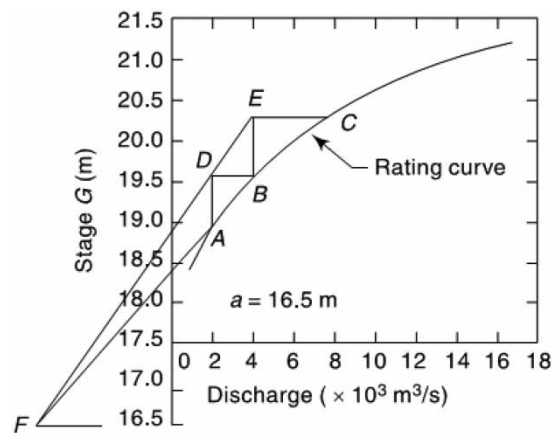


Figure 5 | Graphical method for estimating the zero discharge constant 'a' (after Subramanya 2009).

G_1 , G_2 , and G_3 , from the curve. Subsequently, refer to Equation (1) for further analysis.

$$(G_1 - a)/(G_2 - a) = (G_2 - a)/(G_3 - a)$$

i.e.

$$a = \frac{G_1 G_3 - G_2^2}{(G_1 + G_3) - 2G_2}$$

- Several optimization methods can be employed to determine the optimal value of 'a.' One such approach involves a trial-and-error search for 'a' that results in the highest correlation coefficient value.

FIELD MEASUREMENT

For the development of the rating curve of the River Ganga at the M-1 cross-section, the continuous measurement of the cross-section is done with the help of ADCP and auto level from November 2012 to March 2013. The water level at the cross-section was measured thrice a day, i.e. at 8.00 A.M., 01.00 P.M., and 6.00 P.M., with the help of an auto-level continuously. For the development of the rating curve, the gauge data have been taken as the average of the readings taken in the whole day for improvement of the rating curve equation. Another measurement for the discharge data ADCP was used at the cross-section M-1. For the measurement of discharge at the cross-section, the whole cross-section is marked with the help of a total station at both ends of the river. After the marking of the points at both ends, a motorboat at which the ADCP was mounted with the recording laptop connected with the ADCP was used for the measurement of discharge, and this process was repeated for the measurement of discharge at the M-1 section of the River Ganga. The calculation of 'a' (gauge height at zero discharge theoretically) is done with the help of the method discussed in step 3 in the section of calculation of stage for zero discharge (theoretically) (Subramanya 2009).

RATING CURVE DEVELOPMENT

A total of 86 discharge data points were collected over a period of 5 months, spanning from November 2012 to March 2013. Out of these 86 data points, 58 (constituting 67% of the total) were utilized in establishing the rating curve for the River Ganga at the M-1 cross-section. The remaining 28 data points (33% of the total) were reserved for validating the generated rating curve equation. The resulting rating curve equation, derived from the discharge and gauge data at cross-section M-1, is presented in Figures 6 and 7, representing the arithmetic and logarithmic scales, respectively. The X-axis denotes gauge height, while the Y-axis represents discharge measurements (Subramanya 2009). The developed rating curve equation in the

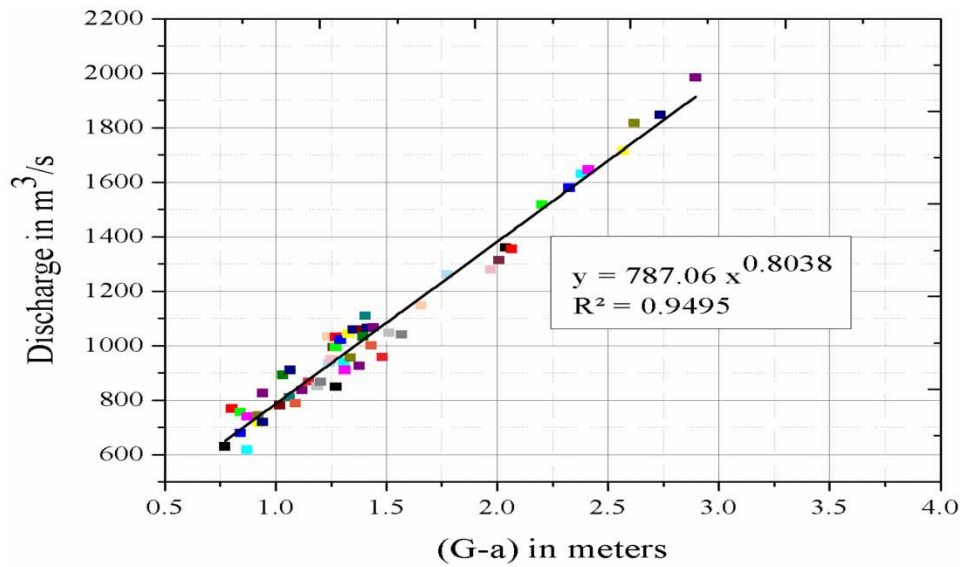


Figure 6 | Arithmetic representation of the rating curve for the River Ganga at the M-1 cross-section.

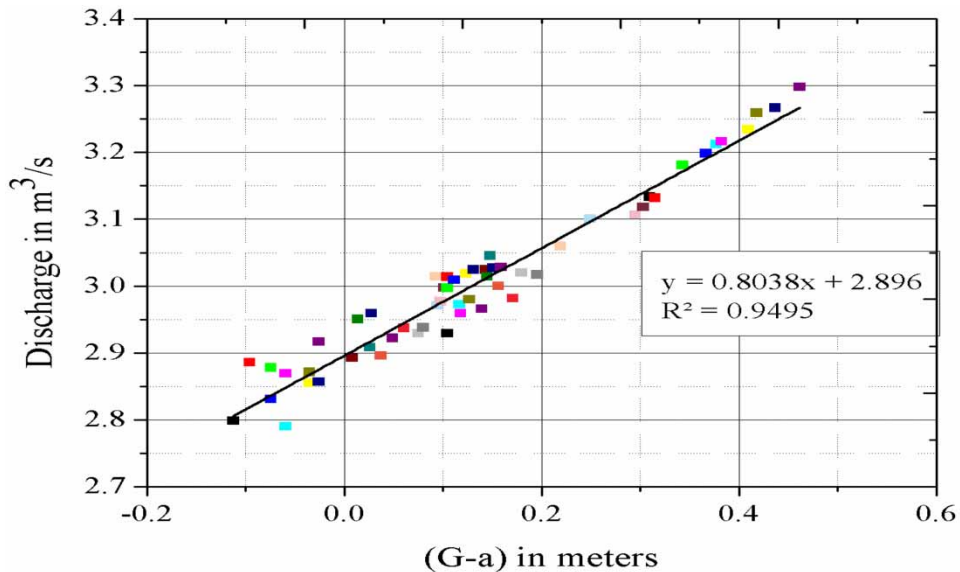


Figure 7 | Logarithmic depiction of the rating curve for the River Ganga at the M-1 cross-section.

arithmetic scale is depicted as follows.

$$Y = 787.06X^{0.8038}$$

where Y represents the discharge; X represents the $(G - a)$ in m; and R^2 value for the rating curve is 0.9495.

VALIDATION OF RATING CURVE EQUATION

The validation of the rating curve was generated for the River Ganga with the help of the remaining 28 data of discharge and gauge height, respectively. These data are randomly selected from the complete data of 86 days from the measurement of 5 months, from November 2012 to March 2013. The percentage error obtained from the equation is a maximum of 11.74% and

Table 2 | Data used for the rating curve development

S. No.	Average Water level (G)	Average Discharge (Q)	G-59.54	Log (G - a) = X	Log Q = Y	XY	X2	Y2
1	60.32	629.26	0.77	-0.11	2.80	-0.31	0.01	7.83
2	60.35	768.66	0.80	-0.10	2.89	-0.28	0.01	8.33
3	60.39	755.35	0.84	-0.07	2.88	-0.22	0.01	8.28
4	60.39	678.03	0.84	-0.07	2.83	-0.21	0.01	8.02
5	60.42	616.68	0.87	-0.06	2.79	-0.17	0.00	7.78
6	60.42	740.24	0.87	-0.06	2.87	-0.17	0.00	8.23
7	60.47	716.64	0.92	-0.04	2.86	-0.10	0.00	8.15
8	60.47	743.90	0.92	-0.04	2.87	-0.10	0.00	8.25
9	60.49	719.30	0.94	-0.03	2.86	-0.07	0.00	8.16
10	60.49	825.33	0.94	-0.03	2.92	-0.08	0.00	8.51
11	60.57	780.82	1.02	0.01	2.89	0.02	0.00	8.37
12	60.58	892.45	1.03	0.01	2.95	0.04	0.00	8.71
13	60.61	810.23	1.06	0.03	2.91	0.08	0.00	8.46
14	60.61	909.97	1.07	0.03	2.96	0.08	0.00	8.76
15	60.64	787.46	1.09	0.04	2.90	0.11	0.00	8.39
16	60.67	836.04	1.12	0.05	2.92	0.14	0.00	8.54
17	60.7	865.65	1.15	0.06	2.94	0.18	0.00	8.63
18	60.72	838.75	1.17	0.07	2.92	0.20	0.00	8.55
19	60.74	850.35	1.19	0.08	2.93	0.22	0.01	8.58
20	60.75	867.25	1.20	0.08	2.94	0.23	0.01	8.63
21	60.79	1,032.85	1.24	0.09	3.01	0.28	0.01	9.08
22	60.79	935.76	1.24	0.09	2.97	0.28	0.01	8.83
23	60.8	948.77	1.25	0.10	2.98	0.29	0.01	8.86
24	60.81	993.99	1.26	0.10	3.00	0.30	0.01	8.98
25	60.82	849.44	1.27	0.10	2.93	0.31	0.01	8.58
26	60.82	1,031.89	1.27	0.10	3.01	0.31	0.01	9.08
27	60.82	993.50	1.27	0.10	3.00	0.31	0.01	8.98
28	60.84	1,021.02	1.29	0.11	3.01	0.33	0.01	9.05
29	60.86	938.85	1.31	0.12	2.97	0.35	0.01	8.84
30	60.86	910.33	1.31	0.12	2.96	0.35	0.01	8.76
31	60.88	1,043.77	1.33	0.12	3.02	0.37	0.02	9.11
32	60.89	955.34	1.34	0.13	2.98	0.38	0.02	8.88
33	60.9	1,058.40	1.35	0.13	3.02	0.40	0.02	9.15
34	60.93	924.91	1.38	0.14	2.97	0.41	0.02	8.80
35	60.94	1,058.57	1.39	0.14	3.02	0.43	0.02	9.15
36	60.94	1,033.23	1.40	0.14	3.01	0.44	0.02	9.09
37	60.95	1,110.38	1.41	0.15	3.05	0.45	0.02	9.27
38	60.96	1,064.93	1.42	0.15	3.03	0.46	0.02	9.16
39	60.98	1,000.25	1.43	0.16	3.00	0.47	0.02	9.00
40	60.99	1,067.67	1.44	0.16	3.03	0.48	0.03	9.17
41	61.03	958.40	1.48	0.17	2.98	0.51	0.03	8.89
42	61.03	1,031.34	1.48	0.17	3.01	0.51	0.03	9.08

(Continued.)

Table 2 | Continued

S. No.	Average Water level (G)	Average Discharge (Q)	G-59.54	Log (G - a) = X	Log Q = Y	XY	X ²	Y ²
43	61.06	1,046.80	1.51	0.18	3.02	0.54	0.03	9.12
44	61.12	1,039.90	1.57	0.20	3.02	0.59	0.04	9.10
45	61.2	1,147.32	1.66	0.22	3.06	0.67	0.05	9.36
46	61.32	1,261.48	1.78	0.25	3.10	0.77	0.06	9.62
47	61.52	1,278.69	1.97	0.29	3.11	0.92	0.09	9.65
48	61.56	1,313.20	2.01	0.30	3.12	0.94	0.09	9.72
49	61.59	1,360.31	2.04	0.31	3.13	0.97	0.10	9.82
50	61.61	1,355.08	2.07	0.32	3.13	0.99	0.10	9.81
51	61.75	1,517.96	2.20	0.34	3.18	1.09	0.12	10.12
52	61.87	1,579.84	2.33	0.37	3.20	1.17	0.13	10.23
53	61.93	1,630.69	2.38	0.38	3.21	1.21	0.14	10.32
54	61.96	1,645.77	2.41	0.38	3.22	1.23	0.15	10.35
55	62.12	1,714.94	2.57	0.41	3.23	1.33	0.17	10.46
56	62.17	1,817.41	2.62	0.42	3.26	1.36	0.17	10.62
57	62.28	1,847.76	2.74	0.44	3.27	1.43	0.19	10.67
58	62.44	1,984.64	2.90	0.46	3.30	1.52	0.21	10.87

a minimum of 0.0351%, as shown in Table 3. It is observed that only about 10% error is obtained in the development of the rating curve. Although the entire data collection work is done by electronic measurements, the cross-section of such a large river is very complex and irregular and accurate measurement of this cross-section is a challenge. Hence, this error of 10% is acceptable.

RESULTS AND DISCUSSION

The development of the rating curve for the Ganga River at the Varanasi bend aims to illustrate the correlation between stage and discharge at the M-1 cross-section. Rating curves typically exhibit a breakpoint, often occurring at the stage where the river overflows its banks or at a lower stage if there is a significant alteration in the riverbed cross-section. Beyond this stage, the river's rise is less rapid, assuming other factors remain constant. Continuous measurement of the river's discharge is impractical. However, the discharge can be determined by applying the stage-discharge relation, commonly known as the rating. These relations are established for stream gauges by physically measuring the river's flow using a mechanical current metre or an ADCP at various stages. Each discharge measurement corresponds to a stage measurement, as illustrated in Tables 2 and 3. Additionally, these relations require constant scrutiny against ongoing discharge measurements due to the dynamic nature of stream channels. Changes in stream channels, such as erosion, deposition of streambed materials, seasonal vegetation growth, debris, or ice, can impact these relations. New discharge measurements plotted on an existing stage-discharge relation graph help identify these changes, allowing adjustments to the rating for accurate discharge estimation at measured stages.

1. The rating curve equation is developed from the measured discharge and gauge data of the river at cross-section M-1 by ADCP, where gauge height is taken at the X-axis and the discharge measurement is taken at the Y-axis, respectively. The developed rating curve equation is given in the following:

$$Y = 787.06X^{0.8038}$$

where Y represents the discharge and X represents the (G - a) in m.

2. The developed equation is validated for the measured data of 28 days, and the result is given in Table 2. Table 3 indicates that the discharge values derived from the rating curve equation align closely with the measured discharge data,

Table 3 | Validation of the rating curve through a dataset of 28 days during 5 months, i.e. from November 2012 to March 2013

S. No.	Average water level (G)	Average discharge (Q)	G-59.54	$x^{0.8038}$	$787.06 \times x^{0.8038}$	$(Q_1 - Q_2)/Q_1$	% error
1	60.38	733.77	0.84	0.87	681.08	0.07	7.18
2	60.40	650.56	0.85	0.88	691.98	-0.06	-6.37
3	60.46	672.61	0.91	0.93	730.89	-0.09	-8.67
4	60.48	821.90	0.93	0.95	743.75	0.10	9.51
5	60.53	878.73	0.98	0.99	775.65	0.12	11.73
6	60.58	888.23	1.03	1.03	807.24	0.09	9.12
7	60.61	921.22	1.07	1.05	828.13	0.10	10.10
8	60.69	992.20	1.14	1.11	875.71	0.12	11.74
9	60.72	948.70	1.17	1.14	894.15	0.06	5.75
10	60.77	971.62	1.22	1.17	924.69	0.05	4.83
11	60.80	945.54	1.25	1.20	942.89	0.00	0.28
12	60.82	968.93	1.27	1.21	954.98	0.01	1.44
13	60.82	963.72	1.27	1.21	954.98	0.01	0.91
14	60.84	978.98	1.29	1.23	967.03	0.01	1.22
15	60.87	934.57	1.32	1.25	985.04	-0.05	-5.40
16	60.89	925.69	1.34	1.27	997.00	-0.08	-7.70
17	60.93	1,024.99	1.38	1.30	1,020.82	0.00	0.41
18	60.95	999.39	1.40	1.31	1,030.70	-0.03	-3.13
19	60.98	975.46	1.43	1.33	1,050.40	-0.08	-7.68
20	61.02	1,012.19	1.47	1.36	1,071.97	-0.06	-5.91
21	61.04	1,111.65	1.50	1.38	1,087.58	0.02	2.17
22	61.16	1,118.29	1.61	1.47	1,155.28	-0.03	-3.31
23	61.38	1,278.98	1.83	1.62	1,278.53	0.00	0.04
24	61.57	1,363.17	2.02	1.76	1,386.10	-0.02	-1.68
25	61.67	1,387.29	2.12	1.83	1,440.94	-0.04	-3.87
26	61.92	1,637.83	2.37	2.00	1,574.11	0.04	3.89
27	62.02	1,680.07	2.47	2.07	1,628.01	0.03	3.10
28	62.24	1,843.45	2.69	2.21	1,742.89	0.05	5.46

showcasing a maximum error within the acceptable range of $\pm 10\%$. This level of deviation falls within the acceptable limits for the equation, particularly considering the inherent challenges in accurately measuring discharge during flood conditions in the Ganga River at Varanasi.

3. The suggested rating curve equation proves beneficial for estimating the discharge of the Ganga River at Varanasi, particularly in flood conditions. In such scenarios, with the gauge height obtained, the proposed equation enables an effective estimation of the river's discharge.

CONCLUSION

The research undertaken to develop and validate a rating curve for the River Ganga at the Varanasi bend, specifically at the M-1 cross-section, has yielded valuable insights into discharge estimation in an open channel flow. The study emphasized the importance of accurate and reliable discharge measurements, acknowledging the challenges associated with traditional methods, especially during flood conditions.

The adoption of advanced techniques, such as the use of ADCP, provided a more robust and remote approach to gauge and discharge measurements. The developed rating curve equation has shown significant promise in accurately estimating river

discharge based on gauge height. The validation process, conducted with a set of 28 randomly selected data points, demonstrated the reliability of the proposed rating curve equation, with percentage errors within an acceptable range of $\pm 10\%$. This is particularly noteworthy given the inherent challenges in measuring discharge during flood conditions, where traditional methods often fall short. The research contributes to the field by presenting a practical and efficient method for estimating river discharge, especially in challenging environments such as the Varanasi bend of the River Ganga. The utilization of modern measurement technologies and the development of a reliable rating curve not only provide a valuable tool for researchers and hydrologists but also offer a means to enhance our understanding of river behaviour and improve flood prediction capabilities.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The authors followed the ethical guidelines and no ethical approval was required and all the authors agreed to participate.

CONSENT FOR PUBLICATION

All authors are agreeing to publish the content.

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AUTHORS' CONTRIBUTIONS

M.S.C., P.K.S.D., and S.B.D. conceptualized the study and developed the methodology; M.S.C and P.J.O rendered support in formal analysis;; M.S.C, P.J.O. investigated the work; M.S.C. and P.J.O. wrote the original draft preparation; M.S.C., P.J.O., P.K.S.D., and S.B.D. wrote, reviewed, and edited the whole article.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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