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Stage-discharge rating curve of Gomati River (alluvial plain tributary of ganga river) at Chandwak, northern India

Abstract

In the northern part of India, the 900-km long Gomati River drains the central Ganga Alluvial Plain and transports its water and sediments to the Ganga River, one of the world's largest fluvial system. The basin experiences a humid, sub-tropical climate characterised with the monsoon season of heavy precipitation. In the distal part of the river basin, hydrological data were collected from Maighat gauging station located at Chandwak for the present stage-discharge relationship study. With increasing fresh water demands from the ever growing human population in the Ganga Alluvial Plain, the Gomati River Basin has been facing acute crises of water resources and environmental degradation. Thus, the primary aim of the present study is (1) to analyse the stage-discharge relationship of the Gomati River, to detect its seasonal characteristics and (2) to elucidate the reliable stage-discharge rating curve for water resource management and environmental conservation.

Findings of the present study indicated that the stage-discharge relationship displayed better correlation coefficient during the summer (R^2=0.9881, N = 23) and the post-monsoon (R^2=0.9166, N = 18) seasons than the winter (R^2=0.8907, N = 27) and the monsoon (R^2=0.8925, N = 36) seasons. The seasonal stage-discharge rating curves are discussed with particular reference to predict the accurate discharge variability for the low-gradient single-channel alluvial river. Based on detailed analysis and goodness-of-fit criteria, the linear stage-discharge rating curve was found to be the best for the Gomati River, and demonstrates good predictive accuracy (R^2=0.9712, n = 66) with discharge condition of <250 m^3/s. The application of results has a great importance due to practicality in water resource management in the densely populated and the highly agricultured alluvial plain of the Gomati River Basin. This is for the first time that the present hydrological rating curve study, based on the real time-series data, has been conducted so far. It is necessary to advance our understanding of the stage-discharge relationship in future studies under the climate change scenario.

Keywords: Gomati river, rating curve analysis, Maighat, monsoon season, alluvial river, ganga plain

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Abbreviations: GRB, Gomati River basin

Introduction

Rivers are essential geomorphic features of our planet's habitability and have the immense significance in the development of humanity. Rivers, most importantly, provide freshwater resources for drinking and to sustain agriculture, which are pre-requisites for human survival and well-being.[1] This human nearness with rivers is established a unique association as a threat via high flood flows and as water scarcity through low flows. More than 90 % of the world population lives in northern hemisphere and mostly in the Southern Asian region. The Ganga Alluvial Plain is one of the most densely populated regions of the world; where low-gradient rivers are vulnerable to annual flooding due to heavy precipitation by the SW monsoon system. The Gomati River, a tributary of the Ganga River, drains the middle part of the Ganga Alluvial Plain in northern India. Over the years, the Gomati River has attracted considerable interest in the field of environmental and geological studies; but hydrological studies are still scarce.[2–5] Therefore, an accurate prediction of water-level and river flow is required to mitigate the flood damage in the monsoon season and to manage the river's water resources during droughts situation in the summer season. The present hydrological study is conducted for the first time on any river of the Ganga River System.

A river's rating curve is a relationship between two variables, usually its discharge and another related variables such as water stage (depth of water above a local datum) and suspended sediment concentration etc. The lack of good quality discharge data from rivers of the Ganga Alluvial Plain also leads to particular difficulties in establishing stage-discharge relationship. Additional challenges associated with establishing stage-discharge relationships for these rivers include locating suitable representative sites for gauging stations. These considerations are vital for the production of stage-discharge curves and are primarily responsible for the lack of establishment of rating curves in this region. Under the present scenario, climate change is altering the atmospheric precipitation and distribution pattern in time and space, along with the occurrences of extreme climatic events. Thus, an accurate prediction of water level and discharge is required in assessing the hydrological impact to fully understand and forecast river discharge variability.

The target of this research work is to represent that river flow monitoring is a meaningful tool to interpret hydrological and climatological changes occurring within a drainage basin under the current climatic change scenario. The significance of river flow monitoring is to understand climate-induced discharge trends and to identify environmental problems within the river basin. In the

Ganga Alluvial Plain, the Gomati River is a groundwater-fed river that supports 50 million population and experiences flooding during every monsoon season. Hence, it is of utmost importance to build robust data bases so that controlling floods, mitigating drinking water scarcity, and preserving water quality are manageable with the most advanced technologies. The aim of the present study, therefore, is to analyse stage-discharge relationship of the Gomati River and to discern the main driving factors for seasonal changes; to explain the usefulness of rating curves that can be extracted from the available data. The present study also describes and characterizes the nature of hydrological and environmental problems caused by over exploitation of ground water resources for irrigation purposes in the basin.

Material and methods

Study area

River discharge is the function of many climatic, geological, topographical, biological and anthropogenic variables coexisting in the river basin. The Gomati River Basin (GRB) is situated between 80° 00′ to 83° 10′ longitudes and 24° 40′ to 28° 40′ latitudes draining the area between the interfluve region of the Ganga and Ghaghara rivers. It is an elongated river basin, stretching in NW-SE direction, and drains an area of 30,437 km^2 of the Ganga Alluvial Plain. Owing to the sub-tropical location, the river basin receives about 1000 mm of rainfall annually; principally responsible for flooding in the river's basin. The maximum and minimum elevations in the basin are about 186 m and 61 m above mean sea-level. The regional upland surface of the basin has distinct undulating topography, characterized by low relief along with entrenched river valleys, ponds, lakes and alluvial ridges. In the GRB, about 76% area of the basin is covered by highly fertile agricultural land. The Gomati River tributaries show dendritic to parallel network of entrenched alluvial tributaries and are locally called *Nala* and/or *Nadi*. Main tributary of the Gomati River is the Sai River which drains nearly one-third part of the basin, along with other 33 micro–basins. All the existing sub–basins of the Gomati River are drained in third to fifth order of small alluvial channels with drainage density from 0.44 to 1.04 km/km^2 and basin relief ranging from 10 to 44 m.[6] The Gomati River originates from the swampy *Gomat Taal* near Madho Tanda and flows 900 km distance covering in the Ganga Alluvial Plain, before joining the Ganga River at Kaithi. The river slope varies in the range of 55–11 cm/km from its upper to lower reaches. As a result of the ever increasing human population, the agriculture land has increased to more than two-thirds of the river's basin area to sustain the agrarian economy. Other important characteristics of the river and its basin are summarised in Table 1.

Table 1 General characteristics of the Gomati River and its basin. Refer Figure 1 for location of the Gomati River Basin in the Ganga Alluvial Plain, northern India

Parameters	Value/range with units
Gomati River Basin	
Human population	~50 million (in 2020)
Drainage area	30,437 km^2
Climate type	Humid sub-tropical climate
Seasons	Monsoon (June to September),
	Post-monsoon (October to November)
	Winter (December to February)
	Summer (March to May)
Annual rainfall range	81 - 125 cm
Maximum and minimum elevation	186 m and 61 m (above mean sea level)
Maximum and minimum temperature	47 °C and 2 °C
Relief	25 m (maximum)
Sub-basins	Sai River sub-basin
Micro-basins	33 microbasins
Basin's Land use pattern	Agriculture (67%), Settlement (13%),
	Barren land (14%), Forest (4%), Water bodies (2%)
Gomati River	
Channel length	900 km
Channel pattern	Single sinous channel
Sinuosity (Range)	1.2 - 2.5
Slope	13.9 cm/km
Valley width (Maximum and minimum)	0.25 km - 10 km
Valley type	Entrenched
Escarpment heights (Range)	2 - 25 m
Low discharge (Summer season)	26 m^3/s (May, 2012)
High discharge (Monsoon season)	712 m^3/s (September, 2009)
Annual water discharge	5.85×10^9 m^3 (June, 2009-May, 2010)
Seasonal water discharge contributions	Monsoon (48%), Post-monsoon (30%)
	Winter (16%) and Summer (6%)

Climate

The first order factor affecting a river's discharge would be climate and weather. The GRB is located in the sub-tropical zone and experiences a humid, sub-tropical climate with four distinct seasons; the monsoon season, the post-monsoon season, the winter season and the summer season.[7] The monsoon season is a warm-wet season extending from June to September and is characterized by high rainfall due to the SW Monsoon System (Indian Summer Monsoon). The GRB receives 84% of total annual rainfall in this season. Rainwater interacts with the alluvium plain and seeps into the groundwater system of the basin to become the water source for all tributaries. In general, the river's flow and discharge are positively related with precipitation during this season. Other water bodies including the low-lying areas of the basin get inundated due to the excessive rainfall in this season. The post-monsoon season extends for two months from October to November. It is characterized by moderate temperature and light rainfall. The temperature varies from the range 7.6 to 38.6 °C and about 9% of annual rainfall is received during this season. The winter season is a cold-dry season that extends from December to February. It is characterized by minimum temperature and low rainfall. The rainfall takes place due to the Western Disturbances and contributes 3% of annual rainfall. The summer season is a hot-dry season that extends from March to May. It is characterized by high temperature as the northwestern winds dominate along with occasional thunderstorms and dust storms. The maximum temperature reaches up to 40 to 44.7 °C and leads to increasing evaporation which results in the decreasing of the river's discharge. The summer season contributes nearly 4% of the total annual rainfall. There is hardly any natural runoff generated from the basin due to low precipitation and high evaporation, except anthropogenic generated runoff through drains from several urban centres located along the river banks. (Figure 1b, c) displays monthly the variation of maximum and minimum temperatures, rainfall and evaporation in all the above seasons, respectively.

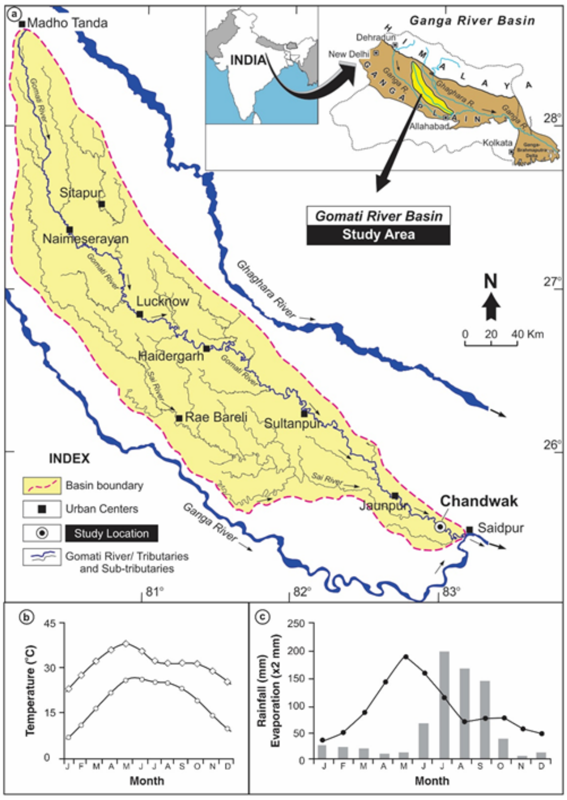

Figure 1 (a) Location map of the Gomati River Basin, draining a ~ 30,500-km^2 interfluve area of the Ganga and the Ghaghara Rivers in the Ganga Alluvial Plain, northern India. Gauging station for the river basin is located in Chandwak at Maighat site. Monthly variation in meteorological parameters used in characterisation of the monsoon, the post-monsoon, the winter and the summer seasons showing (b) average monthly maximum and minimum temperatures at Lucknow and (c) average monthly precipitation at Lucknow (bar) and evaporation (line with symbol) at Delhi. (after CPCB, 2002; Dasgupta, 1984).

River hydrology

River hydrology plays an important role in the present study as the Gomati River is a groundwater fed river of the Ganga Alluvial Plain and its discharge is controlled by the intensity and duration of precipitation. The river has a slow-moving flow (<100 m^3/s) more than half of the year, except during the monsoon and post-monsoon seasons. The intensity of rainfall and the duration of the monsoon season causes 25 to 50-folds increase in the river's runoff. The river's hydrograph is seasonally controlled and highly peaked with annual flood discharge.[8] More than 75% of total annual discharge flows during the monsoon and post-monsoon seasons; whereas as low as nearly 5% of total annual discharge flows during the summer season. The intensive demand of irrigation water for agriculture could be the most important factor for decline of the river's discharge and flow during the winter and summer seasons. Moreover, during the summer season, high air temperature (>40 °C) leads to high evaporation, which further results in the decline both the river's flow and discharge. Under the present situation, rising temperature and changing rainfall pattern have led to an increase in the frequency of floods and droughts that are fundamental to sustaining the river's ecosystem as well as the livelihoods and health of the local communities. Therefore, ecological flow of the Gomati River to sustain good survival and for well-being of many aquatic life forms is documented to be around 55 m^3/s; 33% of the mean average discharge. Human population growth, coupled with rapid socio-economic development, is primarily responsible for the present extreme conditions during the summer and monsoon seasons.

Maighat gauging station

Maighat is located on the right bank of the Gomati River near Chandwak at 60 km upstream of the Ganga River's confluence in the distal part of the GRB (Figure 1). This location is ideal as it covers the whole drainage area by all the tributaries of the Gomati River and unaffected by the backwater flows of the Ganga River floods during the monsoon season. It would not have been possible to derive a meaningful stage-discharge relationship for the Gomati River; if the channel cross-section at Maighat is unstable.[9] Therefore, field observations play an important role in helping to understand the nature of the river's flow regime in deciding the location of the gauging station to achieve a good understanding of channel, flow velocity and cross-sectional changes on flow and flood regimes. Geological reviews of the lower GRB suggest that the river channel found in this part is laterally stable due to the cohesive sediments of the Ganga Alluvial Plain and also predominantly due to the very low slope of the river (10 cm/km). The river valley as well as the active channel morphology of the gauging site indicated that for flow discharges pass through the active channel of the river as shown in Figure 2 b. However, it is possible that high flow at the time of peak monsoon discharges may be missed due to very heavy rains, that would thereby affect the stage measurements and the relationship. Single or multiple flood events take place during every monsoon season, however no changes were observed in the overall shape of the channel cross-section or position of the main channel, throughout its geological evolution. Field observations of the rising or falling stages of the annual flood cycles indicated that insignificant topographical variations had been recorded on the channel cross-section. On the basis of fluvial geomorphological surveys and erosion-deposition observations at Maighat location, the channel cross-section appears laterally stable for a range of flood events. It is, therefore, the most suitable site for the establishment of a gauging station of the GRB (Figure 2a, b).

Figure 2 Google Earth images showing (a) distal part of the Gomati River Basin and the confluence of the Gomati River with the Sai and the Ganga Rivers. Gauging station for the Gomati River is located on the left bank at Chandwak and (b) a 100-m wide single sinuous channel of the Gomati River flowing in SE direction at Maighat gauging site.

Standard equipment, acceptable methods and specifications were reported to be used in the daily measurement of water level and velocity. The river cross-sectional area was estimated by gauge height, depth at the y-axis and product of channel width multiplied by the depth at the y-axis. At Maighat gauging station, the river-bed is free of scouring activity and channel deposits and therefore, is considered as stable for the use of gauge height to estimate the river cross-sectional area. The river water-levels were daily measured and these measurements were available for the entire period of discharge gauging. Discharge measurement was made by current-meter using a two-point method. Stage height of the riverbed in zero discharge was fixed at 60 m above mean sea-level. The collection of primary hydrological data on daily basis is administrated and controlled by the Varanasi office of the Middle Ganga Division-III, Central Water Commission, Government of India. Google Earth images display the location map of Maighat gauging station on the single sinuous channel of the Gomati River in Figure 3 a, b.

Hydraulic relationship

River discharge is the volume of water flowing through a cross-section in a given amount of time and provides useful information for the understanding of hydrological processes operating in the river basin. This information is very useful for water resources planning, designing of hydraulic structures, river hydrologic analysis, water quality monitoring, flood warning/control/mitigation and decision making processes, etc. In the open channel of a river, an empirical or theoretical relationship exists between the water-level and simultaneous flow discharge which is known as the stage-discharge relation or rating curve. It is established from the periodic measurements of the river's discharge and corresponding water surface elevation, known as stage, at the river's observation site. The stage-discharge relationship is a very important tool in surface hydrology as the discharge is highly dependent on a satisfactory stage-discharge relationship at the gauging station. It is a fundamental and an extensively used technique employed to estimate the discharge in natural or artificial open channel for the hydrological studies of the river. It is a known fact that the direct measurement of discharge is a time consuming and costly procedure, and sometimes impractical during high-flood conditions. Therefore, the simple way to gather information on current discharge is to measure the water level with gauges and to use the stage-discharge relationship to estimate the discharge. The relationship is neither easy to quantify even under meticulous observations nor unique as any river if often influenced by climatological, geological and anthropological factors.[10] At the same time, the quality of stage-discharge rating curve determines the accuracy of the computed discharge data and therefore, an examination of goodness-of-fit of the rating curve is considered by the coefficient of determination (R^2). This is particularly important for tropical monsoon rivers carrying huge volumes of flood water.[11,12]

Figure 3 (a) Downstream view of the Gomati River at Maighat gauging station. The river bed is exposed during onset of the monsoon season in the foreground and treeline representing the right margin of the 10-m deep entrenched river valley in the background. (b) Southern view of the 100-m wide cross-section of active channel flowing in the entrenched Gomati River Valley with verticak water-level staff gauges. The flow direction is from right to left. [Photographed by SS on June 6, 2023 at 10:05 am].

Hydraulic relationship between stage (H) and discharge (Q) is normally expressed by a simple plot of H against Q and this plot is known as stage-discharge rating curve. The rating curve is established using earlier gauging of discharges and water levels. These gauged discharges are often based on the measured flow velocities and channel cross-sectional geometry. River discharge plotted against stage should be steady-state discharge. During the period of gauging, the changing stage is often adjusted to the measured discharge. These were the initial approaches adopted for the assessment of stage-discharge rating curves. The aim is to produce a continuous time-series discharge. Rating curves are usually constructed using linear (log–normal) or nonlinear (log–log) regression, where parameters are fitted by the least squares method. These curves are used to forecast a variable that is difficult to measure continuously, from another variable that is easier to determine.

(i) Logarithmic relationship

It can be either in natural or log space, and an equation is fitted to it as below:

$$Q = a(h_0 + h)^b \quad \text{or}$$

$$\log Q = \log a + b \log (h_0 + h)$$

In these equations, Q is the discharge (m^3/s), h is the water level (m), and a, h_0, b are the constants. These constants are site-specific and depend on geometrical characteristics and hydrological controls. These constants are decided in different ways, such as direct method, trial and error method, regression analysis, or Bayesian method (Le Coz et al, 2014). These equations are simple to understand and easy to determine the relationship between the selected variables for any hydrological studies.

The stage-discharge relationship is a single value relation and obeys the equation expressed by the following equation (Rantz, 1982) as:

$$Q = a(h - h_o)^b \quad (1)$$

Where Q is the discharge (m^3/s), h is the measured stage level or gauge height (m), a is the coefficient (constant) that reflects the scales being used for stage and discharge; and b is the exponent (constant) that denotes the degree of curvature or slope of the estimated relationship; and h_o is stage level of discharge zero (m). Under uniform flow conditions, discharge is then obtained by the measured stage and stage-discharge rating curve. For the analytical fitting, logarithmic transformation of equation (1) may be made in the form of a straight line (y = bx + a) as the following equation (2):

$$\log Q = b\log(h - h_o) + \log a \quad (2)$$

(ii) Semi-logarithmic relationship

The relation between stage and discharge is determined by plotting gauge height (h) linearly on the ordinate and log Q on the abscissa. The equation for discharge Q can be determined by taking coordinates on a straight line as the following equation (3):

$$\log Q = (h - h_o)\log b + \log a \quad (3)$$

The semi-logarithmic stage-discharge relationship is rarely used now. It has particularly one specific advantage over the logarithmic relationship by the identification of breaking points more efficiently than equation (1).

(iii) Polynomial relationship

The general polynomial equation for stage(h) and discharge (Q) is expressed as the following equation (4):

$$Q = b_0 + b_1h + b_2h^2 + b_3h^3 + \ldots\ldots b_nh^n \quad m^3/s \quad (4)$$

(iv) Quadratic relationship

The relationship between stage and discharge is also expressed by the quadratic equation (5).

$$Q = b(h - h_o)^2 + a \quad (5)$$

Where *b* and *a* are the two coefficients, which can be determined by appl

ying the method of least squares. RPT et al. (1989) proposed the above quadratic stage and discharge relationship for the Brahmaputra River.

In theory, establishing a stage-discharge rating curve is straightforward; but in practice, it is a complex and difficult procedure that is heavily influenced by both the methodology adopted and quality of data used, particularly during the monsoon and the post-monsoon seasons.[13] In the present study, all four-season based stage-discharge rating curves were examined for the Gomati River. The suitability of semi-logarithmic, polynomial and quadratic stage-discharge rating curves has not been investigated.

The data

The task of data collection began after the hydrological research problem related to the Gomati River had been identified and research plan chalked out accordingly. The primary data with original characteristics, were collected afresh and for the first time. The discharge is a common multiple of water velocity and channel cross-sectional area. The Varanasi office of the Middle Ganga Division-III, Central Water Commission, Government of India, was responsible for the collection of primary hydrological data of the Gomati River on a daily basis at Maighat gauging station. The flow gauging was carried out daily throughout the years and therefore, the observed gauging can be treated as a time series. At the same time, it is possible to treat the days without gauging as days with missing values. These missing values can be estimated by the routine incorporation of statistical values. The data that support the findings of this study are available from the Central Water Commission, Government of India; but certain restrictions apply to the availability of these data and so there are not available publicly.

The secondary data, which have been passed through the statistical processes of the mean value of 10 days, were used in the present study. Three years; 2009-10, 2010-11 and 2011-12, were chosen for the specific reasons that each year represented all the four seasons with the monsoon flood cycles. A total of one hundred and eight stage and discharge data were available for a duration of 3 years. Thirty-six and eighteen data are available for the monsoon and the post-monsoon seasons, respectively. Twenty-six data are available for both the winter and summer seasons. The river discharge varies from 64 to 712 m^3/s during the monsoon season, from 79 to 721 m^3/s during the post-monsoon, 133 to 169 m^3/s during the winter season and from 32 to 64 m^3/s during the summer season. The river water velocity increases from 0.42 to 1.18 m/s during the monsoon season. The minimum river water velocity was recorded 0.25 m/s during the summer season. Table 2 presents the three-years long time-series data of stage, velocity and discharge at Maighat gauging station of the Gomati River collected from June, 2009 to May 2012. It is possible to use all the available data of stage (n=108) and discharge (n=108) for the present study. As the GRB experiences a humid sub-tropical climate with four distinct seasons; season-based rating curve analysis was also carried out for the present study. The rating curve analysis was also carried out under the condition of seasonal variation of discharges and stages.

Table 2 The Gomati River's stage, velocity and discharge data of from June, 2009 to May, 2012 duration. Hydrological data were measured daily at Maighat gauging station located near Chandwak and their mean values at ten days' interval were presented here. Zero stage level is 62 m above mean sea level. Refer Figure 2 for the location and Figure 3 for field photographs of Maighat gauging station

S. No.	Year	Season	Monitoring month	Date (dd.mm.yyyy)	Stage (m amsl)	Velocity (m/sec)	Discharge (m^3/sec)
1.	2009	Monsoon	June	10.06.2009	63.35	0.494	88.17
2.	„	„	„	20.06.2009	63.43	0.488	95.86
3.	„	„	„	30.06.2009	63.01	0.42	63.76
4.	„	„	July	10.07.2009	63.06	0.42	66.03
5.	„	„	„	20.07.2009	63.41	0.489	95.02
6.	„	„	„	31.07.2009	66.02	1.153	611.73
7.	„	„	August	10.08.2009	64.19	0.718	209.91
8.	„	„	„	20.08.2009	64.44	0.705	227.13
9.	„	„	„	31.08.2009	64.59	0.69	232.66
10.	„	„	September	10.09.2009	65.29	0.896	409.92
11.	„	„	„	19.09.2009	66.22	1.183	711.83
12.	„	„	„	30.09.2009	65.11	0.91	380.57
13.	„	Post-monsoon	October	10.10.2009	66.43	1.153	721.32
14.	„	„	„	20.10.2009	66.19	1.18	697.56
15.	„	„	„	31.10.2009	64.68	0.685	280.8
16.	„	„	November	10.11.2009	63.89	0.572	174.49
17.	„	„	„	20.11.2009	63.47	0.389	91.43
18.	„	„	„	30.11.2009	63.24	0.367	78.59
19.	„	Winter	December	10.12.2009	63.78	0.498	110.45
20.	„	„	„	19.12.2009	63.79	0.593	168.7
21.	„	„	„	31.12.2009	63.28	0.466	102.34
22.	2010	„	January	09.01.2010	63.54	0.51	128.5
23.	„	„	„	20.01.2010	63.76	0.58	164.37
24.	„	„	„	30.01.2010	63.66	0.536	145.3
25.	„	„	February	10.02.2010	63.04	0.309	61.42
26.	„	„	„	20.02.2010	63.62	0.506	132.7
27.	„	„	„	26.02.2010	63.23	0.451	98
28.	„	Summer	March	10.03.2010	63.07	0.316	63.95
29.	„	„	„	20.03.2010	63.04	0.313	65.11
30.	„	„	„	31.03.2010	62.86	0.397	53.3
31.	„	„	April	10.04.2010	62.96	0.424	60.17
32.	„	„	„	20.04.2010	62.65	0.27	42.67
33.	„	„	„	30.04.2010	62.58	0.266	36.59
34.	„	„	May	10.05.2010	62.56	0.264	35.84
35.	„	„	„	20.05.2010	62.48	0.249	31.85
36.	„	„	„	31.05.2010	62.59	0.259	33.5
37.	„	Monsoon	June	10.06.2010	62.73	0.275	42.25
38.	„	„	„	19.06.2010	62.57	0.26	35.1
39.	„	„	„	30.06.2010	62.69	0.282	42.52
40.	„	„	July	10.07.2010	62.88	0.317	56.68
41.	„	„	„	20.07.2010	62.97	0.332	61.31
42.	„	„	„	31.07.2010	64.08	0.684	250.4
43.	„	„	August	10.08.2010	65.12	0.924	428.8
44.	„	„	„	20.08.2010	64.1	0.646	200.2
45.	„	„	„	31.08.2010	65.35	0.665	335.7
46.	„	„	September	10.09.2010	65.82	0.749	416.5
47.	„	„	„	19.09.2010	66.17	0.786	465.8
48.	„	„	„	30.09.2010	66.8	0.895	628.7
49.	„	Post-monsoon	October	10.10.2010	66.33	0.878	562.9
50.	„	„	„	20.10.2010	64.68	0.787	328.3
51.	„	„	„	31.10.2010	64.28	0.6	209
52.	„	„	November	10.11.2010	63.77	0.5	132.7

Table 2 Continued...

S. No.	Year	Season	Monitoring month	Date (dd.mm.yyyy)	Stage (m amsl)	Velocity (m/sec)	Discharge (m^3/sec)
53.	,,	,,	,,	20.11.2010	63.22	0.5	99.83
54.	,,	,,	,,	30.11.2010	62.98	0.495	84.13
55.	,,	Winter	December	10.12.2010	62.89	0.482	75.94
56.	,,	,,	,,	19.12.2010	63.45	0.502	110
57.	,,	,,	,,	31.12.2010	63.31	0.5	100.4
58.	2011	,,	January	09.01.2011	63.26	0.499	96.95
59.	,,	,,	,,	20.01.2011	63.49	0.49	104.7
60.	,,	,,	,,	30.01.2011	63.16	0.481	91.65
61.	,,	,,	February	10.02.2011	62.86	0.426	67.56
62.	,,	,,	,,	20.02.2011	62.82	0.375	56.2
63.	,,	,,	,,	28.02.2011	62.99	0.37	63.7
64.	,,	Summer	March	10.03.2011	62.52	0.371	64.5
65.	,,	,,	,,	20.03.2011	62.44	0.371	60.14
66.	,,	,,	,,	31.03.2011	62.53	0.371	54.54
67.	,,	,,	April	10.04.2011	62.92	0.378	58.41
68.	,,	,,	,,	20.04.2011	62.85	0.35	53.22
69.	,,	,,	,,	30.04.2011	62.74	0.342	47.36
70.	,,	,,	May	10.05.2011	62.52	0.291	34.64
71.	,,	,,		20.05.2011	62.44	0.282	31.06
72.	,,	,,		31.05.2011	62.53	0.296	35.32
73.	,,	Monsoon	June	10.06.2011	62.84	0.363	54
74.	,,	,,	,,	20.06.2011	62.8	0.357	52.71
75.	,,	,,	,,	30.06.2011	63.96	0.597	167.5
76.	,,	,,	July	10.07.2011	65.4	0.848	390.2
77.	,,	,,	,,	20.07.2011	63.95	0.583	156.5
78.	,,	,,	,,	31.07.2011	66.11	0.562	309.1
79.	,,	,,	August	10.08.2011	65.92	0.651	344.7
80.	,,	,,	,,	20.08.2011	68.57	0.703	638.7
81.	,,	,,	,,	31.08.2011	68.07	0.695	581.2
82.	,,	,,	September	10.09.2011	67.03	0.8	559.9
83.	,,	,,	,,	19.09.2011	66.88	0.805	558.5
84.	,,	,,	,,	30.09.2011	67.36	0.824	610.4
85.	,,	Post-monsoon	October	10.10.2011	65.69	0.92	457.1
86.	,,	,,	,,	20.10.2011	64.46	0.672	228.4
87.	,,	,,	,,	31.10.2011	64.04	0.603	176.6
88.	,,	,,	November	10.11.2011	63.4	0.544	116.2
89.	,,	,,	,,	20.11.2011	63.16	0.494	91.24
90.	,,	,,	,,	30.11.2011	62.3	0.456	75.09
91.	,,	Winter	December	10.12.2011	63.22	0.457	86.25
92.	,,	,,	,,	19.12.2011	63.42	0.46	99.24
93.	,,	,,	,,	31.12.2011	63.54	0.473	106.8
94.	2012	,,	January	09.01.2012	64.07	0.604	181.1
95.	,,	,,	,,	20.01.2012	64.3	0.635	204.2
96.	,,	,,	,,	30.01.2012	63.5	0.491	108.8
97.	,,	,,	February	10.02.2012	63.24	0.51	94.13
98.	,,	,,	,,	20.02.2012	63.25	0.539	97.58
99.	,,	,,	,,	29.02.2012	63.03	0.558	82.22
100.	,,	Summer	March	10.03.2012	62.21	0.49	65.06
101.	,,	,,	,,	20.03.2012	63.05	0.472	68.76
102.	,,	,,	,,	31.03.2012	62.97	0.446	60.14
103.	,,	,,	April	10.04.2012	62.9	0.447	56.8
104.	,,	,,	,,	20.04.2012	62.8	0.428	50.31
105.	,,	,,	,,	30.04.2012	62.56	0.368	35.87
106.	,,	,,	May	10.05.2012	62.44	0.337	28.9
107.	,,	,,	,,	20.05.2012	62.38	0.323	26.28
108.	,,	,,	,,	31.05.2012	62.39	0.33	27.01

Results and discussion

The examination of original data from reveals the strong evidence of seasonal influence in water-level and flow characteristic of the Gomati River at Maighat gauging station (Table 2). High temperature (30 to 40 °C) during the summer season and heavy precipitation (20 to 80 mm/d) during the monsoon season appear to be the main factor determining such hydrological behaviour. Figure 4 illustrates valuable information that the investigation of time series can provide an understanding of the river's hydrological characteristics. The Gomati River flows under the low discharge condition of <100 m^3/s for more than six months; whereas under the extremely high discharge condition of >500 m^3/s for nearly one month, as shown in Figure 4a. Figure 4b displays the seasonal variability of three-years long time series data of the measured gauge heights at Maighat gauging station. Low gauge-levels frequently determine low discharges of the winter and the summer seasons; whereas high gauge-levels define discharges that generally correspond to the monsoon and the post-monsoon seasons.

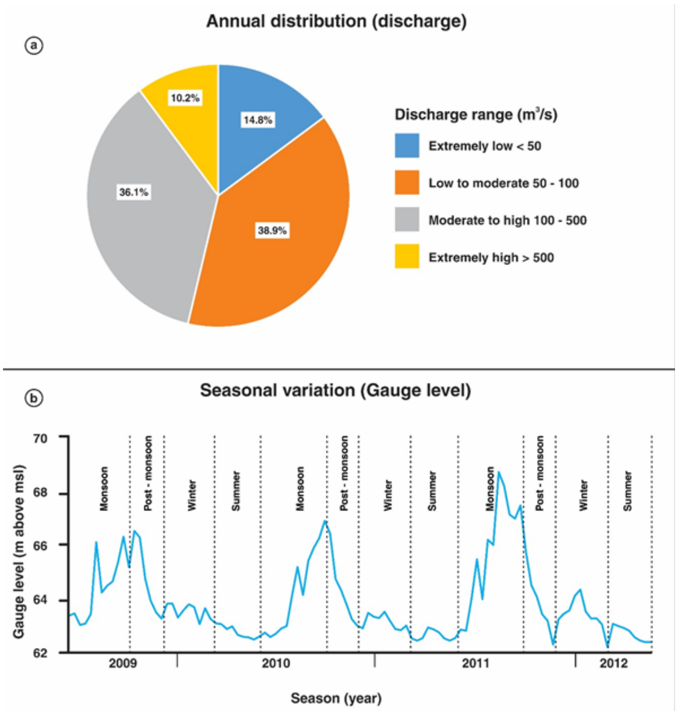

Figure 4 (a) Pie diagram showing the annual contribution of discharge ranges <50, 50–100, 100–500 and >500 m^3/s and (b) Three-years long time series of gauge levels in the Gomati River at Maighat gauging station from June 2009 to May 2012. The river discharge <100 m^3/s accounts nearly half of the year. The extremely high discharges (>500 m^3/s) flow nearly for one-month duration. Note the seasonality and cyclic variation of gauge levels during the monsoon to the summer seasons. [Data source: Table 2]

Results of the stage-discharge rating curve analysis are presented in Figure 5, 6 and 7, by using the original data from June 2009 to May 2012 (Table 2). As the Gomati River is a low-gradient river, it's discharges have proportionately altered corresponding stages in all the seasons of a year. Therefore, the first observation is about representing the stage and discharge relationship according to the monsoon, the post-monsoon, the winter and the summer seasons. The examination of data clearly indicates that the records of gauging were carried out under the rising stage during the monsoon season and under the falling stage during the post-monsoon season (Table 2). The stage-discharge relationship, either in natural or log space, may be made fitted in the simple form of a straight line with equation and therefore, designated for the present study. Figure 5(a) shows the normal stage-discharge rating curve during the three monsoon seasons of 2009, 2010 and 2011. The relationship, obtained by the time series data of stage and discharge during the three monsoon seasons in Maighat gauging station, is expressed by an equation (6) as follows:

$$Q_m = 121.4\, H_m - 44.318 \tag{6}$$

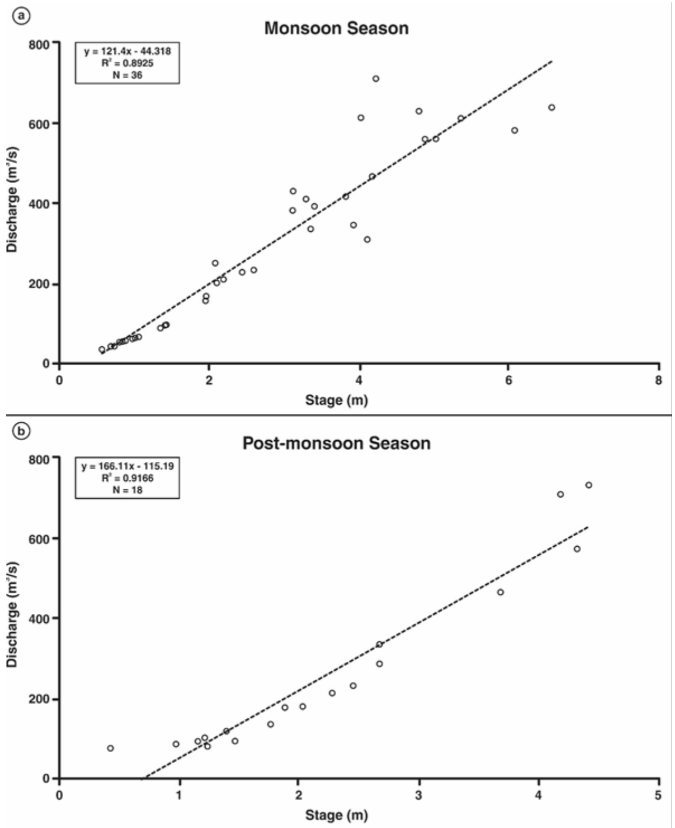

Figure 5 Stage-discharge rating curve (a) using all discharge data (R^2 = 0.8925; N = 36) during the monsoon season and (b) all discharge data (R^2 = 0.9166; N = 18) during the post-monsoon season of years 2009, 2010 and 2011 for the Gomati River at Maighat gauging station. [See Table 2 for the data source].

[Q_m and H_m are observed discharge (m^3/s) and stage (m) during the monsoon season; number of observation N = 36; coefficient of determination R^2 = 0.8925]

The linear stage-discharge rating curve by using selected data (N = 18) during the three post-monsoon season is shown in Figure 5(b). The relationship is expressed by an equation (7) as follows:

$$Q_{pm} = 166.11\, H_{pm} - 115.19 \tag{7}$$

[Q_{pm} and H_{pm} are observed discharge (m^3/s) and stage (m) during the post-monsoon season; number of observation N = 18; coefficient of determination R^2 = 0.9166]

The linear stage-discharge rating curve by using selected data (n = 27) during the three winter season as shown in Figure 6(a). The relationship is expressed by an equation (8) as follows:

$$Q_w = 96.525\, H_w - 25.203 \tag{8}$$

[Q_w and H_w are observed discharge (m^3/s) and stage (m) during the post-monsoon season; number of observation N = 27; coefficient of determination R^2 = 0.8907]

The linear stage-discharge rating curve by using selected data (n = 27) during the three summer seasons is shown in Figure 6(b). During the summer season, the stage of <1 m situation yielded the corresponding discharge of <75 m³/s. The relationship is expressed by an equation (9) as follows:

$$Q_s = 34.893\ H_s - 24.22 \quad (9)$$

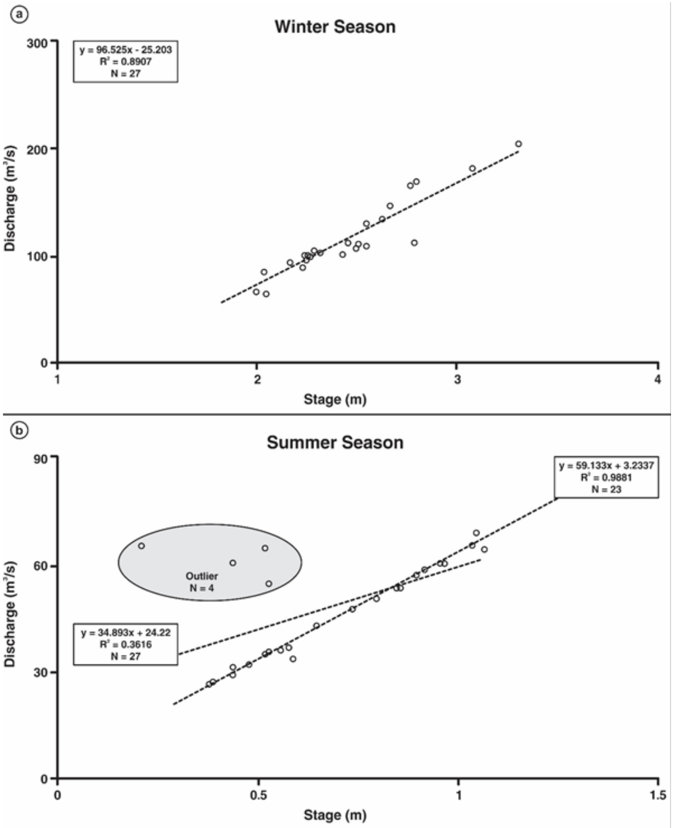

Figure 6 Stage-discharge rating curves during (a) the winter season – including all discharge data (R^2 = 0.8907; N = 27) and (b) the summer season – excluding identified outliers (N = 4) in regression run for discharge data (R^2 = 0.9881; N = 23) for years 2009, 2010 and 2011 of the Gomati River at Maighat gauging station. [See Table 2 for the data source].

[Q_s and H_s are observed discharge (m³/s) and stage (m) during the summer season; number of observation N = 27; coefficient of determination R^2 = 0.3616]

By removing the outliers (N = 4), the above relationship is expressed in an equation as $Q_s = 59.133\ H_s + 3.2337$ with a significant improvement in the coefficient of determination R^2 = 0.9881.

During the course of the present study, it was found that the coefficient of determination between discharge and stage were different during the summer and the post-monsoon seasons. Considering the consistent seasonal changes in the discharge of different magnitudes, the whole discharge data is divided into two grades of >250 m³/s and <250 m³/s to get the best rating curve. Figure 7(a) shows the linear stage-discharge rating curve with N=23 data and the coefficient of determination R^2=0.4513 in the high discharge condition of >250 m³/s. The linear relationship associated rating equation with this plot is expressed by an equation (10) as follows:

$$Q = 94.152\ H - 107.1 \quad (10)$$

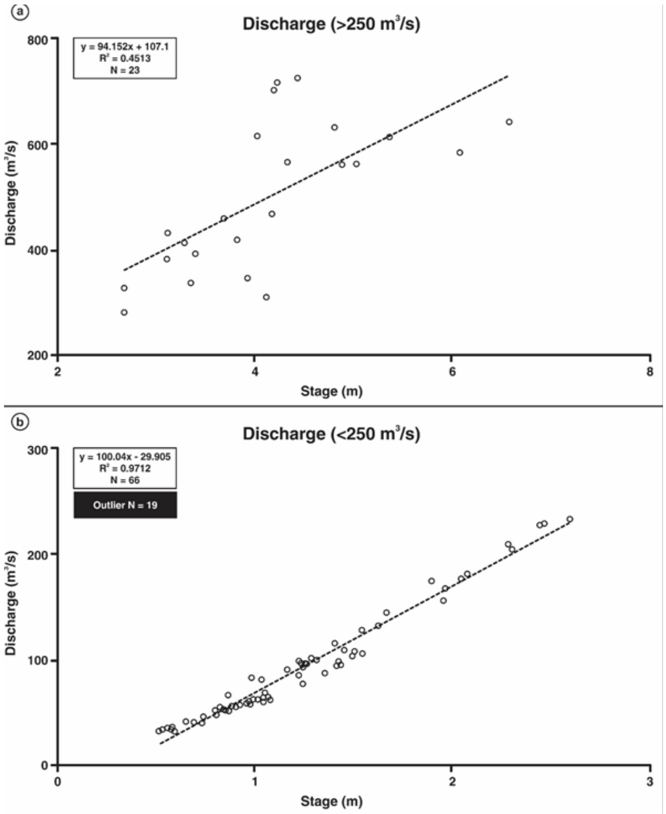

Figure 7 (a) Stage-discharge rating curve during the high flow condition of >250 m³/s showing the coefficient of determination (R^2 = 0.4513; N = 23) and (b) Liner stage-discharge rating curve during the low flow condition of <250 m³/s showing the best coefficient of determination (R^2 = 0.9712; N = 66) – excluding identified outliers (N = 19) in regression run for years 2009, 2010 and 2011 of the Gomati River at Maighat gauging station. [See Table 2 for the data source].

[Q and H are observed discharge (m³/s) and stage (m) flow condition of >250 m³/s; number of observation N = 23; coefficient of determination R^2 = 0.4513]

It was assumed that the gauging data contained errors of unknown magnitude, therefore, it was not possible to use all the available data for the best rating curve, due to the coefficient of determination. The goodness-of-fit criteria (R^2) was chosen in order to select the best rating curve for the Gomati River. The linear stage-discharge rating curve during the winter and the summer seasons displayed higher values of the coefficient of determination than the monsoon and the post-monsoon seasons. Based on these observations and by excluding all outliers (n=19) identified by regression run, the linear stage-discharge rating curve with the coefficient of determination (R^2=0.9712) in flow condition of <250 m³/s is shown in Figure 7 (b). The linear relationship associated rating equation with this plot is expressed by an equation (11) as follows:

$$Q = 100.04\ H - 29.905 \quad (11)$$

[Q and H are observed discharge (m³/s) and stage (m) flow condition of <250 m³/s; number of observation N = 66; coefficient of determination R^2 = 0.9712]

Based on the present study, the above linear stage-discharge rating curve was found to be suitable for the Gomati River. Figure

7(b) suggests that several points plotted can be explained by normal or natural stage variation inherent in discharge processes of the Gomati River. If the stage-discharge rating curve suggested in this study is used, the change of water level, even subtle differences in the river discharges of 1 m^3/s, can be estimated. Due to technological advancement, Rai et al.,[14] recently estimated discharge under good to satisfactory category at the seven virtual locations (Kachla bridge, Kanpur, Shahzadpur, Prayagraj, Mirzapur, Azmabad and Farakka) along the Ganga River by acquiring the water level data from the satellite altimeter missions ERS-2, ENVISAT, and Jason-2.[15–17]

Conclusion

In the sub-tropical climate, the application of conventional methods has been unsuccessful due to impracticality and difficulty in measuring the long ranges of a river's discharge. As the flooding risks are coupled with the monsoon dynamics, flood discharge data are scarce due to the conventional methodology. The results provide proof that the rating curve analysis can be successful in measuring discharges and their seasonal variations in other alluvial rivers of the Ganga River System. The segmented rating curve for the Gomati River discharge of <250 m^3/s was found to be suitable and could serve as a cheap, quick, accurate and practical alternative. It would also fill the gap in knowledge, if applied, by increasing the efficiency of rating curve of sub-tropical region in inter- and extrapolation of other river discharges.

This research is limited to an early study of the application of rating curve in estimating discharge of the Gomati River; so that manpower and financial resources for operating the Maighat gauging station can be reduced. Further studies could be extended to establish the potential use of modern instruments to explore the possibility of automating flood discharge measurements. The present study will also provide hydrologists with a better method to estimate discharges along with possible automatic discharge measurement that can be annually applied to real-time forecasting of alluvial rivers. It would be recommended to expand and optimize gauging station network in the Ganga River Basin for detecting and assessing recent ongoing environmental impacts of climate change. More hydrological researches are necessary for the best water resource management to support the quality life of millions of people living in the Ganga Alluvial Plain. It is time to understand the planet's fluvial environment to build a future in which people can live in harmony in the present Anthropocene Era.

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Conflicts of interest

All authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the present hydrological research reported in this paper.

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