Journal of Hydrology 603 (2021) 126860

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Estimating discharge of the Ganga River from satellite altimeter data

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ARTICLE INFO

This manuscript was handled by Emmanouil Anagnostou, Editor-in-Chief

Keywords:
Satellite altimeter
Ganga River
Stage-discharge rating curve

ABSTRACT

We use the water level data from multiple satellite altimeter missions to estimate discharge at different reaches of varying channel width (130 m to 2 km) of the Ganga River in India. We have established five (Kachla bridge, Kanpur, Shahzadpur, Prayagraj, and Mirzapur) virtual stations in the middle and two (Azmabad and Farakka) in the lower reaches of the Ganga River. For these stations, we acquired the water level from different satellite altimeter mission ERS-2 (1995–2007), ENVISAT (2002–2010), and Jason-2 (2008–2017) from publicly available databases. We applied datum and offset corrections on the altimeter data to make them comparable with the water level measured at the nearest gauge station. At each location, water level from the altimeter and gauge station show a good agreement with root mean square (RMS) error in a range between (22 −71 cm).

We plot the altimeter water level as a function of their corresponding discharge measured at the nearest gauge station to establish a stage-discharge rating curve for each location. We then use these rating curves to estimate monthly discharge of the Ganga River from the altimeter water level. Based on the overall performance analysis of the statistical parameters, i.e; Nash–Sutcliffe efficiency (NSE); 0.86–0.98, RMS-observations Standard deviation Ratio (RSR); 0.15–0.38, Percent Bias (PBIAS); 13–27, and the coefficient of determination (R^2); 0.87–0.98, we show that the estimated discharge from altimeter water level accord well with the in-situ discharge measured at the gauge station. According to the Moriasi guideline, our estimate of discharge at all the virtual stations (except Kanpur) can be categorised between “good” to “satisfactory”.

1. Introduction

Terrestrial runoff of rivers is an important component in the global water balance. It is an important source of fresh water for humans and the ecosystem. Measurement of river discharge is essential to understand the flood hazards, sediment transport, fluvial processes, and terrestrial water budget. Despite its importance, yet discharge is not available for many rivers, especially those are located in poor and developing countries (Alsdorf et al., 2007; Mersel et al., 2013). In the Indian subcontinent, the Himalayan Foreland basins are drained by several large rivers (i.e; Ganga, Yamuna, Brahmaputra, Gandak, Kosi) and characterized by large catchment size, length, and large volume of water and sediment discharge (Hovius, 1998; Tandon and Sinha, 2007). These rivers constitute about 63% of the total annual flow and about 50% of the total ‘utilizable’ flow. This underlines their importance in freshwater supply for the country. It is important to note that the discharge of many of the Himalayan rivers is measured at sparsely distributed networks along their course. For example, the Ganga River flows about 2100 km from the Himalayan foothills in the upstream to the Farakka in the downstream. Presently, discharge is recorded at only 95 (manual-71, telemetry-24) gauge stations installed at different locations along the Ganga River in India (https://indiawris.gov.in/wris/). This hinders our ability to quantify discharge at any location between two or more sparsely distant gauge stations. Under such conditions, often discharge in between any two or more measurement stations is estimated by interpolation (Smith and Pavelsky, 2008; Lin et al., 2019).

Generally, discharge is measured at specific gauge stations installed at fixed locations along a river. Such stations are locally calibrated to predict discharge as a function of change in water level or stage. The calibration of a specific gauging station is derived from repeated measurements of the water-surface level and the corresponding water discharge. These measurements are performed throughout the hydrologic cycle to ensure that the calibration is valid during all flow periods. The river water level is then plotted as a function of the corresponding discharge. Based on a regression analysis, a best fit curve is established that relates water level to the discharge (Rantz, 1982; Herschy, 1993). Such a curve is universally known as stage-discharge rating curve and expressed as;

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https://doi.org/10.1016/j.jhydrol.2021.126860
Received 6 October 2020; Received in revised form 7 August 2021; Accepted 19 August 2021
Available online 28 August 2021

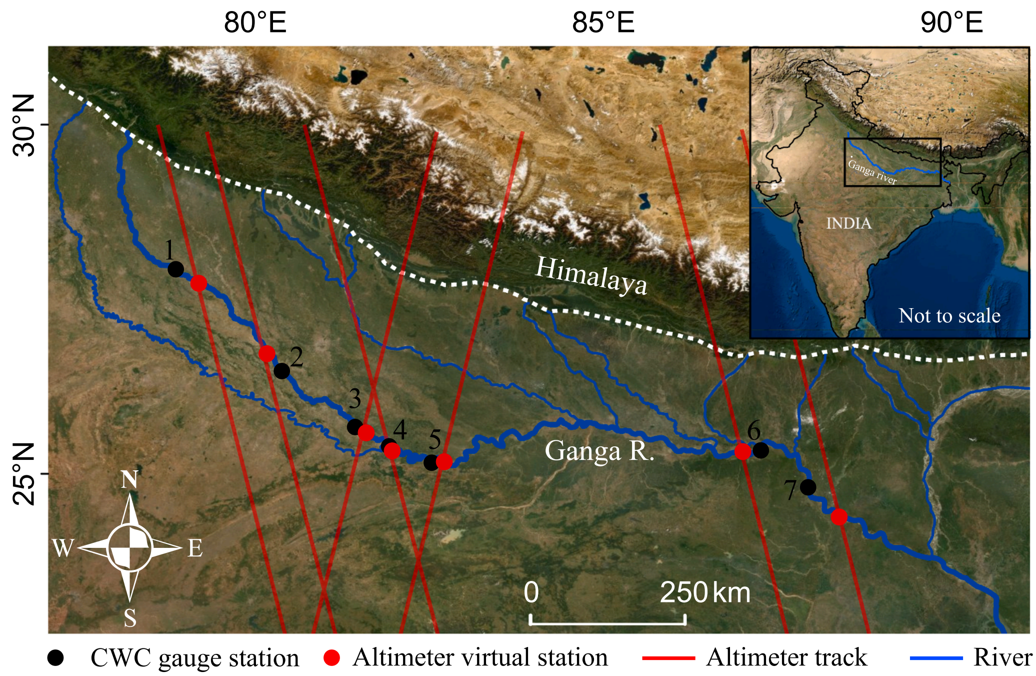

Fig. 1. Distribution of the CWC gauge stations (black circles) and altimeter virtual stations (red circles) along the main stream of the Ganga River. Red solid line shows the footprint of satellite altimeters near the existing CWC gauge stations; (1) Kachla bridge, (2) Kanpur, (3) Shahzadpur, (4) Prayagraj, (5) Mirzapur, (6) Azmabad, and (7) Farakka.

$$Q = a(Z - e)^m, \tag{1}$$

where the coefficients a and m are constants specific to the channel cross-section surveyed, e is the elevation of zero flow, Z is the stage, and Q is the discharge. The term $(Z - e)$ is often interpreted as equivalent to the mean river flow depth (H). Once a stage-discharge relationship is established, the discharge can be inferred from the measurements of the water level at any given gauging station.

Recently, a decline in the historical gauge network is reported worldwide due to their high operational and maintenance costs (Shiklomanov et al., 2002; Vörösmarty, 2002). Fekete and Vörösmarty (2007) and Tourian et al. (2013) compiled a time series plot of the in-situ gauge stations from World Meteorological Organization (WMO) (https://public.wmo.int/en) and publicly available Global Runoff Data Centre (GRDC) (https://www.bafg.de/GRDC/EN/Home/homepage_node.html) data, that indicates a significant decline of gauge stations worldwide from 1980 to 2010. This has resulted in the discontinuity of discharge measurement for various rivers globally. Such a gap is a real challenge for many scientific analyses (Sichangi et al., 2016).

To overcome this problem, researchers proposed to use remote sensing as an alternative to estimate water discharge (Smith et al., 1995; Smith et al., 1996; Smith, 1997; Alsdorf et al., 2007; Ashmore and Sauks, 2006; Marcus and Fonstad, 2008; Gleason and Smith, 2014; Sulistioadi et al., 2015; Biancamaria et al., 2017; Bogning et al., 2018; Gaurav et al., 2021). These studies rely on the establishment of rating relationships between some image derived parameters, such as channel width, water level/stage to the in-situ discharge measured at the ground stations. Radar altimeter is an active microwave instrument that measures the surface elevation of an object over a fixed datum. Altimeters were originally designed to monitor changes in ocean water level and ice sheets from space (Birkett, 1998; Alsdorf and Lettenmaier, 2003; Felikson et al., 2017; Stammer and Cazenave, 2017; Passaro et al., 2018). Later, researchers explored its potential to measure the fluctuation of water level in large rivers. Altimeters record the reflected echoes from the object by transmitting a high frequency signal to the nadir (Calmant et al., 2008). The range is then estimated by the travel time of the signal between the altimeter and surface. The water level is calculated by subtracting satellite to surface range from a reference datum. Taking into account the various errors, water level to a common datum can be estimated according to;

$$H = h - R - \sum e \tag{2}$$

where H is the water level, h is the satellite altitude, R is the nadir altimeter range and $\sum e$ is the propagated time delays due to atmospheric and geographic errors.

From the last two decades, satellite altimeter has become an important tool to remotely monitor the water levels and discharge in large rivers (width of few kilometers). For example, Koblinsky et al. (1993) used Geosat altimeter data to measure the change of water level in the Amazon River basin with a vertical accuracy of the order of 0.7 m. Similarly, Birkett (1998) and Birkett et al. (2002) used TOPEX/Poseidon (T/P) altimeter to track water-level in the Amazon Basin, the Okavango River, the Indus River, and the Congo River with the accuracy ranging from 11 to 60 cm. Further, Birkett et al. (2002) used the river stage from T/P data to calibrate discharge rating curves at many locations in the Amazon Basin. Similarly, Kouraev et al. (2004) estimated the daily discharge of the Ob River in the Arctic. Coe and Birkett (2004) used T/P altimeter to estimate a monthly average discharge of the Chari River at N'Djamena, Chad.

Later Papa et al. (2010) used T/P, ERS-2, and ENVISAT data to track water level at the mouth of the Ganga and Brahmaputra rivers in Bangladesh. Using these measurements and calibrated stage-discharge rating curves, they estimated the monthly average discharge time series for both rivers from 1993–2008. They found a mean error of the order of about 15% for the Brahmaputra and about 36% for the Ganga using T/P and ERS-2 data respectively. In another study, Papa et al. (2012) used Jason-2 radar altimeter measurements to estimate water discharge in the Ganga and the Brahmaputra rivers. They found that the Jason-2 radar altimeter could detect water level fluctuations in the Ganga and the Brahmaputra rivers within 4% of the ground-measured stage. They also estimated monthly average discharge for the years 2008 –2011, and found that the Jason-2 radar altimeter measurements could be used to infer the discharge with the uncertainty ranging from

Table 1
Details of the CWC gauge stations used in this study. The base level datum of the gauge stations is from the mean sea level.

River Reach	Gauge station	Location		Period	Gauge base datum (m) (Mean Sea Level)
		Latitude	Longitude		
Middle Ganga	Kachla bridge	27°55′52″	78°51′20″	June 2005 to Dec 2009	158
	Kanpur	26°28′10″	80°22′35″	June 2005 to Dec 2009	106
	Shahzadpur	25°40′00″	81°25′48″	Jan 2008 to Dec 2018	81
	Prayagraj	25°23′35″	81°54′59″	Jan 2003 to Dec 2010	69
	Mirzapur	25°09′22″	82°31′49″	Jan 1995 to Dec 2010	60
Lower Ganga	Azmabad	25°20′00″	87°15′15″	Jan 2002 to Dec 2010	30
	Farakka	24°48′14″	87°55′52″	Jan 2001 to Dec 2007	10

6.5% to 13%. Dubey et al. (2015) used Jason-2 altimeter data to estimate the discharge of the Brahmaputra River near Guwahati, Assam in India. They found a good correlation ($R^2 = 0.94$) between the estimated and measured discharge at the gauge station. Schröder et al. (2019) have used ENVISAT and SARAL/Altika to simulate water discharge of the Niger River. Huang et al. (2020) used water level from Jason 2 satellite mission to estimate discharge of the major rivers (Mekong, Brahamputra, and Salween) in the Tibetan plateau. Recently, Bogning et al. (2020) used ENVISAT and Jason-2 altimeter data to estimate discharge in the poorly gauged Ogooué River basin in central Africa.

Most of the studies discussed above are applied to the large rivers having the channels width of few kilometers. Only a few studies are available that use satellite altimeter data to estimate discharge in relatively narrow width (< 1 km) rivers (Tourian et al., 2013; Sulistioadi et al., 2015; Zakharova et al., 2020). This study uses publicly available water level data from multiple satellite altimeter missions (ERS-2, ENVISAT, and Jason-2) to estimate discharge of the Ganga River at seven different locations from Kachla bridge in the upstream to Farakka in the downstream. We have selected five locations (Kachla bridge, Kanpur, Shahzadpur, Prayagraj, and Mirzapur) in the middle and two (Azmabad and Farakka) in the lower reaches of the Ganga River. The channel width of the Ganga River in the middle and lower reaches vary between 150 to 700 m and 0.85–2 km respectively.

The main objective of this study is to evaluate the potential of multi-mission satellite altimeter data to estimate monthly average discharge at different reaches of varying width along the Ganga River. In doing so, we first apply the datum and offset corrections on the altimeter water level for all the stations and compared them with the water level measured at the nearest gauge station. For each virtual station, we plot the altimeter water level against the corresponding discharge measured at the gauge station to establish a stage-discharge rating curve. Finally, we use these rating curves to estimate the average monthly discharge at each virtual station from the altimeter water level. This study could be a useful tool for a quick assessment of discharge for monitoring river health, flood management, and many other applications. It may be used to construct supplementary data to fill the gap in discharge time series in case of missing data values at the gauge stations.

2. Material and methods

2.1. Dataset

This study uses stage and water discharge measured at different gauge stations along the Ganga River and water level recorded from satellite altimeters. We obtained stage and corresponding discharge data from the Central Water Commissionhttp://cwc.gov.in/ (CWC), New Delhi for seven different gauge locations (4–15 years), five from the middle and two from the lower reaches of the Ganga River (Fig. 1 & Table 1). The reference datum for CWC gauging stations is the Mean Sea Level (MSL). Our in-situ archive consists of average of every ten days measurements of stage and discharge at the gauge stations. We have aggregated them to obtain the monthly average quantity.

At or near the in-situ gauge stations, we obtained the water level recorded from different satellite altimeters (Table 2). Hereafter, we refer to these altimeter locations as virtual stations along the Ganga River. We used two different open archive sources- Hydroweb (http://hydroweb.theia-land.fr/) & DAHITI (https://DAHITI.dgfi.tum.de/en/map/) to download the altimeter dataset. The accuracy of altimeter data from both these databases are in cm to mm level (Schwatke et al., 2015; Dubey et al., 2015). Hydroweb delineates the virtual station at high frequency (18–20 Hz) in a rectangular window (Da Silva et al., 2010). It has four different satellite altimeter datasets; ENVISAT, Jason 2, Sentinel 3A, and Sentinel 3B for the Ganga River basin. All these datasets come with preliminary corrections such as orbital, ionosphere, troposphere, polar, and sea bias (Dubey et al., 2015). DAHITI is a multi-mission altimetry archive that is similar to Hydroweb, except it uses the Kalman filter for rejecting the outlier in the measurement (Schwatke et al., 2015). For our purpose, we have used the ERS 2 (1995–2007),

Table 2
Details of the satellite altimeter used to established virtual stations and their distance from the existing CWC gauge station on the Ganga River. The base level datum is the Earth Gravitational Model 2008. Width is the average channel width during the non monsoon and monsoon period respectively. Arrow indicate the position of virtual station with reference to the CWC gauge station (↑ = Upstream, ↓ = Downstream).

Station	Altimeter with orbit cycle	Location		Period	Number of altimeter data points	Width (m)	Base datum (m)	CWC gauge station
		Lat.	Lon.					
VS 1	ENVISAT (395)	27.73	79.18	June 2005 to May 2009	36	130, 180	−60.8	Kachla Bridge (42 km ↓)
VS 2	ENVISAT (853)	26.71	80.17	June 2005 to May 2009	34	150, 220	−63.7	Kanpur (68 km ↑)
VS 3	Jason 2 (3)	82.17	26.82	Aug 2008 to Dec 2017	113	350, 400	−62.2	Shahzadpur (22 km ↓)
VS 4	ENVISAT, ERS 2 (767)	25.33	81.96	Oct 2003 to June 2010	57	470, 560	−62.0	Prayagraj (10 km ↓)
VS 5	ENVISAT, ERS 2 (410)	25.11	82.82	June 1995 to Sep 2010	117	550, 700	−62.5	Mirzapur (32 km ↓)
VS 6	ENVISAT (967)	25.32	86.99	Oct 2002 to June 2010	51	900, 1200	−60.6	Azmabad (40 km ↑)
VS 7	ENVISAT (66)	24.38	88.38	Dec 2002 to Nov 2007	40	1100, 2000	−55.9	Farakka (80 km ↓)

Table 3
Difference in water level at the virtual and corresponding gauge station due to the datum difference and distance offset.

CWC station	Virtual station	Difference in height (m)	Offset (m)
Kachla Bridge	VS 1	1.30	−8.2
Kanpur	VS 2	0.20	7.1
Shahzadpur	VS 3	−0.02	−1.9
Prayagraj	VS 4	−0.20	−0.6
Mirzapur	VS 5	0.20	−0.2
Azmabad	VS 6	0.90	3.6
Farakka	VS 7	−0.90	3.2

ENVISAT (2002–2010), and Jason 2 (2008–2017) satellite altimeter data. Table 2 reports the detailed specification of the altimeter dataset.

2.2. Processing of altimeter data

Altimeter data obtained from the open source databases are presumed to be accurate (Schwatke et al., 2015; Dubey et al., 2015). However, there are a few errors that still exist in the database. For example, Hydroweb uses EGM2008 geoid, which does not fit correctly for inland water (Crétaux et al., 2011). It may lead to uncertainty in the water level gauged from the satellite altimeter. To assess the accuracy of water level derived from the satellite altimeter, we compare them with the corresponding in-situ measurement at the gauge station. To minimise this difference, we further process the altimeter data as discussed in the following subsections.

2.2.1. Orthometric correction

The altimeters provide water level in EGM2008 geoid model, whereas CWC uses mean sea level to measure water level at the gauge stations. Hence to compare the in-situ and altimeter measurements, we need to bring them into a common datum. To do this, we have taken the datum height of gauge stations in EGM2008 geoid model. We then transfer the reference height of the altimeter at the virtual stations with respect to their nearby gauge data. For example, the EGM2008 reference value at Farakka station and nearby virtual station (VS 7) is −56.80 and −55.89, respectively. The height difference is −0.91; this difference we add in VS 7. In general, the reference height of altimeter water level is $h_{EGM2008}$ and δh is the difference between gauge station and altimeter datum. The height H is the reference height of the altimeter to the observed stage datum and it can be calculated according to;

$$H = h_{EGM2008} - \delta h \quad (3)$$

Using Eq. (3), we have corrected water level at the virtual stations. Table 3 reports the height difference between the gauge and virtual stations due to the datum differences.

2.2.2. Offset measurement

Even after the datum corrections, sometimes water level obtained from the satellite altimeters is not comparable to the measurement at the corresponding gauge stations. This discrepancy is not uniform throughout; it changes with the seasonal variability. This is probably due to the fact that the location of gauge stations and virtual stations do not coincide. In our case, gauge and virtual stations are separated by the vertical distance ranging from 0.3 m to 1 m. We added an offset value Z in the water level to minimize this gap for all virtual stations. This value can be obtained by computing the median of the error between the gauge and virtual station. Assuming virtual and gauge height at a given time, t, is H^t and H_o^t respectively, then the offset value Z for the virtual station at a concurrent time can be computed according to;

$$Z = median(H_0^t - H^t)_i^n \quad (4)$$

The corrected value of water level H at the virtual station is;

$$H^t = H_i^t + Z \quad (5)$$

where i is the continuous variable for different time instances which ranges from $i = 1, 2, 3, \ldots, n$. The offset value is then added to all the altimeter water levels to make them comparable to the river stage measured at the in-situ gauge station. Offset values for our virtual stations are listed in Table 3.

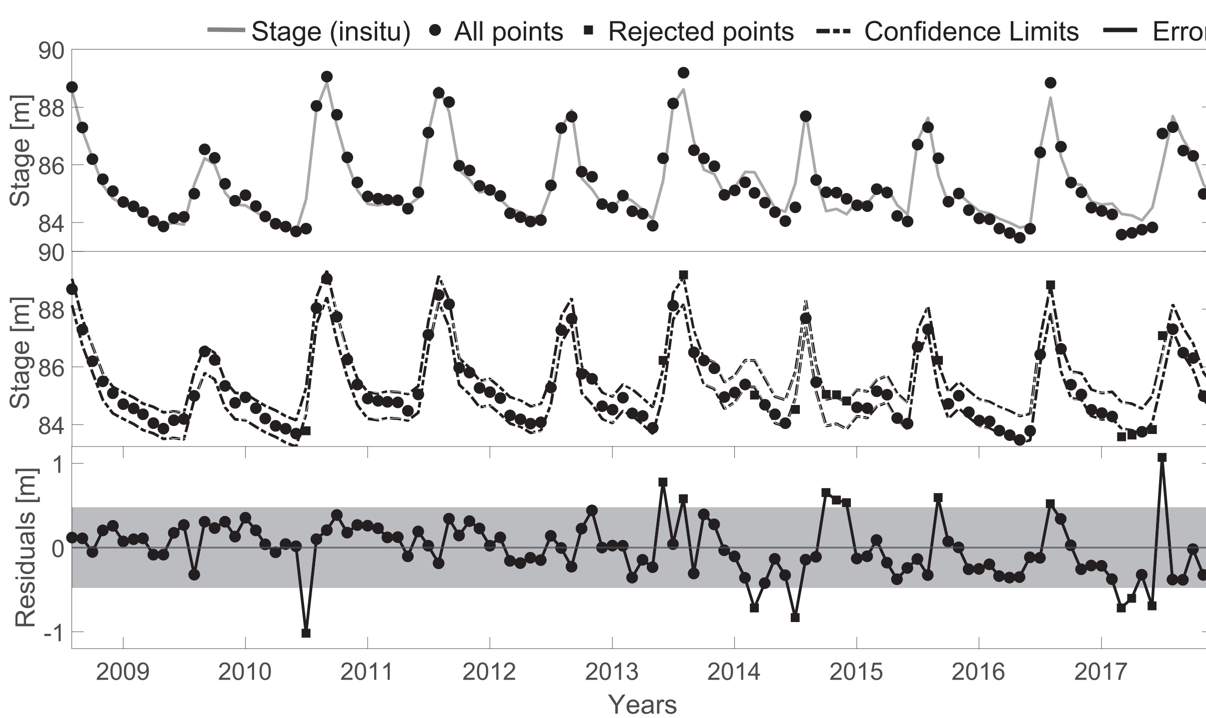

Fig. 2. (a) Time series of river stage obtained from the satellite altimeter (circles in black) at virtual station 3 and Shahzadpur gauge station (grey solid line), (b) the dashed line is the confidence limit obtained from t-statistics analysis at 99% confidence limit. Data points that do not fall within this limit are considered outliers (squares in black) and removed from the analysis, (c) residual is the difference between gauge and altimeter water level. The Shaded region is the confidence limit.

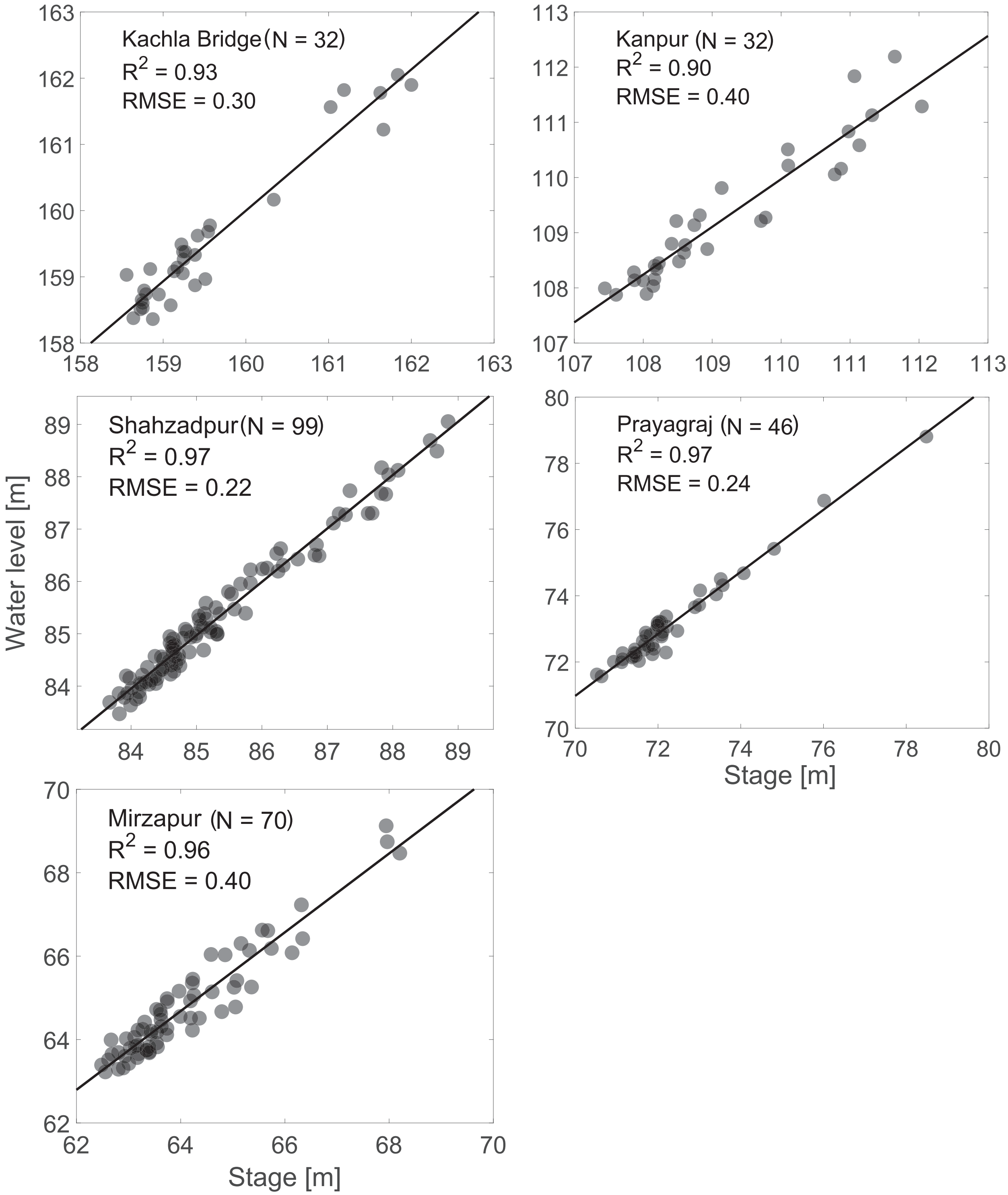

Fig. 3. Water level from the altimeter is plotted as a function of stage measured at the gauge station the middle reaches of the Ganga River.

2.2.3. Rejection of inaccurate points

Water level at the virtual stations still has some random values. These are topography errors that occur due to strong echoes return from the off-nadir view. For example, during the winter season in July 2017 at Shahzadpur, the monthly average gauge height is 86.01 m and the corrected altimeter height is 87.08 m. This makes a difference of 1.07 m to the height measured at the gauge station. To remove erroneous points from the virtual stations, we have performed one sample student t-test at 99% confidence limits on the altimeter derived water level (Birkinshaw et al., 2010). We set the upper and lower limit of t-test of the altimeter data. We reject the data points that do not fall within the limit of the t-test. Fig. 2 illustrates the procedure of the rejection of invalid data points.

2.3. Development of rating curves

We have used altimeter water level and corresponding discharge measured at the nearest gauge station to develop stage-discharge rating curves. At the virtual stations, we split the data into two groups; one to construct the rating curves and the other for validation purpose. First,

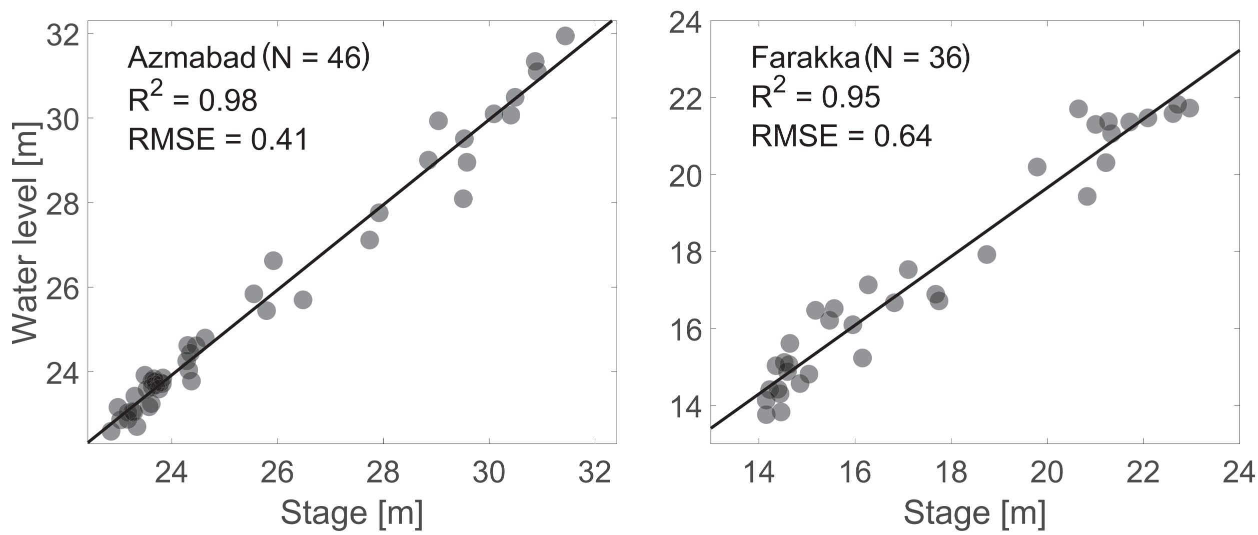

Fig. 4. Water level from the altimeter is plotted as a function of stage measured at the gauge station the lower reaches of the Ganga River.

we construct the rating curve for each virtual station separately using the full length of the available records from the dataset. The resulting empirical curves suggest water levels follow a power-law scaling relation to the discharge.

Further, to evaluate the statistical significance of the coefficients of rating curves, we artificially produce smaller datasets by bootstrapping and fit a power law on them. In doing so, we set 10000 iterations and at every iteration randomly replace 50% of the data points from the dataset used to develop the rating curves. We observed bootstrap does not result in any significant difference in the rating curve parameters. For all the virtual stations the change in the mean value of slope and intercept are less than 7% and 1% respectively. This gives us confidence that 50% of our data can be used to develop rating curves and the remaining 50% for the validation purpose.

2.4. Calibration of rating curves

Before using our rating curve equations to estimate discharge, we need to calibrate them for the strong seasonal variation in the study area. We have calculated the calibration function by median regression technique between the measured and test discharge of 50% rating curve data (Bjerklie et al., 2005; Birkinshaw et al., 2010). This is a robust process and not affected by residual errors. The result of the correction factor is then multiplied to the rating curve according to Eq. (6).

$$Q_i^m = Q_i^p \cdot \beta_{0.5} + e_i \tag{6}$$

where (Q_i^m) is the corrected discharge, (Q_i^p) is the predicted discharge from the rating curve, β is the correction factor, and e_i is model predicted errors.

3. Result

3.1. Accuracy of the altimeter data

We plot the water level at the virtual station against the stage recorded at the corresponding gauge station (Figs. 3 and 4). We observed for all our stations, the water levels at the virtual and gauge stations are highly correlated. Their correlation of determination vary in a range between (R^2 = 0.90 –0.98) with the Root Mean Square Error (RMSE) from 0.22 m to 0.64 m. We noticed a relatively high (RMSE = 0.64 m) for the virtual station at Farakka in the lower Ganga Plain. This appears to be associated with the large distance (81 km) between the virtual and corresponding gauge stations.

After applying the corrections on altimeter data, we observed the accuracy of water level at the virtual stations has improved significantly. In the middle Ganga, initially, the RMSE on the regression between the water level at the virtual and the corresponding gauge station is in a range between 0.33 to 1.30 m. After corrections, the RMSE at the virtual stations has reduced in a range between 0.22 to 0.44 m. Similarly, in the lower Ganga, RMSE has improved from (0.77–1.3) m to (0.41–0.64) m for the virtual stations near Azmabad and Farakka respectively.

3.2. Stage-discharge rating curves

At each virtual station we used 50% of the data to establish rating curves and remaining data for the validation. We do this by selecting the altimeter water level and the corresponding discharge at every alternate month (i.e; Jan, March, May, etc.) from the database. We now plot the monthly average water level against their corresponding monthly average discharge at the nearest gauge station. We observed water level increases non-linearly with the discharge, this can be modeled by a power-law curve (Fig. 5 and 6).

To obtain the coefficients of the best-fit curve of our data points, we have performed a Reduced Major Axis (RMA) analysis at 95% confidence limits. RMA assumes error in both the response and predictor variables and computes the best estimate of slope and intercept of the rating curve (Sokal and Rohlf, 1981; Gaurav et al., 2017). Table 4 reports the rating curve parameters of the virtual stations obtained from the RMA analysis. The rating curves are generated with the assumption that for a shorter distance, the variability in discharge between the gauge and virtual station will be less. Practically, at a gauge station more than one rating curve can be established corresponding to the different hydrologic regimes (Kouraev et al., 2004).

Since we have established one rating curve at each gauge station, we can expect the effect of inter-seasonal variation. This variation is more prominent at the stations where discharge is very low. In our case, discharge in the non-monsoon period is very low (< 1000) m^3s^{-1} and increases drastically during the monsoon period (3000–20,000) m^3s^{-1} in the middle reaches of the Ganga River. In contrast, this difference is relatively less at the downstream gauging stations (Azmabad and Farakka) of the Ganga River.

3.3. Measured vs. predicted discharge

Our estimated discharge at the virtual station compares with the monthly discharge measured at the corresponding ground station. Figs. 7 and 8 show the time series of estimated and measured discharge

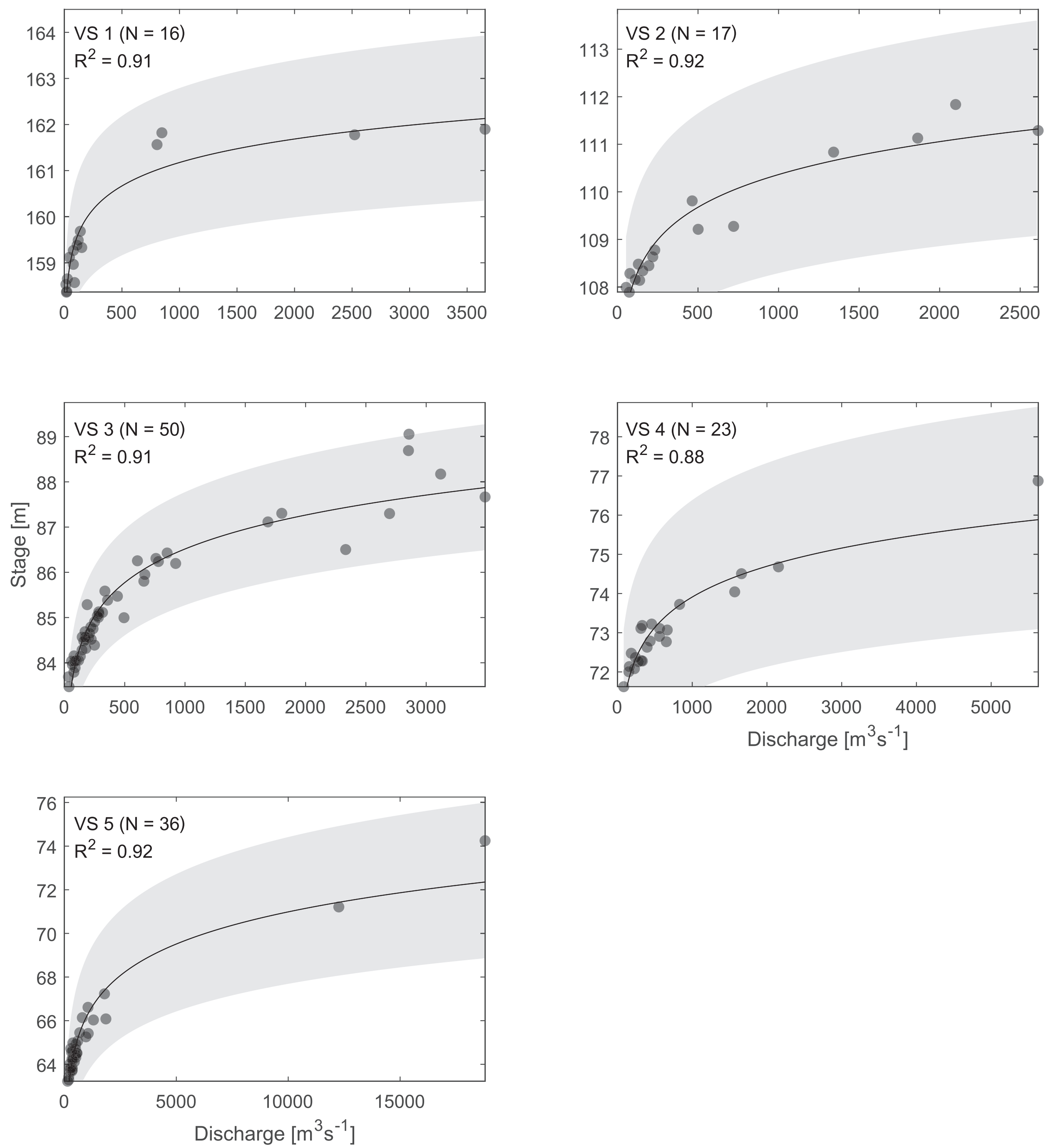

Fig. 5. Stage-discharge rating curve established at the virtual stations (VS 1 to VS 5) in the middle reaches of the Ganga River. The shaded region shows the 95% confidence level.

at the virtual stations in the middle and lower reaches of the Ganga River. A qualitative assessment of the discharge hydrographs reveals a closer agreement between the measured and predicted discharge. However, there are a few instances when the predicted and measured discharge do not compare. For example, at the virtual station near Kanpur, the difference between measured and predicted discharge in September 2008 is about 4161 m^3s^{-1}. Such differences are rare in our record and do not show any temporal correlation.

Further, we compare the average monthly discharge of the virtual and ground stations. We computed the uncertainties in the measured discharge at the ground station along with their mean values. We have removed simulated discharge values that are over-predicted. To compute the monthly average discharge at the virtual station, we considered the months for which at least altimeter data is available on two different dates. Usually a difference of about (15–20)% between the measured and simulated discharge is acceptable in the scientific community. However, this limit is not valid in the narrow rivers (Calmant et al., 2008). The width of our rivers is less than 1 km (Table 2), we expect a bit higher uncertainty in the simulated discharge as compared to the permissible range. Table 5 reports the error between the discharge estimated at the virtual and measured at the corresponding gauge station. In the non-monsoon period, the Ganga River flows at shallow depth in the middle reaches (Kachla bridge and Kanpur). This is reflected in the discharge time series of these stations. For example, during the non-monsoon period, the average monthly discharge of the Ganga River at Kachla bridge is below 200 m^3s^{-1}. The shallow flow depth of the Ganga

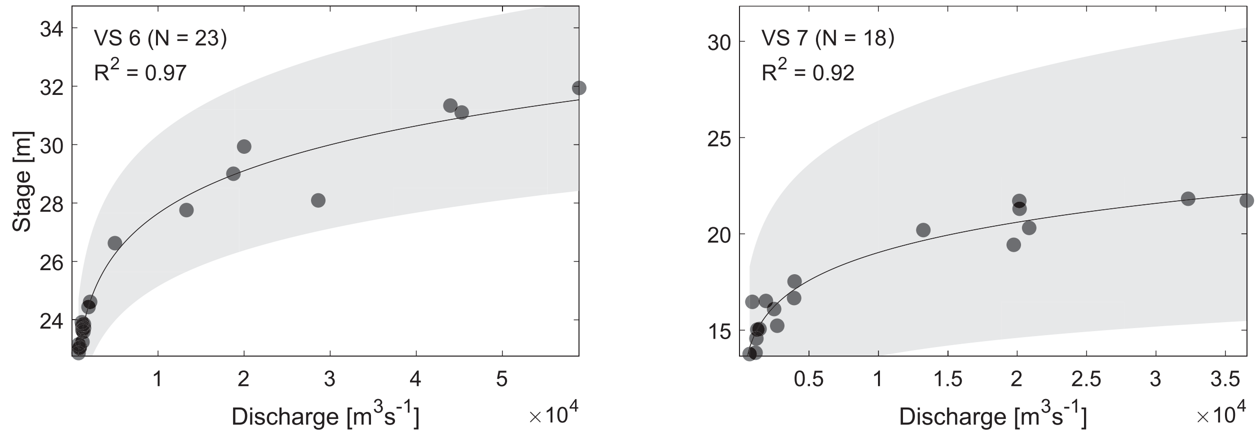

Fig. 6. Stage-discharge rating curve established at the virtual stations (VS 6 and VS 7) in the middle reaches of the Ganga River. The shaded region shows the 95% confidence level.

Table 4
Rating-curve coefficient of virtual stations established at different locations in the middle and lower reaches of the Ganga River. R^2 is the coefficient of determination and RMSE is the root mean square error of the regression equations.

Location	Intercept	Slope	R^2	RMSE
Kachla Bridge	156	0.005	0.91	0.41
Kanpur	104	0.009	0.92	0.38
Shahzadpur	79	0.012	0.91	0.39
Prayagraj	65	0.019	0.86	0.54
Mirzapur	55	0.026	0.91	0.40
Azmabad	14	0.074	0.91	0.49
Farakka	7	0.115	0.92	0.83

River in the middle reaches results in high uncertainty in the measurement of water level from satellite altimeter and eventually in discharge. We observed the simulated discharge in the lower Ganga River accord well (< 25%) with the measured discharge.

We have also performed the sensitivity analysis of our result. In doing so, we assumed ±10 cm error in altimeter water level. This results in about less than 10% difference in mean annual discharge of all virtual stations to their initial estimates. Except for the Kachla bridge and Kanpur during the non-monsoon period, the difference in average monthly discharge is less than 10% for all months. The difference in average monthly discharge at Kachla bridge and Kanpur in the non-monsoon period is about 15%.

4. Discussion

To evaluate the performance of virtual stations, we calculate Nash–Sutcliffe efficiency (NSE), RMSE-observations Standard deviation Ratio (RSR), and PBIAS (Nash and Sutcliffe, 1970; Gupta et al., 1999; Moriasi et al., 2007). NSE is used to quantify the magnitude of relative variance with measured discharge, the RSR for the error-index, and PBIAS for the average bias in the simulated values.

Figs. 7 and 8 show a comparison between the observed and estimated discharge. We followed the performance rating to evaluate the result obtained for each of the virtual stations (Moriasi et al., 2007). The estimated discharge is considered satisfactory, if NSE > 0.5, RSR < 0.7, and PBIAS ± 25. Table 6 reports the quantitative statistics of the predicted discharge at each of the virtual stations.

Based on these indices, we report the performance of our rating curves to estimate discharge at the virtual stations (Table 6). We observed estimated discharge at the virtual stations compare well with the average monthly discharge measured at the gauge station. The correlation of determination (R^2), between the estimated and measured discharge is in range between (0.87–0.98), NSE (0.84–0.98), and RSR (0.15 to 0.38). According to (Moriasi et al., 2007), the values of our indices can be considered satisfactory. We observed PBIAS in range (13–27), based on this value we can qualitatively categorise the estimated discharge at the virtual stations as satisfactory and unsatisfactory.

For any model it is important to estimate the associated uncertainty in the result. To assess the uncertainty, we have considered NSE, RSR, and PBIAS indices. In the Lower Ganga reaches, the estimated discharge accord well with the measured discharge at the nearest gauge station. For example, estimated discharge near Azmabad (NSE = 0.98, RSR = 0.15, PBIAS = 13, and R^2 = 0.98) and Farakka (NSE = 0.96, RSR = 0.21, PBIAS = 17, and R^2 = 0.96) are highly correlated with the discharge measured at the nearest gauge station. In-contrast, virtual stations (Kachla bridge, Kanpur, Shahzadpur, Mirzapur) in the middle Ganga relatively exhibit a large uncertainty in the estimated discharge. This is probably associated with the relatively less discharge in the middle reaches of the Ganga River as compared to the lower reaches.

Another source of uncertainty in the estimated discharge is due to the temporal resolution of the satellite altimeter. We have used data from different satellite altimeter missions to estimate the monthly discharge at the virtual stations. Compilation of water level data from multiple altimeter satellites can provide a repeat measurement at higher frequency. Some altimeter missions provide more than one repetitive measurement of the stage in a month whereas other provide just one measurement. The repetitive altimeter data of a given month is averaged to get the monthly estimate of the water level. Whereas, if a satellite altimeter has just one pass that water level has been considered a representative value for that month. This irregular sampling may result in a discrepancy between the estimated discharge and average monthly discharge at the ground station.

Especially during the peak flow, we observed that the discharge estimated from the satellite altimeter having a single pass in a given month results in a large difference from the measured discharge at the gauge station. According to (Papa et al., 2010), the estimated discharge of the Ganga–Brahmaputra river should not exceed or below more than 20% from gauge discharge using 35 days sampling resolution. In our case, (80–90)% discharge residual errors are under the range of 20%. We notice estimated discharge at the virtual stations is relatively high at the locations where flow of the Ganga River is relatively less. The uncertainty in the simulated discharge is also due to the proper calibration of the water level between the gauge and virtual stations. In rivers, it has been observed that the accuracy of water level obtained from publicly available satellite altimeter data varies in a range between 10 cm to 100 cm (Dubey et al., 2015; Schwatke et al., 2015), whereas, the Central Water Commission (CWC), New Delhi reports the water level for the Indian rivers within an accuracy of 5 mm. This difference in the accuracy

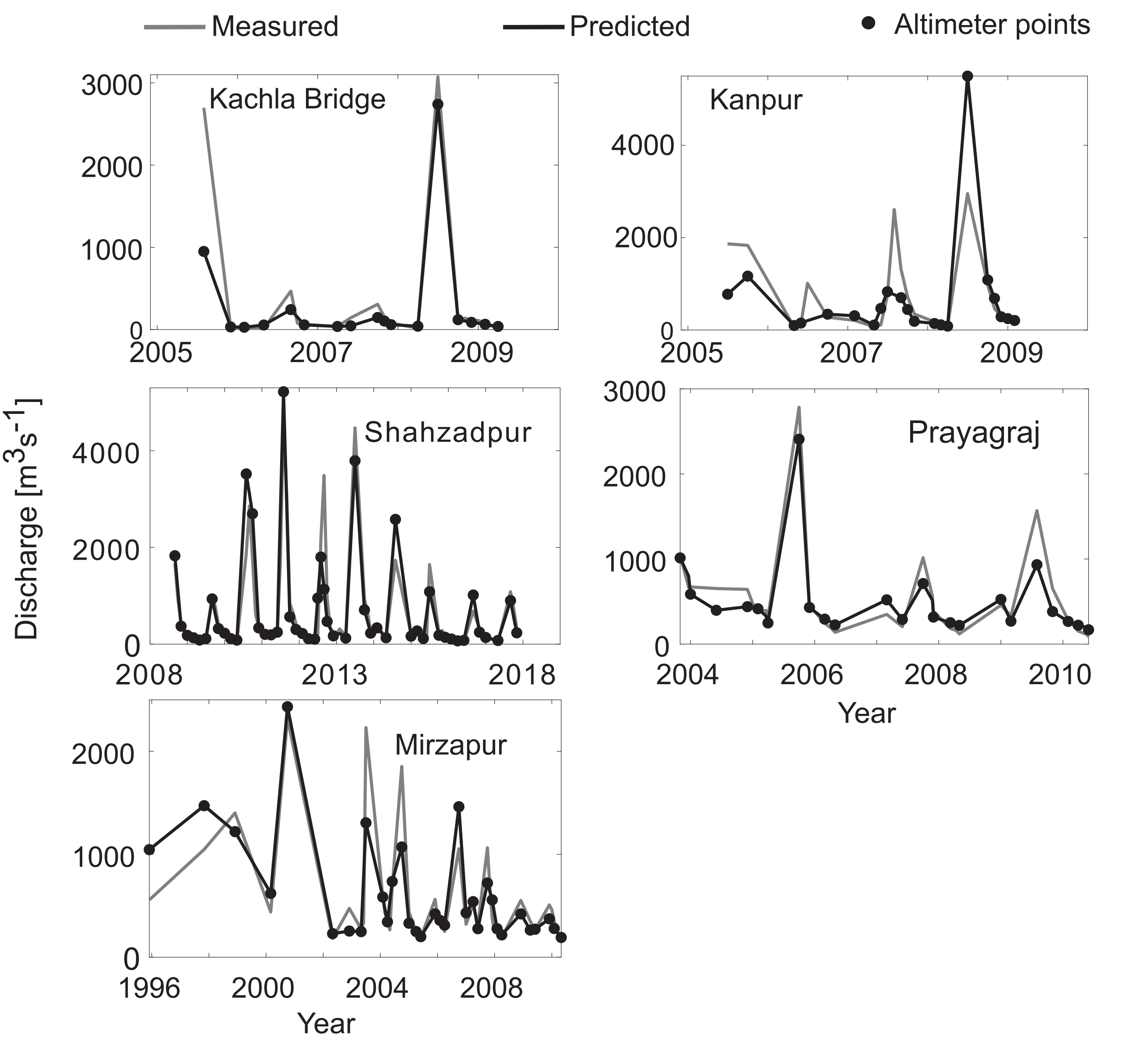

Fig. 7. Time series of a monthly average discharge in the lower reaches of the Ganga River. The Solid lines in grey and black are the measured and predicted discharge respectively.

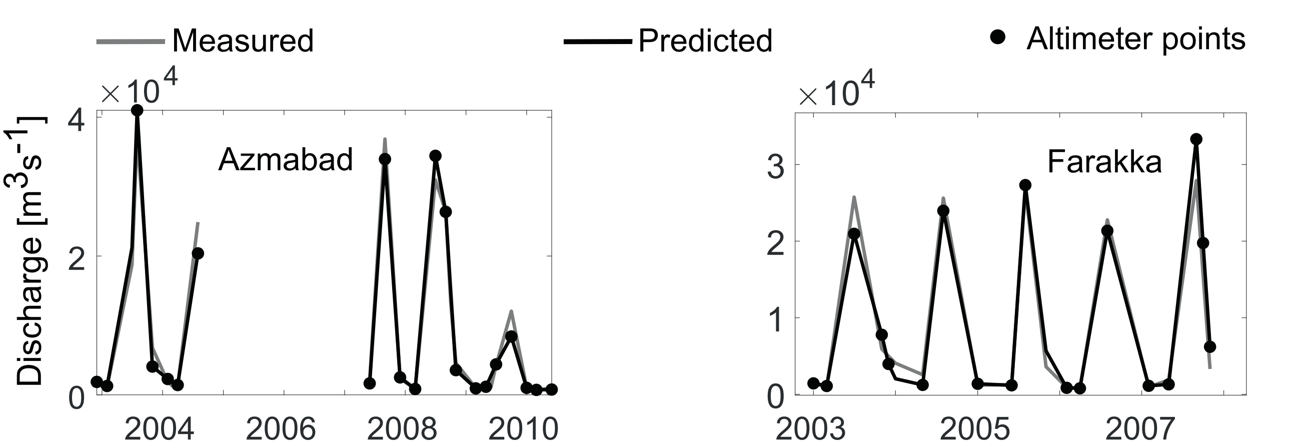

Fig. 8. Time series of a monthly average discharge in the lower reaches of the Ganga River. The Solid lines in grey and black are the measured and predicted discharge respectively.

Table 5
Average monthly values of river discharge from satellites altimeter and in-situ data at the middle and lower Ganga. Error % is the residual error between measured and estimate discharge.

	Station	Discharge (m^3s^{-1})	January	February	March	April	May	June	July	August	September	October	November	December
Middle Ganga	Kachla Bridge	Q_m	68±60	54±41	NA	34±6	NA	NA	NA	NA	NA	168±123	117±47	76±41
		Q_p	54	46	NA	38	NA	NA	NA	NA	NA	139	88	60
		Error%	19.8	14.46	NA	−12.9	NA	NA	NA	NA	NA	17.2	24.96	19.81
	Kanpur	Q_m	180±37	188±17	NA	85±3	NA	104±29	1309±789	1977±898	1592±384	830±691	437±109	NA
		Q_p	188	225	139	80	86	112	1344	2083	1456	647	556	NA
		Error%	3.52	16.27	21.90	6.35	36.71	7.15	2.73	5.4	9	22.10	27	NA
	Shahzadpur	Q_m	225±59	193±64	187±76	147±73	106±30	100±80	2049±1725	1941±1360	1845±1163	837±432	435±144	257±81
		Q_p	200	177	152	117	103	126	2016	1602	1607	752	385	214
		Error%	11.03	8.31	18.85	20.58	3.22	26.15	1.60	17.46	12.89	10.13	11.46	16.7
	Prayagraj	Q_m	522±130	331±72	274±104	208±91	123±13	313±300	NA	NA	NA	1900±1251	754±256	494±133
		Q_p	513	341	313	235	147	285	NA	NA	NA	1560	637	396
		Error%	1.7	−2.97	14.2	12.90	−19.45	9.07	NA	NA	NA	17.88	15.56	19.89
	Mirzapur	Q_m	522±130	331±72	274±104	208±91	229±60	319±179	NA	4429±886	31624±7398	1542±499	792±186	633±345
		Q_p	439	394	381	341	257	364	NA	4555	25411	1364	779	627
		Error%	12.19	10.83	−15.01	−5.35	12.07	−14.16	NA	−3.30	20	11.55	1.66	0.87
Lower Ganga	Azmabad	Q_m	1143±105	1318±519	996±269	1173±258	1158±248	1589±625	24860±8632	NA	31624±7398	12679±886	5678±1546	2119±315
		Q_p	1288	1474	1166	1288	1344	1654	27826	NA	30165	11684	4567	2188
		Error%	3.25	12.7	11.8	17.04	19.7	16.1	4.13	NA	−4.61	-7.85	19.58	3.26
	Farakka	Q_m	2182±1633	1049±207	NA	NA	2219±490	NA	NA	26168±777	NA	NA	NA	NA
		Q_p	1614	1064	NA	NA	1796	NA	NA	25639	NA	NA	NA	NA
		Error%	−14	−1.4	NA	NA	19.06	NA	NA	2.02	NA	NA	NA	NA

Table 6
The calibrated water level (H) and Discharge (Q) rating curve and the performance evaluation at different virtual stations established on the Ganga River.

Virtual Station	Water Level (m)	Rating curve (Eq. 6)	NSE	RSR	PBIAS	R^2	Performance
Kachla Bridge	158–162	$Q = 1.27\left[\frac{H+8.2}{155}\right]^{207}$	0.92	0.23	25	0.98	Satisfactory
Kanpur	108–112	$Q = 1.03\left[\frac{H-7.1}{103}\right]^{107}$	0.84	0.38	27	0.87	Unsatisfactory
Shahzadpur	84–89	$Q = 1.09\left[\frac{H+1.9}{79}\right]^{77}$	0.91	0.21	25	0.91	Satisfactory
Prayagraj	72–80	$Q = 0.95\left[\frac{H+0.6}{64.8}\right]^{51}$	0.91	0.25	22	0.95	Satisfactory
Mirzapur	64–74	$Q = 0.86\left[\frac{H+0.2}{54.4}\right]^{39}$	0.86	0.30	21	0.88	Satisfactory
Azmabad	22–32	$Q = 0.93\left[\frac{H-3.6}{13.9}\right]^{14}$	0.98	0.15	13	0.98	Good
Farakka	14–22	$Q = 1.04\left[\frac{H-3.2}{6.32}\right]^{8}$	0.96	0.21	17	0.96	Satisfactory

of the water level introduces uncertainty in the final discharge estimated from the satellite altimeter.

5. Conclusion and future outlook

Water level derived from satellite altimeter mission can be used to estimate monthly average discharge at different reaches along the Ganga River. This study relies on empirical stage-discharge relationship between the water level obtained from the satellite altimeter to the discharge measured at the nearest gauge station. Our rating curves provide an accurate estimate of discharge at the lower reaches (Azmabad and Farakka) of the Ganga River. This is probably associated with the deeper flow, wider channel, and high discharge regime (Table 5) in the lower Ganga. Similarly, in the middle Ganga, shallow flow, and low discharge (Table 5) results in relatively high uncertainty in the estimated discharge. Based on the statistical evaluation, for all our virtual stations the estimated monthly average discharge fall in the range between good to satisfactory.

This study is a step towards estimating discharge in the ungauged river basins from satellite altimeter data. Though we applied our methodology only on alluvial reaches of the Ganga River, it can be extended to other alluvial and bedrock rivers of different geological and climatic regimes, if the ground measurement of discharge is accessible. At present, our methodology requires at least one gauge station in the proximity of altimeter track to establish a stage-discharge rating curve. In the absence of gauge discharge, establishing such a curve will be challenging. The upcoming SWOT mission is expected to fill this gap in estimating discharge in ungauged river basins solely from satellite data.

CRediT authorship contribution statement

Atul Kumar Rai: Conceptualization, Data curation, Methodology, Software, Writing – original draft. **Zafar Beg:** Conceptualization, Data curation, Methodology, Software, Writing – original draft. **Abhilash Singh:** Formal analysis, Software. **Kumar Gaurav:** Conceptualization, Methodology, Writing – review & editing, Project administration, Funding acquisition, Investigation, Resources, Supervision, Validation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are thankful to the Central Water Commission, Ministry of water resources, New Delhi, and global river discharge databases (RivDIS v1.0) for providing the discharge data. We are thankful to DAHITI and Hydroweb altimetry data archives for making available altimetry data points in public domains. We are thankful to the Indian Institute of Science Education and Research Bhopal for providing institutional support. We acknowledge the funding from the Ministry of Earth Sciences, New Delhi through grant: MoES/PAMC/H & M/84/2016-PC-II and Ministry of Education, New Delhi through grant: STARS/APR2019/ES/787/FS.

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