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Satellite altimetry for Indian reservoirs

Kaushlendra Verma [a], Akhilesh S. Nair [a,e], Indu Jayaluxmi [a,b,*], Subhankar Karmakar [b,c], Stephane Calmant [d]

[a] Department of Civil Engineering, Indian Institute of Technology, Bombay 400076, India
[b] IDP in Climate Studies, Indian Institute of Technology, Bombay 400076, India
[c] Environmental Science & Engineering Department, Indian Institute of Technology, Bombay 400076, India
[d] Institut de Recherche pour le Developpement (IRD), Laboratoire D'études En Géophysique Et Océanographie Spatiales, France, in Deputation at IISc, Bangalore 560012, India
[e] Geophysical Institute, University of Bergen, Bergen 5020, Norway

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Abstract

Satellite radar altimetry has immense potential for monitoring fresh surface water resources and predicting the intra-seasonal, seasonal, and inter-annual variability of inundated surface water over large river basins. As part of the Preparation for the Surface Water and Ocean Topography mission scheduled for launch in mid-2022, the present study aimed to evaluate the performance of radar altimetry over the inland water bodies of India. The Joint Altimetry Satellite Oceanography Network (Jason) and Satellite with ARgos and ALtiKa (SARAL/AltiKa) data were used to derive the water levels of 18 major reservoirs in India by incorporating the geophysical and propagation corrections into the radar range. In situ gauge data were used to evaluate the performance of the altimetry-derived water level time series from 2008 to 2019. The results showed a strong correlation between Jason-2 and in situ data with the determination coefficient (R^2) and root mean squared error ($RMSE$) ranging from 0.96 to 0.99 and from 0.28 m to 1.62 m, respectively. The Jason-3 data had the highest correlation with the in situ observation ($R^2 = 0.99$) and the lowest correlation ($R^2 = 0.82$), with $RMSE$ values ranging from 0.11 m to 1.18 m. With an R^2 range of 0.93−0.99 and an $RMSE$ range of 0.20−1.05 m, the SARAL/AltiKa mission presented greater accuracy than the Jason altimetry mission. The estimated water levels can be utilized in remote, inaccessible, or ungauged areas and in international transboundary rivers for water storage and river discharge estimations. However, the accuracy of remotely sensed data depends on such factors as along-track distance, water body area, and geographical and terrain conditions near water bodies.

Keywords: Satellite altimetry; Inland water body; Reservoir; SWOT; SARAL/AltiKa

1. Introduction

River discharge is an important freshwater resource that is directly accessible to ecosystems and human civilization but produces natural hazards such as floods and droughts. Approximately 90% of global natural disasters are related to water (UNESCO, 2019). From 1995 to 2015, floods and droughts accounted for 43% and 5% of the total natural disasters, respectively (Wallemacq et al., 2015). Hydro-climatic extreme events affected 3.4 billion people, resulting in the deaths of 179 000 and an overall damage amounting to 762 billion US dollars (Wallemacq et al., 2015). These hydro-climatic extremes are difficult to predict but can be monitored by measuring the change in water levels of rivers, reservoirs, and lakes. The continuous monitoring of water

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[*] Corresponding author.
E-mail address: indus.j@gmail.com (Indu Jayaluxmi).

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level fluctuations in continental surface water bodies indicates the long-term changes in climatic parameters such as evaporation and precipitation (Nielsen et al., 2015). Given that water levels in rivers and associated discharges are fundamental contributors to the water cycle, it is important to evaluate their spatiotemporal variability on global and regional scales (Alsdorf et al., 2007; Papa et al., 2010; Frappart et al., 2012). The traditional method for river discharge monitoring uses indirect measurements with a rating curve that is a functional law established between water level and river discharge (Chow et al., 1998).

Over the last two decades, satellite missions such as the Environmental Satellite (ENVISAT), European Remote Sensing (ERS), Topography Experiment (TOPEX)/Poseidon, and Joint Altimetry Satellite Oceanography Network (Jason) have been launched to monitor water levels in lakes (Birkett, 1995; Alsdorf et al., 2007; Calmant and Seyler, 2006; Papa et al., 2006; Domeneghetti et al., 2014, 2015; Schwatke et al., 2015), reservoirs (Crétaux et al., 2015), and rivers (Kouraev et al., 2004; Pandey et al., 2014). Meanwhile, the altimetry-based water levels have been used to monitor the storage of reservoirs (Alsdorf et al., 2007; Calmant et al., 2008; Crétaux et al., 2016) and several lakes in the Tibetan Plateau (Zhang et al., 2013; Kleinherenbrink et al., 2015; Jiang et al., 2017). Moreover, satellite altimetry has been used to estimate the complementary information of inundated surface water extent (Shamsudduha et al., 2009) and river discharge (Birkinshaw et al., 2010; Getirana, 2010; Michailovsky et al., 2013; Tarpanelli et al., 2013; Paris et al., 2016). Altimetry-based water levels have been utilized to monitor transboundary river basins such as the Brahmaputra (Michailovsky et al., 2013; Maswood and Hossain, 2016), Amazon (Seyler et al., 2008; Silva et al., 2010, 2012), Orinoco (Frappart et al., 2015a), and Congo rivers (Becker et al., 2014) through the observations of hydraulic variables such as cross-sectional area, width, slope, and surface water level (Kouraev et al., 2004; Bjerklie et al., 2005; Brakenridge et al., 2005; LeFavour and Alsdorf, 2005; Alsdorf et al., 2007; Hossain et al., 2014; Gleason and Hamdan, 2017). The primary satellite missions launched by the Department of Defence/National Aeronautics and Space Administration (NASA), which include the Geodynamics and Earth Ocean Satellite 3, Seafaring Satellite, Geodetic/Geophysical Satellite (GEOSAT), and GEOSAT Follow-on, have fundamentally improved the accuracy of satellite radar altimetry estimates. In addition, TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 of NASA, the National Centre for Space Studies (CNES), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)/National Oceanic and Atmospheric Administration (NOAA), and satellite missions such as ERS-1/2, ENVISAT, Cryosphere Satellite 2, and Sentinel-3, of the European Space Agency, have substantially enhanced the performance of radar altimetry. Some other missions in operation are also dedicated to radar altimetry, such as the Satellite with ARgos and ALtiKa (SARAL/AltiKa) sponsored by CNES and the Indian Space Research Organisation (ISRO) and Hai Yang 2A supported by China (Verron et al., 2018).

The Surface Water and Ocean Topography (SWOT) mission developed by NASA and CNES in association with the Canadian Space Agency and the United Kingdom Space Agency, is scheduled to be launched in mid-2022. The SWOT mission is committed to surface hydrology. It will provide surface water elevation and water mask of water bodies using a two-dimensional wide-swath Ka-band radar interferometer (Durand et al., 2010; Fu et al., 2012). SWOT is designed to sense the ground at a higher spatiotemporal resolution in comparison to the existing altimetry missions (Durand et al., 2010; Biancamaria et al., 2016; Rodriguez and Callahan, 2016). It is designed to have a temporal resolution of 21 d with 2−4 observational revisits depending on the latitude (Biancamaria et al., 2010, 2016). Before the launch of the SWOT mission, investigations are required to examine the potential applicability of the existing altimetry-based reservoir water levels. This study evaluated the performance of current satellite radar altimetry for India's inland freshwater bodies for the planned SWOT mission. We summarized the satellite altimetry missions over India and conducted an intercomparison of data from satellite altimetry missions with in situ gauge data. The article is organized as follows. Section 2 provides information on satellite radar altimetry data used in the present study and details the in situ gauge observations of Indian reservoirs. Section 3 describes the methodology, and Section 4 provides the results and a discussion of this study.

2. Data

2.1. Satellite radar altimetry data

In this study, the available satellite radar altimetry data of Jason-2, Jason-3, and SARAL/AltiKa level-2 in geophysical data records were used to estimate the satellite-derived reservoir water levels. Jason-2 and Jason-3 were launched in 2008 and 2016, respectively, and included a Poseidon-3 radar altimeter operated in Ku (13.575 GHz) and C (5.3 GHz) microwave bands, a real-time geographic positioning system, a laser reflector array, Doppler Orbitography and Radio-Positioning Integrated by Satellite, and an advanced microwave radiometer. The sampling frequency of the 20-Hz waveform retracted through the Ice-1 algorithm, which is equivalent to a 315-m posting along-track distance of Jason-2 and Jason-3, was used for the range values. Similarly, the SARAL/AltiKa mission data at a Ka-band (35.75 GHz) observed microwave frequency of 40-Hz waveform, which are retracted through the Ice-1 algorithm at an along-track distance 170 m, were used for the period of 2013−2016. Given that the improved bandwidth of 500 MHz enhances the vertical resolution, SARAL/AltiKa is particularly suitable for rivers and lakes (Verron et al., 2018). Table 1 shows the characteristics of satellite data used in this study.

2.2. In situ data

In situ gauge reservoir water level data were collected from the India Water Resources Information System portal. All

Table 1
Characteristics of satellite altimetry missions.

Satellite mission	Along-track distance (m)	Repeat cycle (d)	Time period	Agency	Retracking algorithm	Frequency
Jason-2	315	10	2008−2016	NASA/CNES	Ice-1	Ku/C
SARAL/AltiKa	170	35	2013−2016	CNES/ISRO	Ice-1	Ka
Jason-3	315	10	2016−2019	NASA/CNES/EUMETSAT/NOAA	Ice-1	Ku/C

reservoirs in India are monitored by the Central Water Commission of India at the state level. Major reservoirs of India were selected for this study according to the satellite tracks directly passing over the waterbodies and the availability of in-situ gauge data. Fig. 1 shows the selected 18 reservoirs. In India, the Great Trigonometric Survey (GTS) is used as the benchmark for the orthometric heights with the Earth reference ellipsoid World Geodetic System 1984. In situ water level data from 2008 to 2019 were used in this study.

3. Methodology

3.1. Satellite-derived water levels

The satellite radar propagates a short pulse of microwave radiation towards the targeted Earth's surface with the speed of light. The satellite senses the two-way travel time of the received pulse between the satellite and Earth's surface and finally interns into the radar range, which is given as follows:

$$R_{\mathrm{r}} = c\Delta t/2 \tag{1}$$

where R_{r} represents the radar range; c is the speed of light (3×10^8 m/s) in a vacuum; and Δt is the travel time of the radar pulse.

The difference between satellite altitude (with reference to Earth ellipsoid) and the radar range gives the height of the reflective surface. As the radar pulse travels through the atmosphere twice, it gets attenuated by dry gases, water vapor, and free electrons in the atmosphere, leading to errors in the calculated reflective surface height. Thus, the propagation corrections such as dry troposphere corrections (DTC), wet troposphere corrections (WTC), and ionosphere corrections (IC), along with the geophysical corrections (i.e., solid Earth tide (SET) and polar Earth tide (PET)) were used to calculate the height of reflective surface:

$$H = a - (R_{\mathrm{r}} + E_{\mathrm{dtc}} + E_{\mathrm{wtc}} + E_{\mathrm{ic}} + E_{\mathrm{set}} + E_{\mathrm{pet}}) \tag{2}$$

where H is the height of the reflective surface, a is the satellite altitude with reference to Earth ellipsoid, E_{dtc}, E_{wtc} and E_{ic} are the errors via the propagation corrections of DTC, WTC, and IC, respectively, and E_{set} and E_{pet} are the errors through the geophysical corrections of SET and PET, respectively. After the geophysical and propagation corrections of the radar range were conducted, the ellipsoidal height was converted into the orthometric height of the reservoir surface, with consideration of the local geoidal undulation (N_{g}):

$$h = H - N_{\mathrm{g}} \tag{3}$$

where h is the height of surface water. Data of surface water height were used to plot the time series after the outliers were removed from the datasets.

3.2. Removal of outliers

It is important to remove the outliers in each satellite track to guarantee the accurate measurement of surface water height. Outlier filtering was conducted by removing the outliers in each track before the averaged water level for each cycle over the reservoir was calculated. In this study, the water level values beyond twice the standard deviation of the absolute median of epochs each day were excluded. This method for outlier removal is robust for the non-Gaussian distribution of samples (Blewitt et al., 2016; Leys et al., 2013).

3.3. Time series evaluation using regression analysis

The time series of satellite-derived water levels were constructed after outlier removal. The combined time series of Jason-2 and Jason-3 with an observation frequency of 10 d and the time series of SARAL/AltiKa with a frequency of 35 d were constructed from 2008 to 2019. Finally, the comparison was carried out between the satellite-derived water level time series and the in-situ gauge data with linear regression and the root mean squared error ($RMSE$).

4. Results and discussion

4.1. Evaluation of Jason-2 and Jason-3 derived water levels

The Jason-2 and Jason-3 altimetry-derived water levels were evaluated for the reservoirs (Figs. 2 and 3). The number of valid samples (N) of Jason-2 and Jason-3 for the reservoirs varied significantly from one place to another and ranged between 90 and 300 in the period of 2008−2016. The water levels derived from Jason-2 and Jason-3 were compared with the in-situ gauge observations. The result for the Bansagar dam showed that the satellite-derived water levels correlated with the in-situ gauge data quite well, with a determination coefficient (R^2) of 0.99 for both Jason-2 and Jason-3 (Figs. 2(a) and 3(a)). With Jason-2, the altimetry observed a higher number of valid samples ($N = 284$) in the Bansagar dam than those in the Supa dam ($N = 32$). Similarly, with Jason-3, the valid sampling by altimetry varied from $N = 95$ at the Bansagar dam to $N = 12$ at the Sardarsarovar dam (Fig. 1(m)). The possible reasons for the large variations

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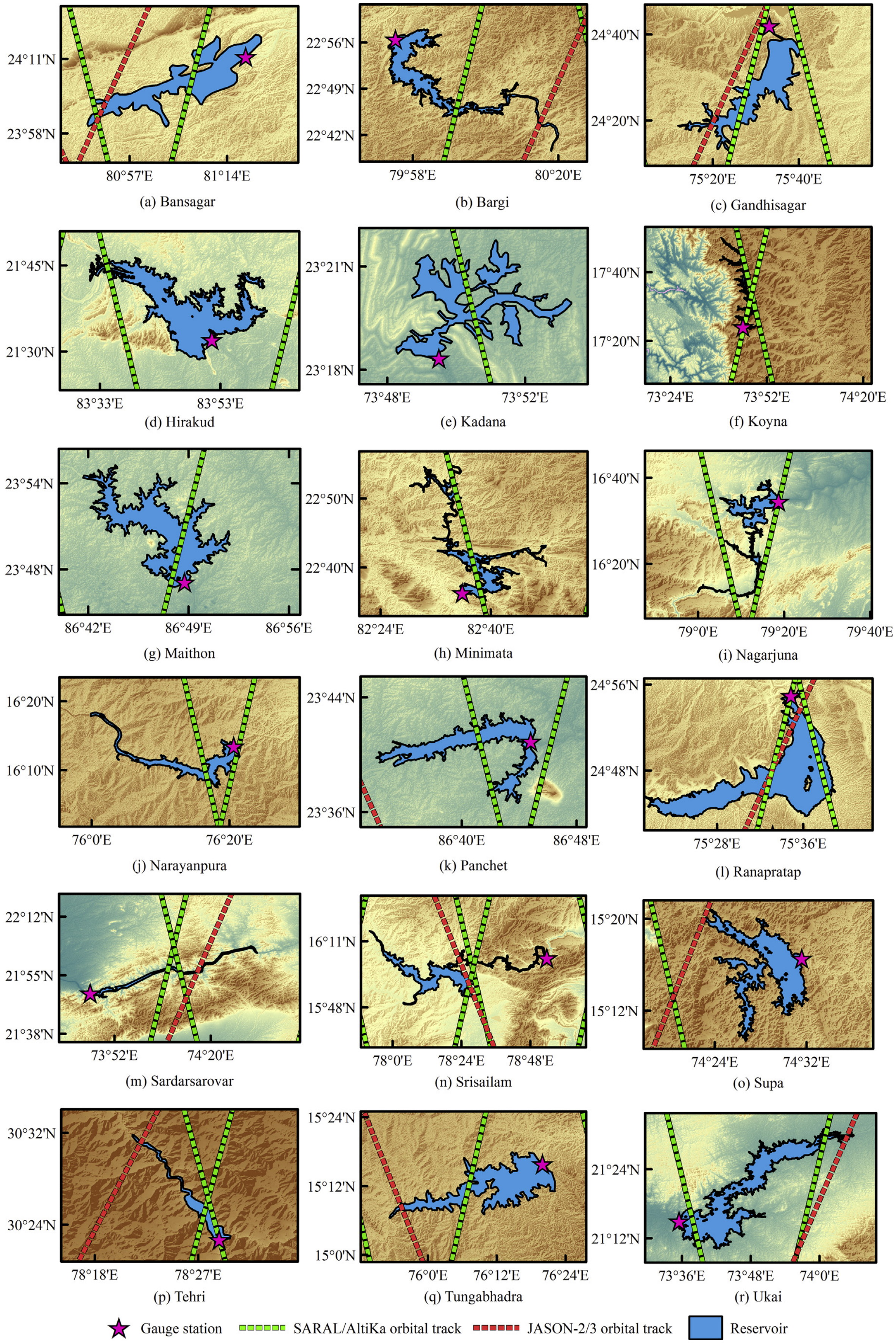

(a) Bansagar (b) Bargi (c) Gandhisagar

(d) Hirakud (e) Kadana (f) Koyna

(g) Maithon (h) Minimata (i) Nagarjuna

(j) Narayanpura (k) Panchet (l) Ranapratap

(m) Sardarsarovar (n) Srisailam (o) Supa

(p) Tehri (q) Tungabhadra (r) Ukai

Fig. 1. Satellite track pass of Jason-2/3 and SARAL/AltiKa over reservoirs.

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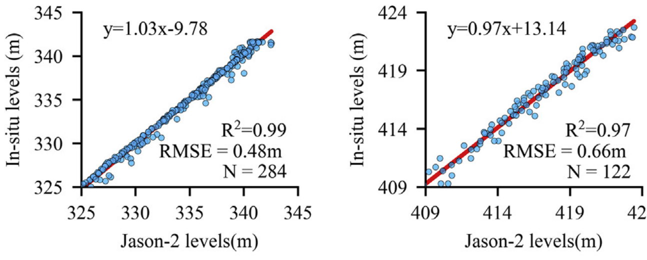
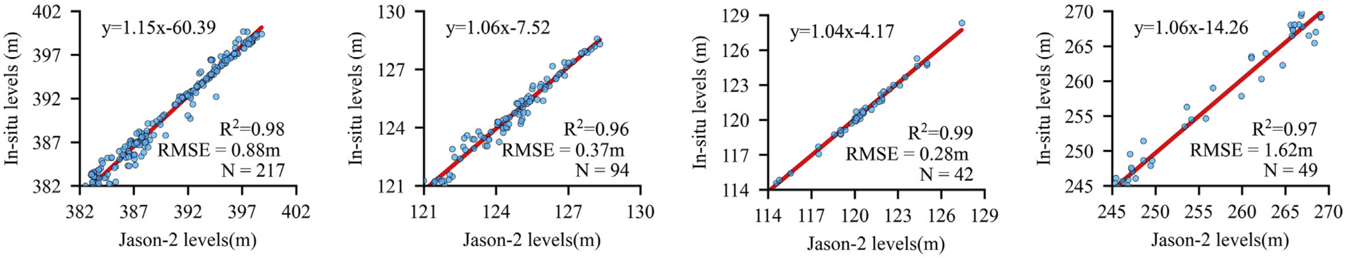
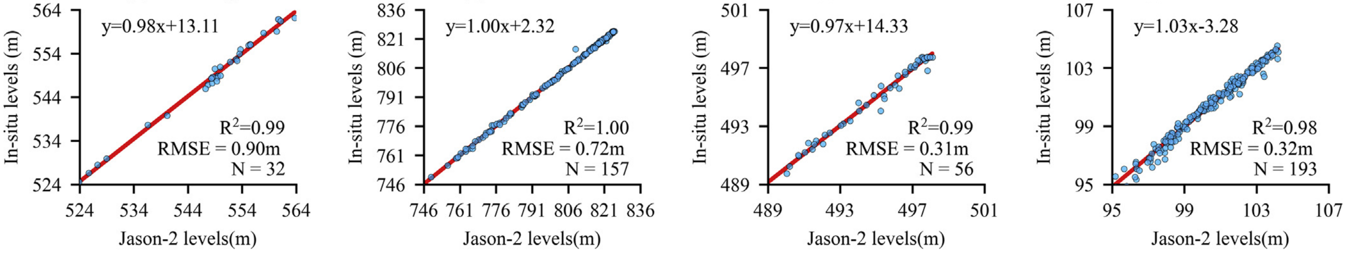


(a) Bansagar (b) Bargi



(c) Gandhisagar (d) Panchet (e) Sardarsarovar (f) Srisailam



(g) Supa (h) Tehri (i) Tungabhadra (j) Ukai

Fig. 2. Scatter plot of Jason-2 and in-situ water levels.

of N include nearby topographic conditions, especially around the Bargi dam. The Bargi dam is situated in the lower middle Himalayas amidst the undulated terrain conditions, which might affect the radar footprint and lead to corrupted or multi-reflected signals (Roohi et al., 2019). With Jason-2, the Supa dam had the least number of valid samples ($N = 32$) due to the small size of its water body.

At the Sardarsarovar dam (Fig. 1(m)), the reservoir water level fluctuation resulted in few corrected over-water radar signals due to land contamination, especially during the non-monsoon season (Figs. 2(e) and 3(e)) (Dubey et al., 2015). In the case of the Tungabhadra dam, water dynamics due to seasonal variability and human intervention also tended to affect the footprint of radar signals (Figs. 2(i) and 3(h)). During the monsoon season, the extended water mask of the dam reflects the backscattered energy better than in the non-monsoon season. As the water level of dam descends, land contamination becomes more severe and leads to an inaccurate estimation of the radar range (Frappart et al., 2015b). Overall, the results showed a high correlation between Jason-2 and in situ data, with a maximum R^2 value of 0.99 at the Tehri dam and a minimum value of 0.96 at the Panchet dam. The *RMSE* values for these two dams were 0.72 m and 0.37 m, respectively. Similarly, the Jason-3 data showed the highest correlation with the in situ observation at the Ranapratapsagar dam ($R^2 = 0.99$) and the lowest correlation at the Tungabhadra dam ($R^2 = 0.82$). It should be noted that in some cases the Jason-3 series started in mid-2017 instead of mid-2016. This data gap was due to the fine-tuning of the internal loop in the altimeter. At launch, Jason-3 was operated in a close loop mode, which automatically adapted the opening of antenna gates to accurately center the echo in the reception window and dynamically avoided signals being saturated. In certain situations, particularly in the cases of rapid changes in terrain height, the altimeter could miss the target or lose track. Hence, an onboard digital elevation model (DEM) with approximately 10 000 targets was uploaded onboard. Since mid-2017, Jason-3 altimeter has been forced to expect the echo within a time window to correspond to a prescribed altitude based on the Shuttle Radar Topography Mission DEM data. Owing to this DEM, the Bargi, Ghandisagar, Sardarserovar, Tungbhasra, and Ukai reservoirs were much better captured by Jason-3 after mid-2017. However, in some cases (e.g., the Sardarsarovar and Tungbhadra reservoirs), water levels were accurately captured only within a certain altitude range. In the open loop mode, the received echo can be strongly offset in the antenna window if the actual water level is largely different from the DEM value at the center of the reception window. This study suggested that the DEM values for these targets should be shifted to better correspond to the range of water level variation in these reservoirs.

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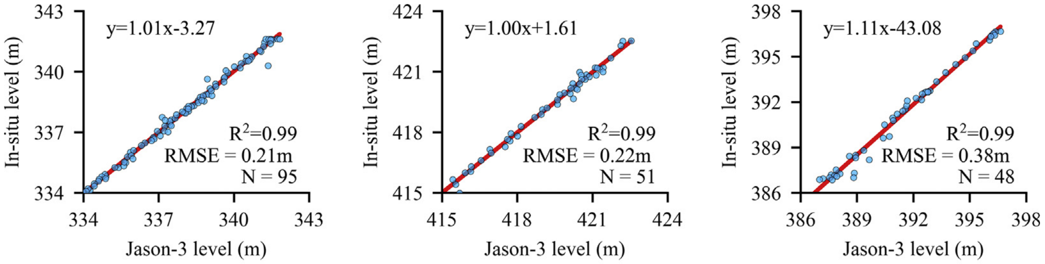
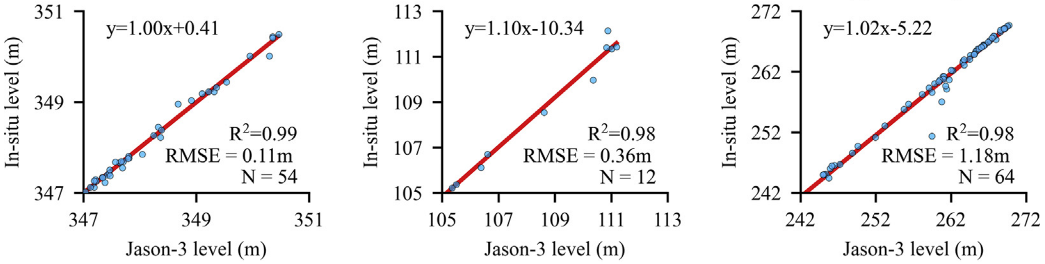
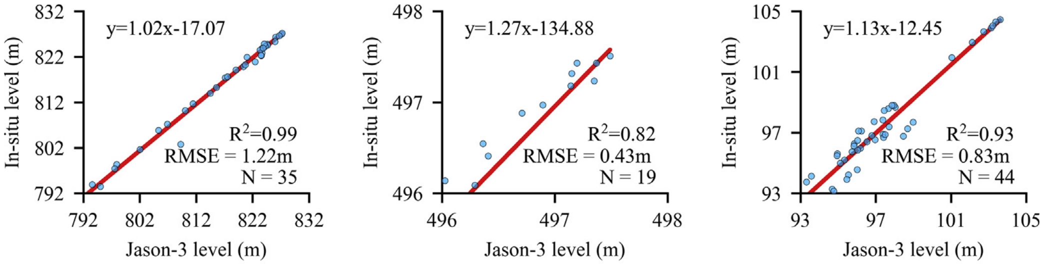


(a) Bansagar (b) Bargi (c) Gandhisagar



(d) Ranapratapsagar (e) Sardarsarovar (f) Srisailam



(h) Tehri (i) Tungabhadra (j) Ukai

Fig. 3. Scatter plot of Jason-3 and in-situ water levels.

4.2. Evaluation of SARAL/AltiKa derived water levels

The SARAL/AltiKa-derived water levels were evaluated for the reservoirs (Fig. 4). It has been found that the smaller footprint (Ka-band) and along-track interval of SARAL/AltiKa increased the number of corrected epochs over small water bodies in comparison to Jason-2/3 (Jiang et al., 2020; Tarpanelli et al., 2019). The temporal sampling frequency of SARAL/AltiKa was found to be 35 from 2013 to 2016 over the reservoirs during the nominal orbital phase. The temporal sampling cycles of SARAL/AltiKa were found be to less than 30 for most reservoirs except the Bansagar ($N = 66$), Ukai ($N = 55$), and Narayanpura ($N = 48$) dams, where two tracks overpassed the water bodies.

As shown in Table 2, the SARAL/AltiKa-derived water levels had greater accuracy than the Jason-2/3-based ones. Given that the datums of the satellite-derived water levels (Earth Gravitational Model, 2008) and in situ observed water levels (GTS) were different, the systematic bias of the satellite-derived water levels was corrected with the outlier removal technique. The correlation between the SARAL/AltiKa-derived water levels and the in situ observations had the R^2 values of higher than 0.90 in most reservoirs, and all *RMSE* values were lower than 0.70 m except for the Nagarjunasagar dam (*RMSE* = 1.05 m). There were two SARAL passes over the Nagarjunasagar dam, with one being exactly over the dam and another being further from the upstream. Due to the small departure of each cycle from the theoretical orbit, the SARAL track passes probably sampled reservoirs and rivers alternately. Due to the complicated shape of the reservoir, it was possible that the variation of water levels observed at the dam (gauge) was not the same as that observed in the small and remote channel sampled by the track at 16°20′38″N. Consequently, the irrational results may result from the differences in water levels derived from the two orbital passes over the reservoir. In the Ukai dam (Fig. 1(r)), two SARAL tracks passed over the dam for 68 cycles, out of which 55 cycles well correlated with the in-situ observations (Fig. 4(n)). The multiple passes over the same reservoir helped remove the systematic bias at the crossovers and improve the accuracy of radar ranges. Similarly, the Minimata dam had a width of approximately 12 km and a large sample size of the SARAL track passes. As a result, the water levels derived from the satellite showed a high accuracy (Fig. 4(h)). The geographic and terrain conditions near the reservoirs also affected the return signals of radar altimetry such as the Kadana and Bargi dams. In the Bargi dam, the SARAL/AltiKa-based sample size was small ($N = 8$) due to the inhomogeneous terrain in the lower-middle Himalayas (Shu et al., 2020). Due to a drought event in the west−central

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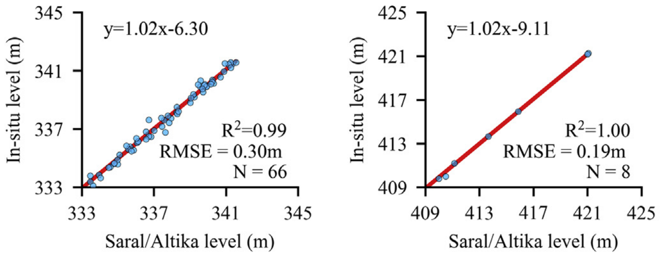
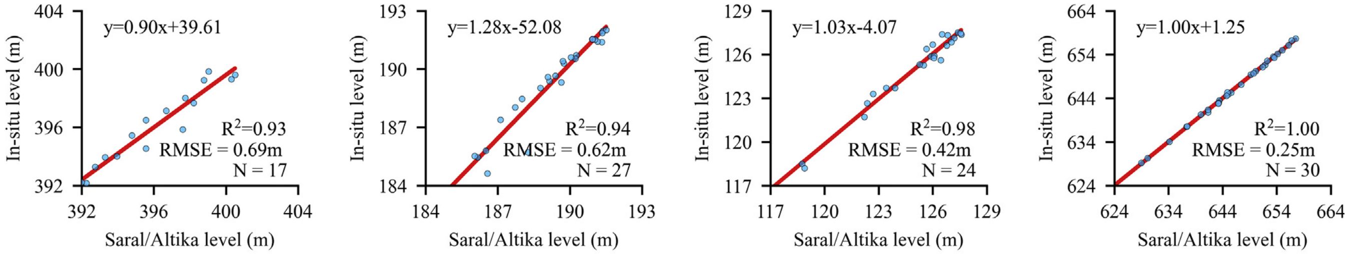
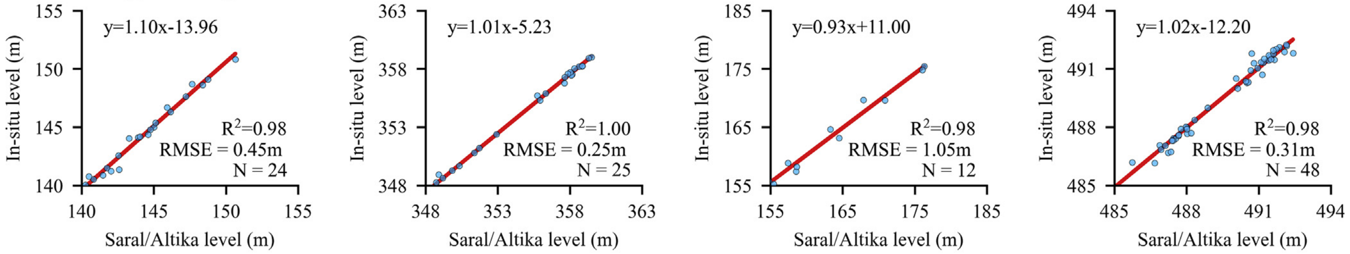


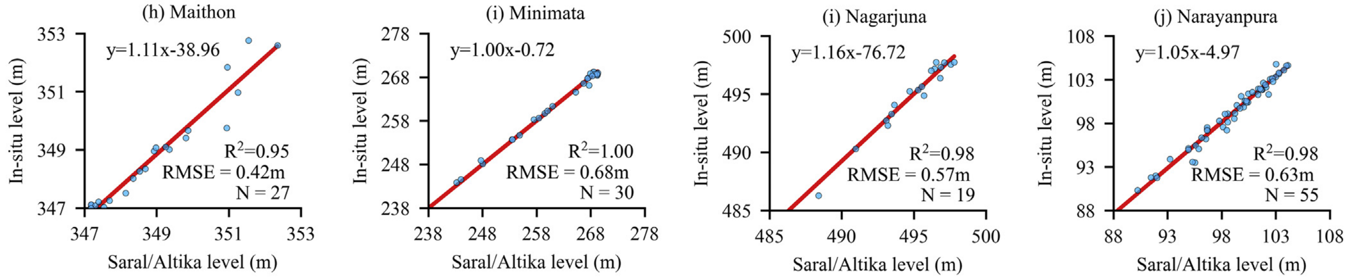
(a) Bansagar (b) Bargi



(c) Gandhisagar (d) Hirakud (e) Kadana (f) Koyna



(h) Maithon (i) Minimata (i) Nagarjuna (j) Narayanpura



(k) Ranapratapsagar (k) Srisailam (j) Tungabhadra (j) Ukai

Fig. 4. Scatter plot of SARAL/AltiKa and in-situ water levels.

Table 2
Performance of satellite altimetry-derived reservoir water levels.

Reservoir	Jason-2		Jason-3		SARAL/AltiKa	
	R^2	*RMSE* (m)	R^2	*RMSE* (m)	R^2	*RMSE* (m)
Bansagar	0.99	0.48	0.99	0.21	0.99	0.30
Bargi	0.97	0.66	0.99	0.22	0.99	0.19
Gandhisagar	0.98	0.88	0.99	0.38	0.93	0.69
Srisailam	0.97	1.62	0.98	1.18	0.99	0.68
Tungabhadra	0.99	0.31	0.82	0.43	0.98	0.57
Ukai	0.98	0.32	0.93	0.83	0.98	0.63

part of India in 2016, the Kadana and Gandhisagar dams had lower numbers of SARAL/AltiKa altimetry observations, with sample sizes of 17 and 24 and *RMSE* values of 0.96 m and 0.42 m, respectively. In addition, the shape of the water body played an essential role in the accuracy of altimetry-based observations, especially in the SARAL drifting phase of the satellite. Due to the east−west oriented shape of the Bansagar reservoir, the satellite altimetry had double sampling with two tracks and possessed the largest sample size for water level monitoring with $N = 66$, $R^2 = 0.99$, and $RMSE = 0.30$ m.

5. Conclusions

The present study evaluated the significance and applicability of satellite radar altimetry data for monitoring and managing India's available inland freshwater resources. The satellite radar altimetry data of Jason-2, Jason-3, and SARAL/AltiKa were used, and their feasibility over major reservoirs in India was investigated. The main conclusions are summarized as follows:

(1) The Jason-2-based water level results highly correlated with the in-situ data, with a maximum R^2 of 0.99 for the Tehri dam and a minimum R^2 of 0.96 for the Panchet dam. Jason-3 data had the maximum correlation with the in situ

observation at the Ranapratapsagar dam ($R^2 = 0.99$ and $RMSE = 11$ cm) and minimum correlation ($R^2 = 0.82$) at the Tungabhadra dam. The SARAL/AltiKa mission showed a higher accuracy than the Jason-altimetry mission, with a maximum correlation at the Minimata dam ($R^2 = 0.99$, $RMSE = 25$ cm, and $N = 25$) and a minimum correlation in the Gandhisagar dam ($R^2 = 0.93$).

(2) The altimetry-derived water levels can be utilized to monitor remote or ungauged lakes and reservoirs with an acceptable accuracy in comparison to the in-situ observations.

(3) Satellite altimetry is feasible for use in India for surface water level estimations. However, the variations of errors in different reservoirs depend on several factors such as along-track distance, reservoir area, shape of the water body, geography, regional climate and terrain conditions, and regional rainfall characteristics during the monitoring period.

(4) The existing satellite altimetry missions have coarse spatiotemporal resolutions, which may not capture water level variations on daily and weekly scales, especially during the low flow season. It is expected that the spatiotemporal resolution of altimetry will be enhanced with the upcoming SWOT mission that is scheduled to be launched in 2022 by NASA/CNES.

Declaration of competing interest

The authors declare no conflicts of interest.

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