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Multi-mission altimetry data to evaluate hydrodynamic model-based stage-discharge rating curves in flood-prone Mahanadi River, India

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Highlights:

- Multi-mission altimetry data used to validate rating curves
- Rating curves estimated using 1D-2D coupled hydrodynamic model
- Results confirmed marginal variation in performance of different altimeters
- Temporal resolution of altimeters does not affect reliability of water level

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences
Discussions

Abstract

River discharge and water level data play a vital role for various hydrological applications worldwide. However, limited availability of in-situ data has drawn attention towards using remote sensing techniques to monitor river flow. Indeed, multi-mission satellite altimetry data has been used to generate stage-discharge rating curves through power-law relations and empirical methods. The validation of hydrodynamic model-based rating curves is missing. We investigate the potential of available altimetry series (Jason 2, Jason 3, Saral/AltiKa, Sentinel 3A and Sentinel 3B) over Mahanadi River to validate the estimated rating curves at virtual stations. The hydrodynamic model (HEC-RAS) was developed and 07 virtual stations were identified for Mahanadi River from Boudh to Mundali Barrage. During calibration (July-October, 2018) and validation (July-October, 2018), Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE) between simulated and in-situ water level was found to be (0.46 m, 0.83) and (0.45 m, 0.76) respectively. The calibrated and validated model was used to generate rating curves at virtual stations. The RMSE ranging between 27 cm to 88 cm was observed between simulated and altimetry water levels, specifying the potential of all the altimeters with varying specifications to validate the rating curves. The rating curves estimated at virtual stations provide a cost-effective tool for monitoring river flows at additional locations, producing discharge time series for various hydrological applications and assessing of contribution of lateral tributaries.

Keywords: Satellite altimetry; Hydrodynamic modelling; Remote sensing; Mahanadi River; Stage-discharge rating curves

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

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Open Access
EGU
Discussions

1. Introduction

Monitoring and assessment of water resources within the watershed play a crucial role in meeting human requirements and influencing socio-economic practices in industrial and agricultural activities. The changing climate and resulting extreme hydrometeorological events in recent decades have increased the frequency of natural disasters (e.g., flood, drought) and stress on water resources (Alfieri et al., 2013; Banholzer et al., 2014; Oki & Kanae, 2006). The hydrological and hydrodynamic models used for various applications (e.g. hydrological forecasting, impact of climate change on water resources, flood risk assessment) typically depends on water level and discharge to test the reliability of the simulated outputs. Perhaps, field measurements over the many parts of the world are either unavailable or sparsely available and decreasing due to the highly economical and temporal efforts required for their maintenance (Andreadis et al., 2007; Bogning et al., 2018). The data-scarcity issue becomes worsen in delta region of the rivers (e.g. Mahanadi River) and high-mountain regions such as Himalayan river basins (Upper Ganga, Brahmaputra, Beas), which experience recurrent flood hazard (Dhote et al., 2021; Kebede et al., 2020).

Spaceborne radar altimetry data has potentially monitored inland water bodies for more than 25 years (Abdalla et al., 2021; Birkett et al., 2002). There are nadir looking altimeter observations from the past (ENVISAT, Jason 1/2, Topex/Poseidon), present (Jason 3, Saral/AltiKa - drifting phase since July 2016, Sentinel 3)(Calmant & Seyler, 2006; Paris et al., 2016) and the forthcoming Surface Water and Ocean Topography (SWOT) missions (Durand et al., 2010). Despite the challenges of inland water due to its complex surrounding environment, long term altimetry data have been used to assess change in water level of

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

large rivers, lakes, wetlands and reservoirs (Dubey et al., 2015; Frappart et al., 2006; Thakur et al., 2021). The upcoming SWOT mission will collect data differently from previous missions. It consists of two wide swath radar interferometers KaRINs (Ka-band Radar INterferometers) separated by the nadir altimeter at the middle (Biancamaria et al., 2016; Durand et al., 2010; Fu et al., 2009). The SWOT will map waterbodies on a global scale, aiming to simultaneously provide high-resolution WSE, slope and river width for rivers wider than 50-100 m. The repeat cycle of the SWOT will be of 21 days, allowing 2-4 visits at specific sites at regular intervals, dependent on the latitude.

Several previous studies revealed that radar altimetry could evaluate water levels in continental environments (Getirana & Peters-Lidard, 2013). The challenge is how to use this altimetry-based water level to estimate river discharge in addition to other methods based on remote sensing. The different approaches can be broadly classified as listed in Table 1.

Table 1: Methods to estimate river discharge using satellite altimetry

Approach	Remote Sensing Data	In-situ Data	References
generation of pseudo rating curves by application of power regression law using altimetry-based water level and in-situ discharge data	water level – altimetry observations	discharge (nearest station)	(Belloni et al., 2021; Dubey et al., 2015; Michailovsky et al., 2013; Papa et al., 2012; Rai et al., 2021; Zakharova et al., 2020)
use of modelled discharge and altimetry-based water to generate rating curves at virtual stations	water level – altimetry observations	discharge river cross-sections (bathymetry) roughness coefficients	(Leon et al., 2006; Paris et al., 2016; Tarpanelli et al., 2013)

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences
Discussions

calibration and validation of hydrodynamic models using satellite altimetry-based water levels	water level – altimetry observations	water level/ discharge river cross-sections (bathymetry) roughness coefficients	(Domeneghetti et al., 2021 ; Brêda et al., 2019; Chembolu et al., 2019; Domeneghetti et al., 2014; Getirana & Peters-Lidard, 2013; Milzow et al., 2011; Pereira-Cardenal et al., 2011; Wilson et al., 2007)
assimilation of altimetry-based water level to improve prediction potential of large-scale hydrological models	water level – altimetry observations	water level/ discharge river cross-sections (bathymetry) roughness coefficients	(Michailovsky et al., 2013; Paiva et al., 2013; Tourian et al., 2017)
the use of flow laws / empirical equations (Manning's equation)	width – (optical/SAR/altimeters) water level – altimetry observations slope - altimetry observations	water level/ discharge river cross-sections roughness coefficients	(Garkoti and Kundapura, 2021 ; Tarpanelli et a., 2013; Zakharova et al.,2019Andreadis et al., 2007; Durand et al., 2016)

Based on the approaches listed in Table 1, researchers have exploited the satellite altimetry data using various approaches to estimate river discharge, generate rating curves and improve the prediction potential of hydrological-hydrodynamic models. Few approaches entirely depend on the in-situ data, while others exploit the altimetry observations with limited in-situ data. Water monitoring agencies often use developed stage-discharge rating curves (e.g. Central Water Commission, India) to estimate discharge corresponding to gauge-based water level. The rating curves developed by classical power regression law using in-situ stage-discharge data are limited to the gauging locations (Herschy, 1993). Further, the rating curves estimated using the hydrodynamic model provides various benefits over traditional approaches, such as considering water surface gradient, roughness coefficient changes, hydraulic factors etc. (Di Baldassarre and Montanari, 2009; Lang et al., 2010; Mansanarez et al., 2019). In this direction, Dhote et al., 2021 used a hydrodynamic model to estimate rating curves at virtual stations and validated those using single mission

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences
Open Access
Discussions

Saral/AltiKa data. It is important to know that they used limited available daily in-situ data to calibrate the hydrodynamic model and not altimetry data. Later, relatively coarse temporal resolution (35 days) altimetry-based water levels were used to evaluate the reliability of the rating curves at virtual stations. However, multi-mission satellite altimetry data is yet to be tested to validate the hydrodynamic model-based rating curves.

The present work proposes to estimate stage-discharge rating curves using a hydrodynamic model and multi-mission satellite altimetry data (category c of Table 1). The analysis was implemented on the Mahanadi River stretch from Boudh to Mundali Barrage (near Naraj), where 7 virtual stations (10 passes) were identified. We specifically refer to altimeter data from Jason 2 (J2), Jason 3(J3), Saral/AltiKa (SA), Sentinel 3A (S3A) and Sentinel 3B (S3B) missions, which were used to retrieve water levels. The hydrodynamic simulations were performed with HEC-RAS software package in a 1D-2D coupled configuration.

2. Study area and data

We focus on the 189 km river reach falling in the lower sub-basin of Mahanadi River, the major inter-state river of India flowing east direction (Fig. 1). The Mahanadi is the 8th largest basin having a total catchment area of 1.4 x 10^5 sq. km, covering 4.28% of the total geographic area of India (CWC & NRSC, 2014). It covers a path of 851 km from an origin in Dhamtari district of Chhattisgarh state until it drains into Bay of Bengal. The analysis in this study focuses on the river reach bounded by gauging station Boudh at upstream and Mundali barrage (near Naraj) at downstream end. Right after the Mundali, delta region of the Mahanadi River starts which experiences severe floods frequently in monsoon season (Samantaray and Sahoo, 2020; Jena et al., 2014). The extreme rainfall events induced flood

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

waves and low main channel carrying capacity at the upstream region, leading to recurrent flood havoc in the delta region. As per Parhi et al., 2012, 69 % of major floods events (1960-2011) in the delta region are due to uncontrolled streamflow from the catchment area above delta head Mundali. Further, relatively low-lying area aggregates the flood situation in this region.

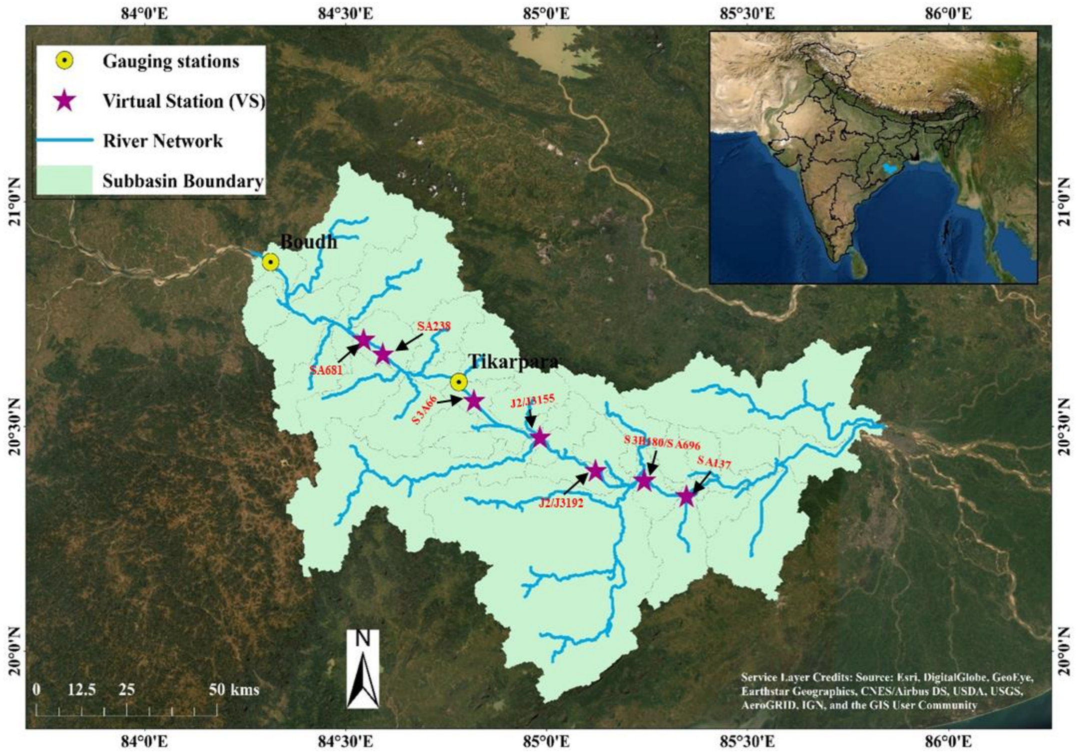


Fig.1. Mahanadi River stretch (Boudh to Mundal Barrage) considered in the study along with locations of gauging stations, outlet and identified virtual stations (VSs) from multi-mission altimetry data (Background image credits: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

The different satellite altimetry missions data considered in this study are Jason 2, Jason 3, Saral/AltiKa, Sentinel 3A and Sentinel 3B (Table 2). The locations of virtual stations (07), VSs

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

(locations where altimeter tracks cross the river) considered in this study are shown in Fig.1. Radiometrically Terrain Corrected (RTC) ALOS PALSAR DEM with a spatial resolution of 12.5 m was downloaded from Alaska Satellite Facility. This RTC DEM (released in 2014) is generated from ALOS PALSAR L1.1 image and global SRTM DEM (GL1: 30 m resolution) having accuracy as 20 m CE90 (Horizontal circular error at 90th percentile); 16 m LE90 (Vertical linear error at 90th percentile). Land use land cover (LULC) map prepared under the Indian Space Research Organization-International Geosphere Biosphere (ISRO-IGBP) Programme was procured from the National Remote Sensing Centre (NRSC), ISRO, Hyderabad, India. (NRSC, 2006).

The stage-discharge data required for hydrodynamic model setup was obtained from Central Water Commission (CWC), Bhubaneswar, Odisha State, India. The gauge data of three stations, namely, Boudh, Tikarpara and Naraj and discharge data of Boudh and Tikarpara stations were obtained. The surveyed river cross-sections (12) of Mahanadi River from Boudh to Naraj were procured from CWC, Bhubaneswar.

Table 2: Satellite altimetry data used in the study

Mission	Temporal Resolution (day)	Height (m)	Inclination (degrees)	Source
Jason 2	9.91	1336	66	AVISO
Jason 3	10	1336	66	AVISO
Saral/AltiKa	35	800	98.5	AVISO
Sentinel 3A	27	814.5	95.65	COPERNICUS
Sentinel 3B	27	814.5	95.65	COPERNICUS

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

3. Methods

The entire methodology used in this study is divided into two parts. The first part involves preparing different input layers to set up a hydrodynamic model using geospatial data and field observations. The stage-discharge rating curves were generated at virtual stations using a hydrodynamic model. The second part includes retrieving water levels from the multi-mission satellite altimeters like SARAL/AltiKa, Jason-2/3, Sentinel-3A/3B using Python & BRAT. The estimated water levels were used to evaluate the hydrodynamic-model based rating curves.

3.1 Model setup

Extensively used freely available physically based hydrodynamic model HEC-RAS (Bruner, 2016) was used to carry out numerical simulations of river reach in 1D-2D coupled configuration. HEC-RAS software provides a solution to full 1D Saint-Venant equations using four-point implicit finite difference technique. In contrast, full 2D Saint-Venant equations are solved using an implicit finite volume algorithm (Bruner, 2016). The 1D-2D coupled configuration used in this study enabled an option to simulate 2D flow dominating region near delta (downstream end, Mundali barrage) using 2D mode and approximate relatively unidirectional flow in rest river reach using 1D mode. This model setup arrangement facilitated the exploitation of both schemes' advantages, reducing computational time. Various studies have been carried out to evaluate the suitability of 1D, 2D, and 1D-2D coupled hydrodynamic models (Ghimire et al., 2022; Shustikova et al., 2019; Dhote et al., 2019); however, detailed analysis on topographic input data, processes and output uncertainties is not within the scope of this study.

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences
Discussions

The different steps followed to set up the model are discussed below:

1) **River network profile**: River network was digitized from Boudh to Mundali barrage using high-resolution images of Google Earth in the RAS Mapper module of HEC-RAS. Later, a digitized river file can also be imported in various formats (.shp, .kml) in other GIS platforms.
2) **Channel-floodplain geometry:** To set up the 1D model, river cross-sections and elevation profiles (left to right bank) were extracted from ALOS PALSAR DEM using the tool available in HEC-RAS. The length of cross-sections was varied to ensure the coverage of floodplain and main channel geometry. Initially, cross-sections were extracted at 500 m spacing in automated mode from Boudh to Mundali barrage. Later few cross-sections were added/deleted/edited to account for the meandering of the river. To represent geometry of 2D flow dominating area near delta-head Mundali, 2D floodplain mesh was generated using ALOS-PALSAR DEM. We specifically represented the floodplain of flood-prone tributaries Kusumi and Rana (kindly refer to Fig. 3 and Boundary condition section) as 2D domain. The lateral structure was used to connect 2D flow areas with 1D main river.

The topography of the floodplain can be well displayed with spaceborne DEM, but bathymetry is rather difficult to represent. Thus, we used the closest surveyed river cross-section data to modify the DEM-based cross-sections. Only 12 surveyed cross-sections were available at an uneven spacing from Boudh to Mundali, first used to correct DEM-based cross-sections. As surveyed cross-sections are referenced to local datum, mean sea level (msl), datum correction was applied ranging from – 0.06 m to +6.2 m. Later, modified bathymetry was interpolated among other intermediate

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences
Discussions

cross-sections. This resulted in hybrid cross-sections (Dhote et al., 2021) used to model setup. The longitudinal profile of the main river channel and typical hybrid cross-section at 102 km chainage is shown in Fig 2.

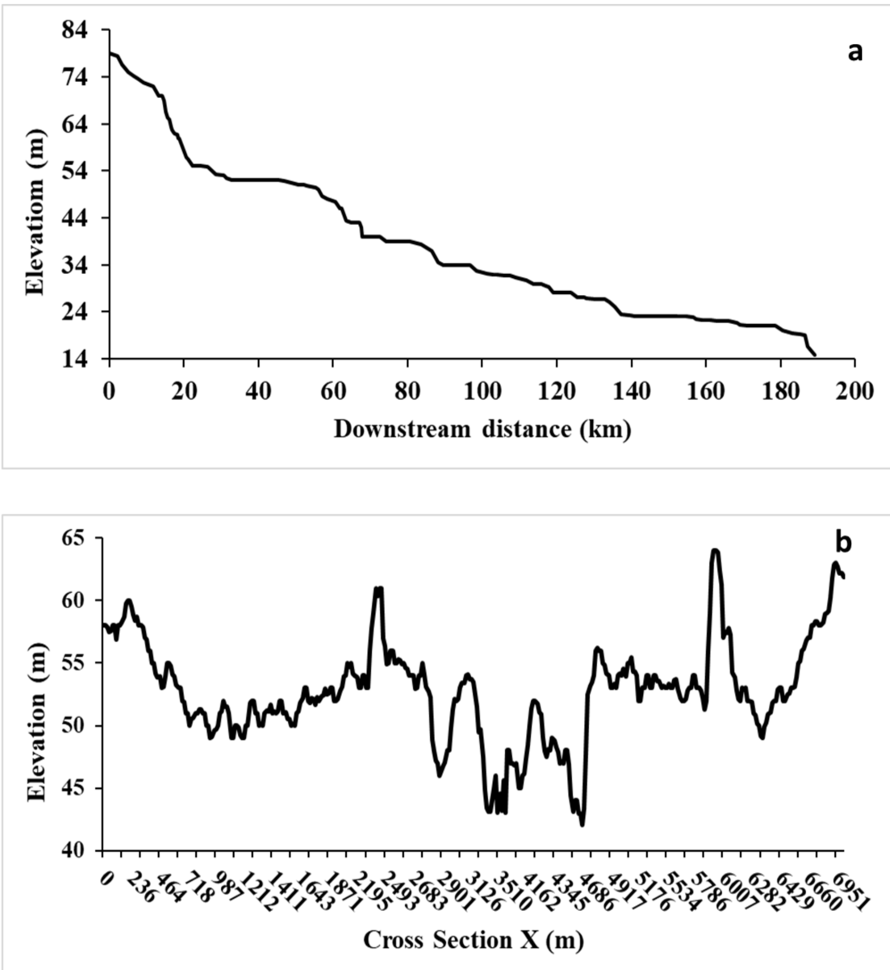
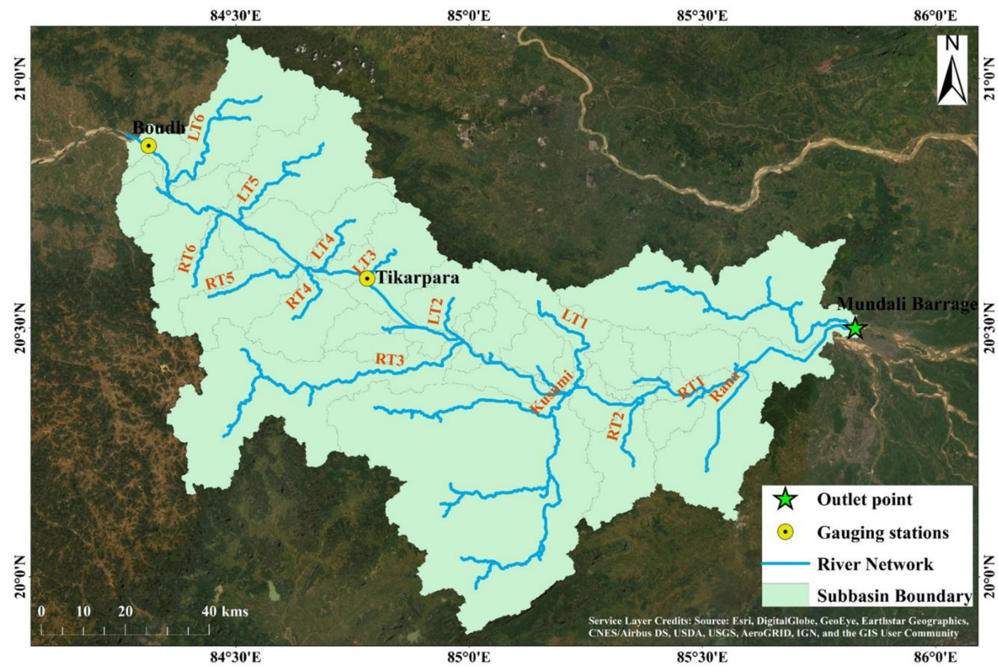


Fig.2. (a) Main channel longitudinal profile from Boudh to Mundali Barrage (b) Hybrid cross-section at 102 km chainage from Boudh station

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences
Discussions

3. **Boundary conditions**: In this study, discharge hydrograph was provided as a boundary condition at all upstream nodes of the river network, while normal depth was provided at the downstream end (Mundali). However, in-situ discharge data were available at limited locations within the study area (Fig.1). Considering the importance of upstream boundary conditions on the accuracy of the model, the contribution of lateral tributaries (Fig. 3) was estimated using the discharge-area ratio method. In this method, discharge data for each tributary was estimated by multiplying drainage- area ratio (= watershed area of tributary/watershed area concerning Tikarpara) with discharge data at Tikarpara. The contribution of each tributary is shown in Table 3, highlighting that the contribution of right bank tributaries near the delta region, namely Kusumi and Rana, is on the relatively higher side.



https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Fig. 3. Mahanadi river tributaries contributing between Boudh and Mundali Barrage (Background image credits: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

Table 3. Contribution of the tributaries

Tributary	Catchment Area (Sq. km)	Contribution in % using drainage-area ratio method
Rana	499	4.96
RT1	103	1.18
RT2	289	2.87
Kusumi	2117	21.07
RT3	1009	10.04
RT4	269	2.68
RT5	287	2.86
RT6	205	2.04
LT1	225	2.23
LT2	205	2.03
LT3	213	2.11
LT4	195	1.94
LT5	540	5.37
LT6	528	5.25

4. **Roughness coefficients**: The lookup table was created to relate the surface roughness coefficient (Manning's *n,* $m^{-1/3}$ s) with varying land use land cover. The ISRO IGBP LULC and high-resolution images of Google Earth were used to identify different classes within a floodplain. The literature and previously published work was used to select *n* values (Chow et al., 1998; Parhi et al., 2013). The n value varied from 0.05 to 0.2 $m^{-1/3}$ s for various classes in the floodplain, while the initial *n* for the main channel was kept as 0.035 $m^{-1/3}$ s.
5. **Simulations**: Hydrodynamic model was set up for a river stretch of 189 km from

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences Discussions

Boudh to Mundali barrage, constrained with discharge data as a boundary condition at upstream nodes and normal depth at the downstream end. We ran this developed model in two phases: calibration and validation corresponding to extreme flood events within available data. The model was calibrated using daily observation for the 2015 monsoon season (July-October). During the calibration phase, a model was simulated for multiple sets by spatially varying the main river channel Manning's *n* in successive iterations (Dhote et al., 2019; Domeneghetti et al., 2021) and calculated the goodness-of-fit. The Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE) were used as the goodness-of-fit criteria between simulated and observed water levels at Tikarpara station. The optimized value of Manning's *n* of the channel (keeping *n* constant for floodplain classes) producing the lowest RMSE and highest NSE was identified during calibration. The model was validated by performing the boundary conditions for a period not included in the calibration phase (July to October 2018), and subsequently estimated statistical parameters. Later, the stage-discharge rating curve was estimated at each virtual station corresponding 2018 flood event.

3.2 Retrieval of water level using satellite altimetry data

Radar altimetry is an advanced remote sensing technique to estimate the water level of inland water bodies. In this study, virtual stations were identified based on tracks of multi-mission altimetry data (Jason 2, Jason 3, SARAL/AltiKa, Sentinel 3A and Sentinel 3B) falling between Boudh and Mundali along Mahanadi River. It was found that 8 virtual stations can be established using data from 10 altimetry tracks having varying time duration (same

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

virtual station /pass for Jason 2 and Jason 3 tracks, see Table 4). To retrieve water level using altimetry data, first of all, we need satellite orbit altitude (Alt) and the altimeter range value (R). A retracing algorithm is applied to correct the range value (R), as the leading edge of the waveform diverges from the defined onboard altimeter gate. We used a standard Off-Center of gravity (OCOG) retracking algorithm to correct the range. Various geophysical corrections (dry tropospheric correction, wet tropospheric correction, ionospheric correction) to account for time delay of microwave pulses due to atmospheric effects, correction for pole and solid tidal effects on the Earth were applied to correct retrieved water level (Chelton et al., 2001; Wahr,1985; Cartwright and Edden,1973). The equation relating different terms to estimate water level is given below. We calculated the orthometric height considering EGM 96 as datum because different altimetry missions use different reference ellipsoids.

$$H = Alt - R - (D_{tc} + W_{tc} + I_{onc} + S_{tc} + P_{tc}) - MSS_{ht} \quad (1)$$

Where H: corrected orthometric height; Alt: the satellite altitude from reference ellipsoid; R: the satellite range; D_{tc}: the dry tropospheric correction; W_{tc}: the wet tropospheric correction; I_{onc}: the ionospheric correction; S_{tc}: the solid tide; P_{tc}: the pole tide correction; and MSS_{ht}: the mean sea surface from the reference ellipsoid.

Table 4: Virtual stations identified based on the altimeter passes

Sl. No.	Satellite	Pass	Data Availability	Nearest Location
1	Jason 2	155	2008-2015	Kanasinga
2	Jason 2	192	2008-2015	Mahukana
3	Jason 3	155	2016-Present	Kanasinga
4	Jason 3	192	2016-Present	Mahukana
5	Sentinel 3A	66	2016-Present	Mahakudpalli
6	Sentinel 3B	180	2018-Present	Khaparmala

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

7	SARAL/AltiKa	137	2013-2016	Badabar
8	SARAL/AltiKa	238	2013-2016	Dubapalli
9	SARAL/AltiKa	681	2013-2016	Badhupalli
10	SARAL/AltiKa	696	2013-2016	Khaparmala

4. Results and discussion

Here we present the findings of calibration and validation of hydrodynamic model (a); and the use of available altimetry series to validate the model-based stage-discharge rating curves (b).

4.1 Calibration and validation of the model

The calibration and validation of the model were carried out for extreme monsoon events, respectively, for 2018 and 2015, at a daily time scale. The channel *n* value was varied from 0.02 to 0.06 $m^{-1/3}$ s, until there was good agreement between simulated and observed water levels at Tikarpara station (Chow et al., 1988; Horritt and Bates, 2002; Dhote et al., 2019). During calibration, the comparison of simulated and observed water levels at Tikarpara produced minimal RMSE (0.46 m) and high NSE (0.83) corresponding to optimized *n* value of 0.03 $m^{-1/3}$ s (Fig. 4). Parhi., 2013 evaluated the channels *n* value of the HEC-RAS model to simulate extreme flood events peak discharge and time of peak in Mahanadi River basin. They showed that, Manning's *n* of 0.029 lead to lowest error of 5.42%, thus validating our calibration performance. It is worth mentioning that, observed water level is reference to local datum (msl), while datum of simulated water level is EGM 96. Thus, datum correction of -0.79 m was applied to the observed stage before comparative assessment. Fair agreement

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

during independent boundary condition of validation year 2015 (RMSE 0.45 m ; NSE 0.76), suggested good performance of hydrodynamic model (Fig 4).

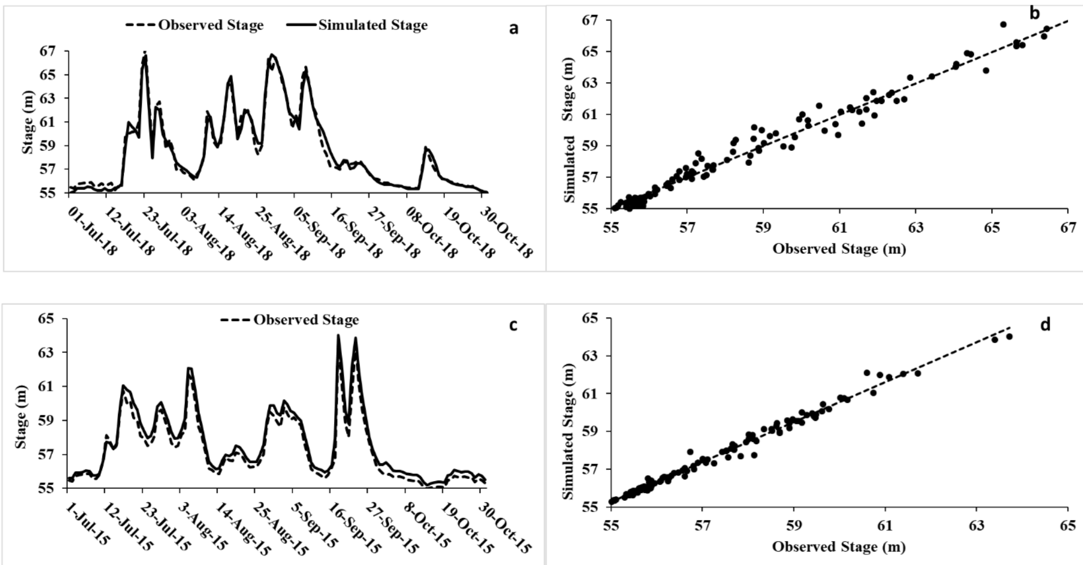


Fig. 4. Calibration (a, b, during year 2018) and validation (c, d, during year 2015) of the hydrodynamic model at Tikarpara.

4.2 Multi-mission satellite altimetry observations to evaluate model-based stage-discharge rating curves

Observations from multi-mission altimeter tracks provide an opportunity to study water level dynamics (courser temporal resolution) at additional locations compared to in-situ gauging stations. The challenging question is how efficiently river discharge can be monitored at these locations (virtual stations, see Fig. 5). The rating curves were estimated at 07 virtual stations using hydrodynamic simulations for extreme flood events during

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

monsoon seasons 2018 and 2015. The comparative assessment was carried out between simulated and altimetry-based water levels at virtual stations.

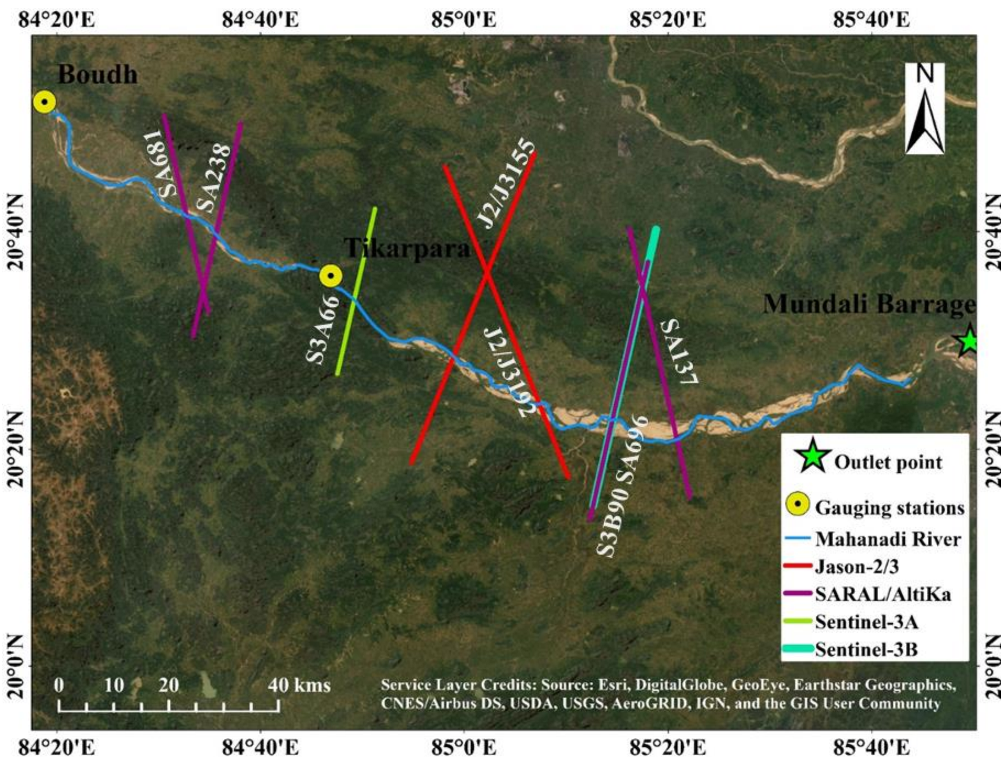


Fig.5. Virtual stations identified using tracks of satellite altimeters over the river stretch (Background image credits: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community)

The simulated model was found to agree with altimeter-based water levels (after applying bias correction) among all the altimetry datasets with different durations (Fig. 6, 7 and Table 5). In general, simulated water levels followed altimeter observations with high accuracy, showing NSE always more significant than 0.76. Even though variation in errors during

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

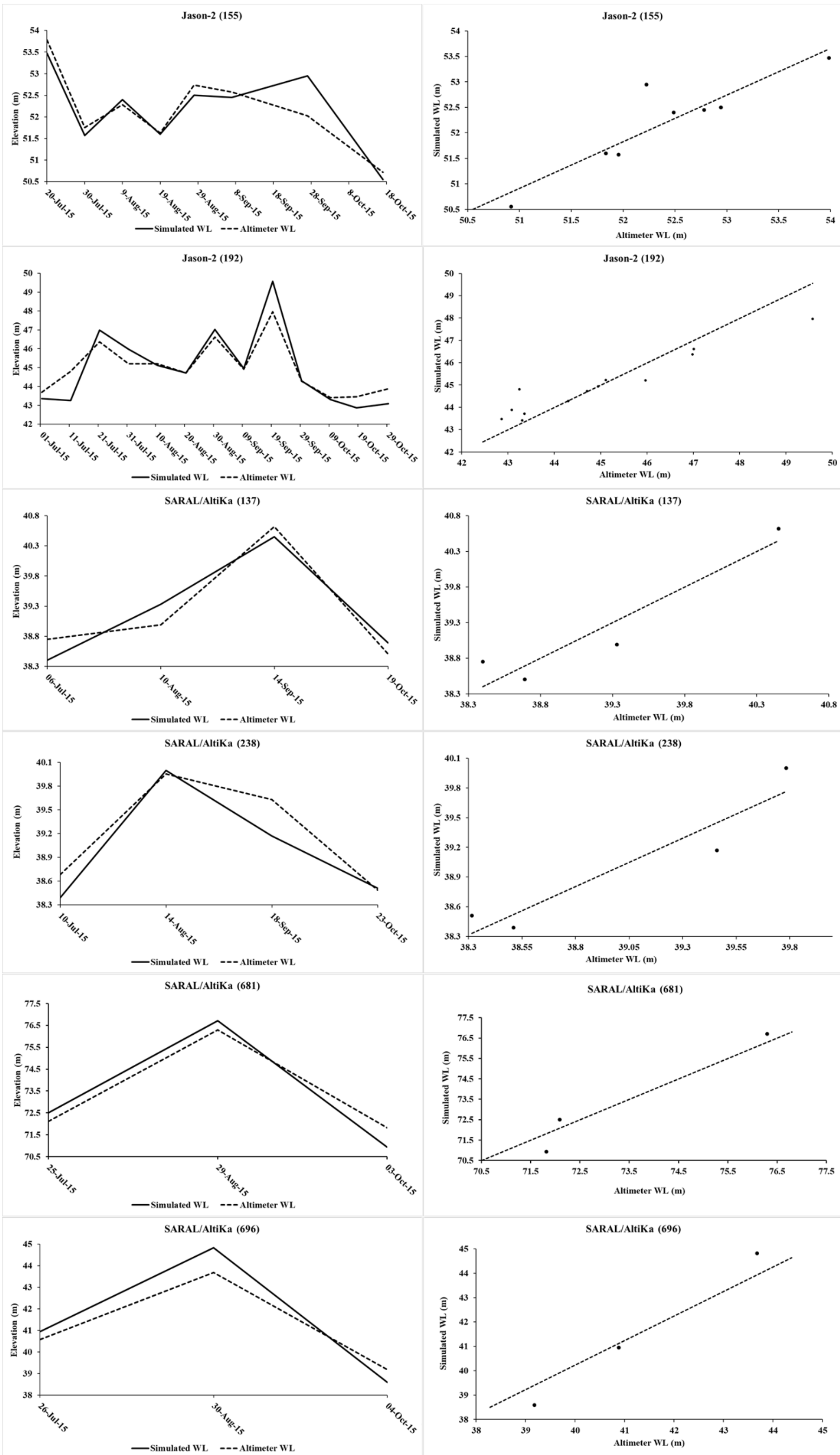
comparison were very marginal, Saral/AltiKa showed the lowest error (average RMSE 0.49 m), followed by Jason 02 (0.58 m), Sentinel 3 (0.72 m) and Jason 3 (0.74 m). Moreover, the temporal resolution of altimeters ranging from 10 days to 35 days did not affect the reliability of the estimated water levels. This compassion at virtual stations ensures the validation of estimated rating curves (Fig. 8). These rating curves can be utilized as a virtual gauging network (in addition to in-situ stations), facilitating a cost-effective tool for monitoring river flows at additional locations, producing discharge time series for various hydrological applications, and assessing the contribution of lateral tributaries.

Table 5: Statistics of the comparison between satellite altimetry water level and modelled water level

Satellite	**Pass**	**NSE**	**RMSE (m)**	**Bias Correction (m)**
Jason 2	155	0.76	0.42	-0.204
Jason 2	192	0.84	0.74	-0.009
Jason 3	155	0.83	0.60	+0.035
Jason 3	192	0.76	0.88	-0.173
Sentinel 3A	33	0.93	0.72	-0.045
Sentinel 3B	90	0.94	0.72	-0.094
SARAL/AltiKa	137	0.76	0.35	+0.270
SARAL/AltiKa	238	0.81	0.27	-0.171
SARAL/AltiKa	681	0.93	0.60	-0.0225
SARAL/AltiKa	696	0.90	0.77	+0.307

https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences
Discussions



https://doi.org/10.5194/nhess-2022-101
Preprint. Discussion started: 25 April 2022

Natural Hazards and Earth System Sciences
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Fig.6. Comparison of the simulated and altimetry-based water level during the year 2015 (black dotted lines in right panes indicates 1:1 line)

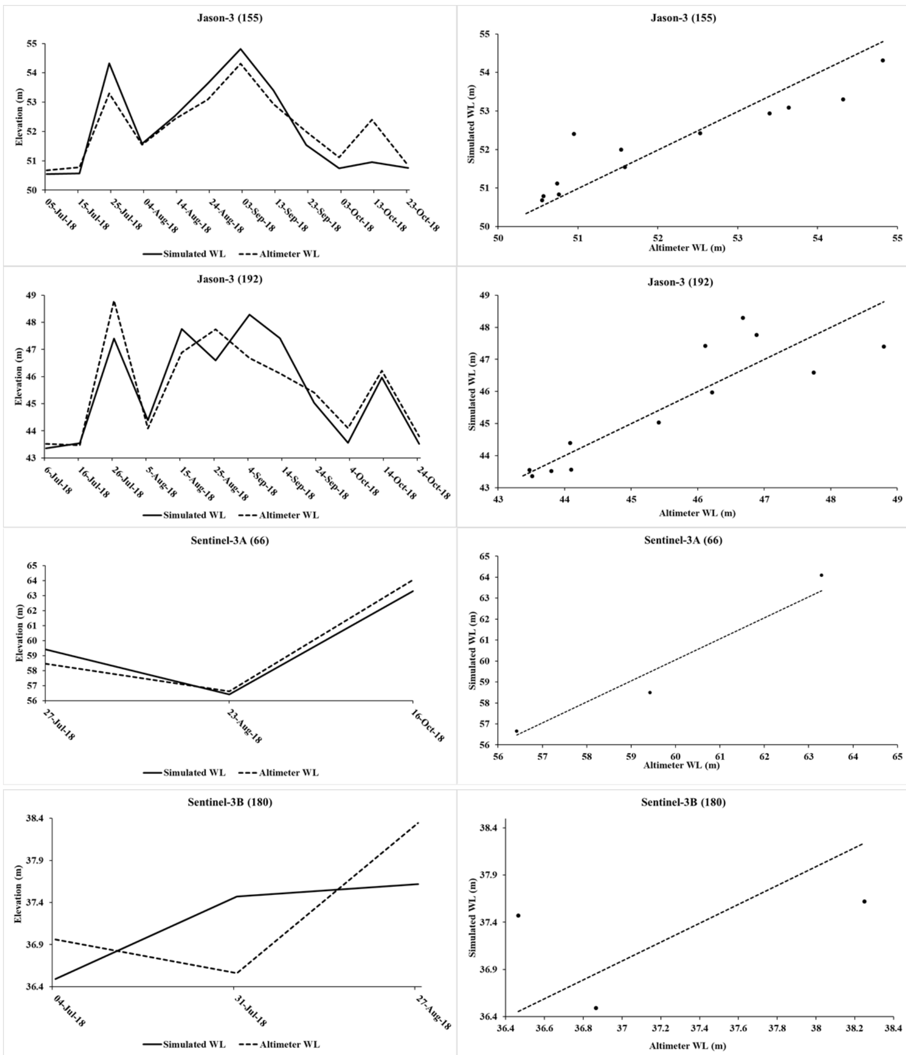

Fig.7. Comparison of the simulated and altimetry-based water level during the year 2018 (black dotted lines in right panes indicates 1:1 line).

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The altimetry-based water level has been the most exploited remote sensing data to estimate river discharge. Most of these approaches (see Table 1) use altimeter data along with the limited in-situ data to develop rating curves. The proposed framework in this study ensures estimation of relatively accurate rating curves, however, restricts its application in ungauged basins. Mere comparison of water levels at virtual stations does not rule out uncertainty associated with the estimated discharge. However, as model was already calibrated and simulated water levels mimicked satellite observations accurately, we can rely on estimated discharge produced from modelled stage-discharge relation (Dhote et al., 2021). The outputs of the physically-based models are governed by adopted modelling scheme and model parameterization. Perhaps, rating curves based on these models (HEC-RAS) eliminates the uncertainty associated with other empirical /power law approaches (Garkoti and Kundapura, 2021 ; Tarpanelli et a., 2013) such as constant roughness coefficient, influence of drainage area, overflows of the banks. Thus, it is tough to remove all the errors but we must be aware of degree of uncertainty associated with the adopted approach. Further, as the proposed framework is generic, it can implemented on the high-mountains data-scarce Himalayan river basins. It will be interesting to evaluate the impact of hilly terrain on accuracy of the altimetry-based water levels and its application to generate stage-discharge rating curves. This could be the potential future work.

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Natural Hazards and Earth System Sciences
Discussions

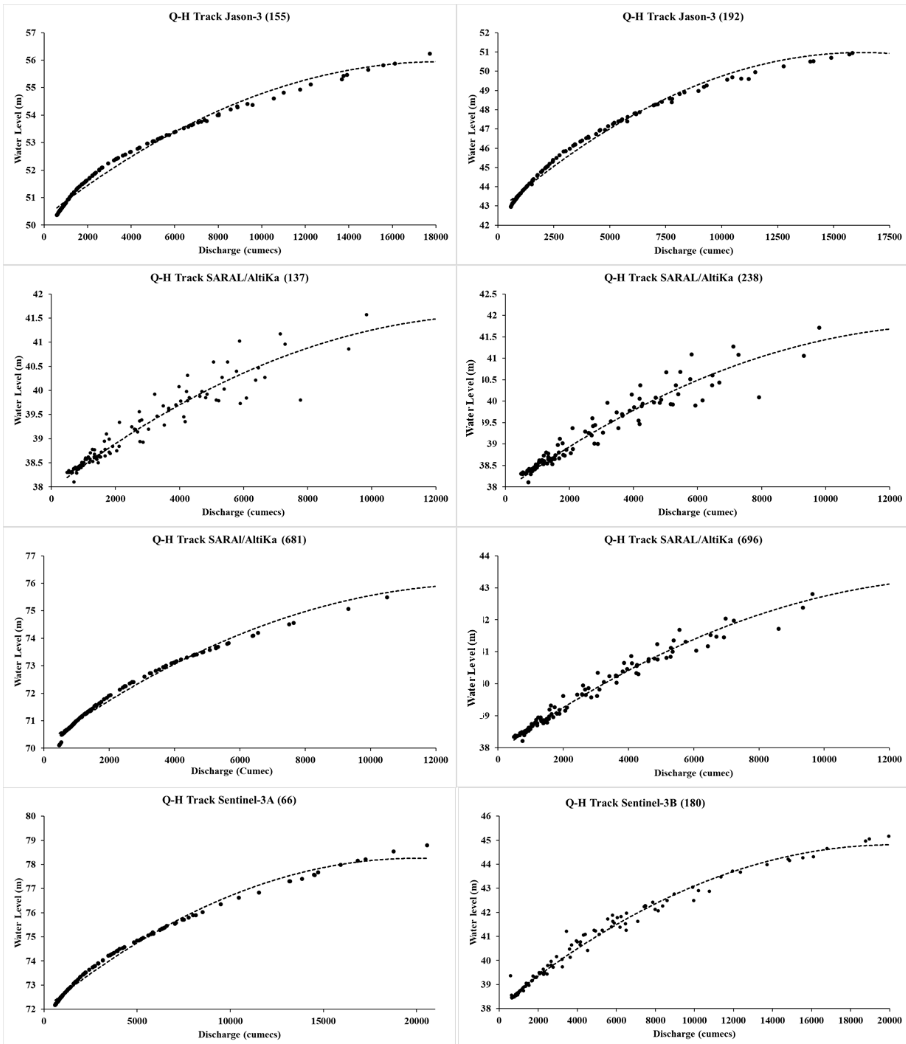

Fig. 8. Rating curves generated at virtual stations using the hydrodynamic model run during the monsoon season of the year 2018 (07 rating curves corresponding 10 altimetry tracks: Pass 155 shared by J2 and J3, Pass 190 shared by J2 and J3, S3B180 shared by SA696).

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Natural Hazards and Earth System Sciences
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5. Conclusions

The present work investigated the use of multi-mission altimeter data to validate the model-based stage-discharge rating curves in Mahanadi River, India. Using hydrodynamic modelling simulations, the rating curves were estimated at 7 virtual stations falling between Boudh and Mundali barrage. The altimeter data from different missions such as Jason 2, Jason 3, Saral/AltiKa, Sentinel 3A and Sentinel 3B were used to retrieve water levels at these virtual stations. The statistical indicators (RMSE 0.27-0.88 m, NSE 0.76-0.94) revealed that simulated water levels could reproduce altimeter observations at these virtual stations with high agreement. Even though the temporal resolution of altimeters ranged from 10 days to 35 days, no substantial implications on the reliability of the water level were observed. The rating curves estimated at virtual stations can be utilized as a virtual gauging network (in addition to in-situ stations), facilitating a cost-effective tool for monitoring of river flows at additional locations, producing discharge time series for various hydrological applications and assessment of the contribution of lateral tributaries.

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Authorship Contribution Statement:

Pankaj R. Dhote: Conceptualization, Funding acquisition, Investigation, Methodology, Data Analysis, Writing – original draft. **Joshal K. Bansal**: Conceptualization, Methodology, Data curation, Formal analysis, Visualization, Writing – original draft. **Vaibhav Garg**: Conceptualization, Methodology, Supervision, Writing – review & editing. **Praveen K. Thakur**: Conceptualization, Supervision, Writing – review & editing. **Ankit Agarwal**: Conceptualization, Supervision, Writing – review & editing.

Data availability:

Processed data may be shared on request by contacting contact authors.

Declaration of Competing Interest

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

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