MONITORING INLAND WATERS OF ASIA USING SARAL ALTIKA SATELLITE ALTIMETER DATASETS

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ABSTRACT: The water level of a water body has been considered as an important climate variable. However, it is being measured regularly for the large or important reservoirs and lakes across globe by federal, private or other agencies. There are numerous small water body those play critical role in hydrology and climate as well, those are not monitored by any of the agency. Satellite based altimeters are there since 1970s, however, the technology primarily was used for sea surface topography. With the advancement in the technology, the researchers have exploited it to assess the water level of inland water bodies, as well. It specifically started with the launch of Indian Space Research Organisation (ISRO) - Centre National d'Etudes Spatiales (CNES) Ka band SARAL AltiKa Satellite altimeter in the year 2013. Therefore, in the present study, an attempt has been made to study the water level of selected 57 lakes and reservoirs across entire Asian continent. Firstly, the water level of water bodies in India (24) having SARAL AltiKa pass was retrieved. On comparing the estimated water level with observed, it was found that both were concurrent to each other for almost all the water bodies. A coefficient of determination in the range of 0.93 - 0.99 was calculated for the major Indian water bodies. Considering the accuracy of SARAL AltiKa datasets in retrieving the water level of the inland water bodies, an attempt was also made to explore the possibility of estimating it for transboundary water bodies. Therefore, water level of different selected water bodies across Asia other than India (33) was assessed using the SARAL AltiKa data. The retrieved water level for selected lakes/reservoir could not be validated due to lack of availability of the observed data. However, it was found that the water level retrieved was very close to the levels reported in literature for most of the lakes. The study also emphasized on the applications of the retrieved water level in hydrological studies. It was concluded that the water level could be retrieved with higher accuracy using space based altimeters such as SARAL AltiKa. The sensors like Jason 3, Jason 6, Sentinel – 3A/B, etc. ensure the availability of the satellite altimeter datasets. The SWOT mission further warrant the future availability of the datasets.

1. INTRODUCTION

The inland water bodies especially the lakes, ponds and reservoirs present across the globe play critical role in the hydrology of region. Apart from hydrology, these are home for millions of inhabitants. Therefore, the hydrology, ecology, economics of any region largely interconnected to these water bodies (VanDeWeghe et al., 2022). In this regard, the availability of water in these system is crucial for sustenance of the habitants depend on these. On the other hand, it is important to assess the historical, present and future quantity and quality of these water bodies to support these activities. The assessment of the capacity of the water bodies is generally being carried out using hydrological models. Mostly, the hydrologic models fail to simulate water inflow to these water bodies due to complex relationships exists among different hydrological variables and its catchment characteristics upstream. Further, the changing climate put additional stress on the availability of water in these inland resources.

Since, the launch of Landsat series of satellites in 1970s, remote sensing technology has played an important role in mapping water spread area. With the improvement in sensor technology, the accuracy of water spread estimation has improved. However, for computing the water stored in a water body, it requires third dimension, i.e., water level. The Global Climate Observing System identified 54 Essential Climate Variables (ECVs) for climate assessment purpose. Out of these 54, water level of a lake with respect to a specified vertical datum at daily time scale is considered as one of the critical ECVs. The water level is generally being measured on field using the instruments like staff gauge, digital water level recorders, etc. However, these physical measurements are difficult at each and every water body across earth in all seasons. Staff gauge measurement has manual interference, on the other hand, the installation of digital water level recorders is expensive instrumentation. Both these kind of observations are also difficult in in-accessible water bodies.

The altimeters may be considered as the best remedial to overcome these issues. The altimeters work on time delay principal. These are active microwave sensors; those emit radar pulse. It measures the two-way travel time of a radar pulse between the satellite antenna and the Earth's surface at the nadir of the satellite (Tarpanelli and Benveniste, 2019). The satellite altimeter sensors record the pulse emitted back by the reflecting surface within the altimeter footprint. The water acts as a perfectly reflecting surface, further, the radar pulse cannot penetrate water; therefore, the radar pulses falling on water surface, reflects back and recorded by the sensor on-board the satellite. The two-way return echoes travel time is generally measured by the on-board tracker (Ghosh et al., 2017). The space based altimeters are not a recent technology; it was there since 1980s. However, the main objective of the space based altimeters was to monitor the sea surface heights. The list of some past, present and future satellite altimeters is provided in Table 1.

Table 1. List of some past, present and future satellite radar altimeters (Thakur et al., 2021)

Satellite	Operation	Repeat Period	Satellite	Operation	Repeat Period
Topex/Poseidon	1992-2002	10 days	ERS-1	1992-1993, 1995-2000	35 days
Jason-1	2002-2008	10 days	ERS-2	1995-2003	35 days
Jason-2/OSTM	2008-2016	10 days	ENVISAT	2002-2010	35 days
Jason-3	2016-	10 days	**SARAL AltiKa***	**2013-2016**	**35 days**
HY-2A	**2011-current**	**14 days**	ICESat-1 (laser)	2003-2009	90 days
Seasat	1978	17 days	**Cryosat-2**	**2010-current**	**365 days**
Geosat	1985-1989	17 days	ICESat-2 (laser)	2018-	variable
GFO	2000-2008	17 days	Jason-CS/Sentinel-6	2020-	variable
Sentinel-3A	**2016-**	**27 days**	SWOT	2020-	variable
Sentinel-3B	**2018-**	**27 days**			

* *drifting orbit*

Over the small to medium or narrow water bodies, the returned signals get affected/contaminated by the topography and land characteristics of the surrounding attributing to large footprint. Therefore, the surface height estimation is more accurate for wider water bodies than the narrow ones. It also depends on the type of altimeter sensor on-board the satellite such as conventional – pulse limited or synthetic aperture radar (SAR). Attributing to their high along-track resolution, the accuracy of water level retrieval enhanced with the use of SAR based altimeters, especially the fully focused SAR sensors. With this advancement, the opportunity to monitor water level for narrower water bodies such as rivers increased (Schneider et al., 2018). Nevertheless, it still remained challenging to retrieve water level of narrower water bodies, in case of across-track direction SAR mode, due to the large antenna footprint. In such a case, it resulted in the same size footprint as of conventional pulse limited altimetry. Different standard retracking algorithms are readily available to identify the nominal gate in the complicated echo waveforms from the water surface affected by multiple targets in the surrounding (Sulistioadi et al., 2015; Biancamaria et al., 2017).

On February 25, 2013; ISRO, India and CNES, France collaboratively launched SARAL AltiKa with a single frequency (35.75 GHz Ka-band) altimeter with a dual frequency radiometer (Ghosh et al., 2015). This is to be noted that the repeat cycle of SARAL AltiKa was 35-days. Since, the ionospheric effects are negligible higher microwave frequencies, the agencies could plan mono-frequency altimeter. With the use of higher frequency, the altimeter footprint reduced resulting in better spatial resolution (Ghosh et al., 2015). The added advantage of sensor is better vertical resolution attributing to its enhanced bandwidth. It is reported that the calculation of water level of the water bodies improved with the utilization of SARAL/AltiKa data attributing to its narrow footprint than other altimetry missions. The aim of the study is to demonstrate the capabilities of SARAL AltiKa in retrieving the water level of water bodies across Asia.

2. STUDY AREA

In the present study, the water level of different water bodies across Asia, over which there was the pass of SARAL AltiKa, were selected, as shown in Figure 1. There were total 57 water bodies, out of which 24 reservoirs and lakes were selected from India; 16 from China; 04 of Kazakhstan; 03 from Russia and Thailand; Iraq 02; and one each from Armenia, Kyrgyzstan, Mongolia, Srilanka, Turkey. The names along with their location coordinates of each lake and reservoir is provided in Table 2. The lakes and reservoirs selected represented the different geographical and environmental conditions. These lakes are of different size and storage capacity. Further, some of them are shallow water body and most are deep. More number of lakes/reservoir selected from India attributing to availability of observed water level from verification of satellite derived water level.

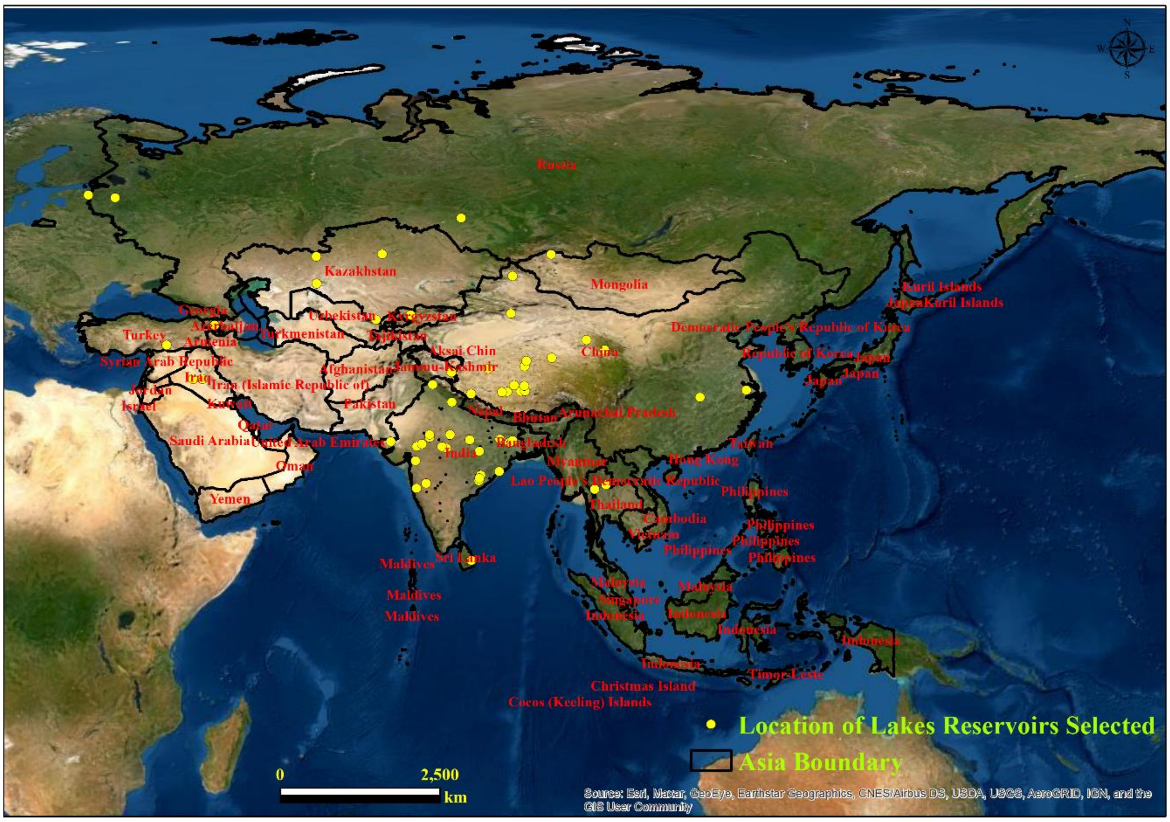

Figure 1. The location of selected water bodies across Asia

Table 2: The list of selected lakes and reservoirs across Asia

Country	Reservoir/Lake	Longitude	Latitude	SARAL AltiKa (Pass No.)
India	Bansagar Reservoir	81.28	24.19	496
	Gandhi Sagar Reservoir	75.59	24.54	840
	Hasdeo Reservoir	82.62	22.61	767
	Indravati Reservoir	82.83	19.23	324, 309
	Jalatput Reservoir	82.56	18.45	324
	Kadana Reservoir	73.83	23.31	281
	Kolab Reservoir	82.60	18.78	324
	Mahi Bajaj Sagar Reservoir	74.54	23.63	382
	Maithon Reservoir	86.81	23.81	152
	Massanjore Reservoir	87.31	24.11	967
	Pong Reservoir	76.05	31.98	926
	Ramganga Reservoir	78.76	29.55	395
	Ranapratap Sagar Reservoir	75.58	24.92	653, 840
	Shivaji Sagar Reservoir	73.76	17.41	840
	Tilaiya Reservoir	85.52	24.32	238
	Ujjini Reservoir	75.12	18.07	281
	Ukai Reservoir	73.64	21.25	825
	Barna Lake	77.99	23.05	668
	Shahjad	78.49	24.94	668
	Upper Bhopal Lake	77.34	23.25	210
	Mansarover Lake	81.45	30.68	582
	Pangong Lake	78.70	33.73	296, 309

	Chilika Lake	85.41	19.76	137
	Rann of Kutch Lake	70.13	23.95	997, 640
Armenia	Sevan Lake	45.33	40.38	197, 900
China	Boston Lake	87.05	42.00	165, 954
	Dagze Co Lake	87.49	31.89	238
	Dogai Coring Lake - I	89	34.56	696
	Dogai Coring Lake - II	89.24	35.32	696
	Gyaring Co Lake	88.45	31.05	795
	Har Lake	97.73	38.29	107
	Kusai Lake	92.82	35.78	451
	Mujui Co Lake	89.06	31.06	251
	Qinghai Lake	100.26	36.9	479, 552
	Siling Co	88.94	31.78	152
	Tai Lake	120.23	31.23	264
	Tangra Yumco Lake	86.54	31.00	782
	Ulungur Lake	87.32	47.28	537
	Wanquan Lake	83.86	34.23	496, 509
	Wuhu Lake	113.74	30.2	793
	Zhari Namco Lake	85.83	30.93	324
Iraq	Qadisiyah Lake	42.26	32.75	986
	Razazza Lake	43.59	32.75	356
Kazakhstan	Barsakelmes Lake	59.68	46.22	711
	Bel`Kopa Lake	59.62	50.05	625
	Syrdarya Reservoir	68.04	41.16	825
	Tengiz Lake	68.95	50.39	567
Kyrgyzstan	Toktogul Reservoir	72.92	41.8	23
Mongolia	Uvs Lake	92.72	50.31	324, 651
Russia	Il'men Lake	31.3	58.29	541, 730
	Peipus Lake	27.5	58.69	255
	Ubinskoye Lake	80.03	55.46	251
Srilanka	Senanayake Samudra Lake	81.5	7.21	238
Thailand	Bhumibol Lake	98.89	17.32	838
	Mae Nam Ping Lake	98.88	17.26	838
	Nan Lake	100.47	17.89	752
Turkey	Atatürk Lake	38.56	37.58	169

3. DATA AND METHODOLOGY

In the present study, the SARAL AltiKa Sensor Geophysical Data Records (SGDR) product, which contains geophysical parameters along with the additional information on sensor corrections, was processed for selected water bodies. The 40 Hz SARAL AltiKa data is generally sampled in 128 gates. The identified SARAL AltiKa pass over each water body is provided in Table 2. The inter-track distance between two successive tracks is approximately 75 km at the equator for the sensor. However, based on its frequency and transmission properties it measures at every 175 m approximately, along the track (SARAL AltiKa Handbook 2013). The available full waveform data of 1st to 32nd cycle have been analysed to retrieve the water level of water bodies, as listed in Table 2. In the present study, the Off-Centre-Of-Gravity waveform retracking algorithm was used to improve the water level estimation. The elevation of the surface (H) is estimated through the equation 1 using the altimeter datasets.

$$H = H_{sat} - R - C_{iono} - C_{dry} - C_{wet} - C_{st} - C_{pt} \pm \mathrm{DC} \quad (1)$$

Where, H_{sat} is precise altitude of the sensor from the datum; R is range, the one-way travel of radar pulse; C_{iono}, C_{dry}, and C_{wet} denote the corrections applied because of the delay in pulse propagation through the ionosphere, humid and dry atmospheres (dry and wet); Polar tide (C_{pt}), and solid Earth tide (C_{st}) effects considered in the calculation of water level, respectively. DC is used for datum correction; it makes the altitude relative to the geoid datum rather than the ellipsoid of rotation. The data was processed in the open Broadview Radar Altimetry Toolbox. The accuracy of retrieved water level was assessed in terms of coefficient of determination (R^2) and root mean square error (RMSE).

4. RESULTS AND DISCUSSION

The main objective of the study was to demonstrate the capabilities of SARAL AltiKa space based altimeter datasets in retrieving the water level of water bodies across Asia. Initially, the water level of 17 large reservoirs located in India was retrieved, as shown in Figure 2. These 17 reservoirs/lakes have track of SARAL AltiKa over them and their observed water level was available. It can be seen that the retrieved water level was in close agreement with the observed water level from almost all the water bodies. The retrieved water level was first validated with the observed water level available at India Water Resources Information System (https://indiawris.gov.in/wris/). The results were evaluated for each reservoir in terms of RMSE and R^2, as tabulated in Table 3.

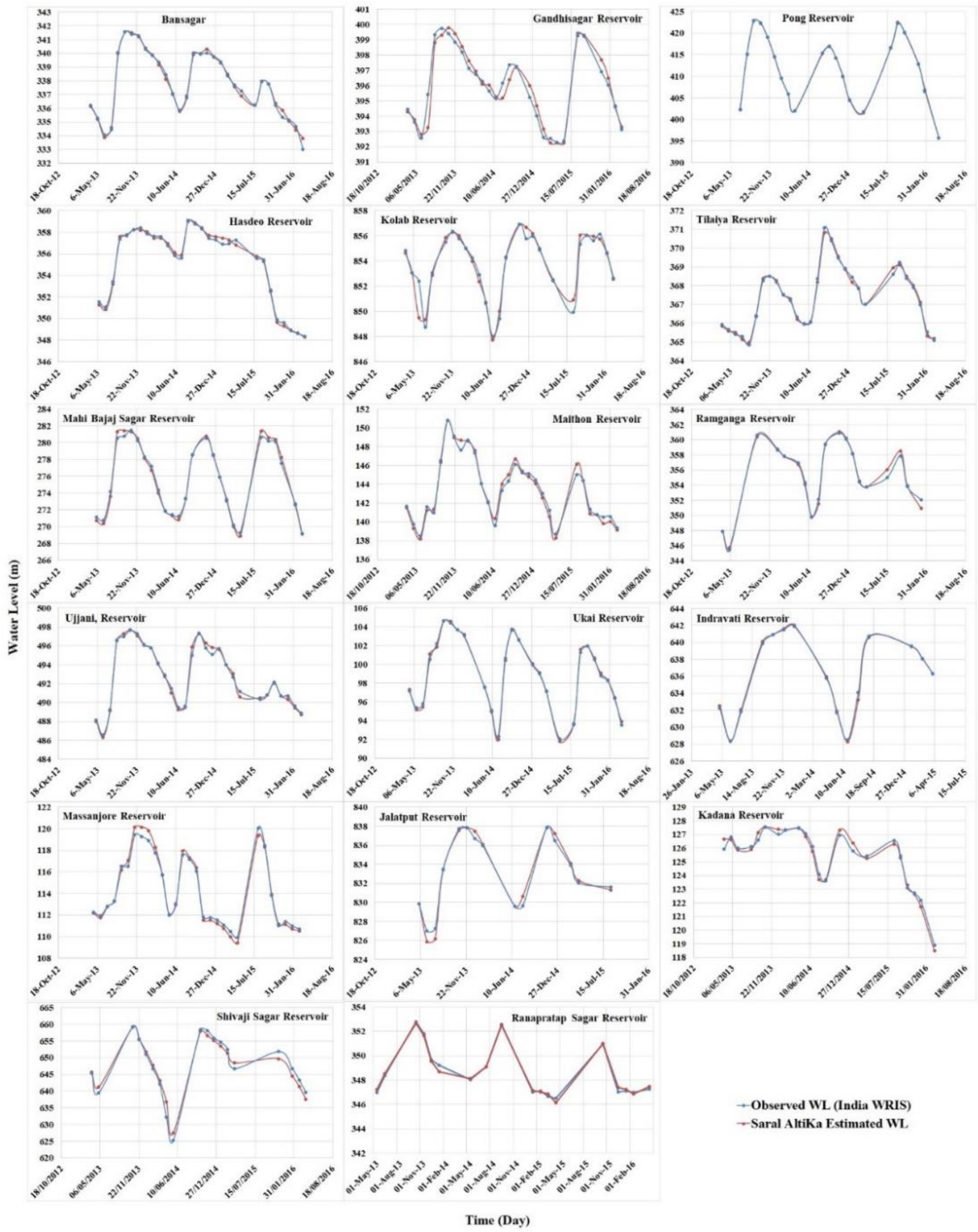

Figure 2. Comparison of retrieved water level time series for each reservoir with observed water level

Table 3. Evaluation of retrieved water level

S.No.	Reservoir	RMSE (m)	R^2	Correction
1	Bansagar Reservoir	0.14	0.996	0.25
2	Gandhi Sagar Reservoir	0.62	0.939	0.47
3	Hasdeo Reservoir	0.24	0.983	-0.27
4	Indravati Reservoir	0.27	0.997	1.23
5	Jalatput Reservoir	0.55	0.984	13.79
6	Kadana Reservoir	0.32	0.938	0.40
7	Kolab Reservoir	0.73	0.925	1.34
8	Mahi Bajaj Sagar Reservoir	0.38	0.995	0.36
9	Maithon Reservoir	0.49	0.981	0.44
10	Massanjore Reservoir	0.41	0.991	0.57
11	Pong Reservoir	0.11	1.000	0.67
12	Ramganga Reservoir	0.35	0.993	1.33
13	Ranapratap Sagar Reservoir	0.21	0.991	0.36
14	Shivaji Reservoir	1.64	0.990	-10.53
15	Tilaiya Reservoir	0.13	0.993	1.41
16	Ujjaini Reservoir	0.32	0.992	0.68
17	Ukai Reservoir	0.21	0.998	0.85

It can be noticed that SARAL AltiKa datasets are capable of retrieving water level of large water bodies with higher accuracy. In the present study, it was found that there was a slightly large error in water level estimation of Shivaji Sagar and Jalatput Reservoirs. These reservoirs require further investigation. It was observed that the R^2 after applying certain correction factor ranges from 0.93 to 0.99. The encouraging results provided impetus to study the water level of some gauges/ungauged lakes namely Mansarover, Pangong, Chilika, Rann of Kutch, Upper Bhopal, Barna, and Shahjad, as shown in Figure 3. The natural variation in water level of these water bodies was observed in the present analysis.

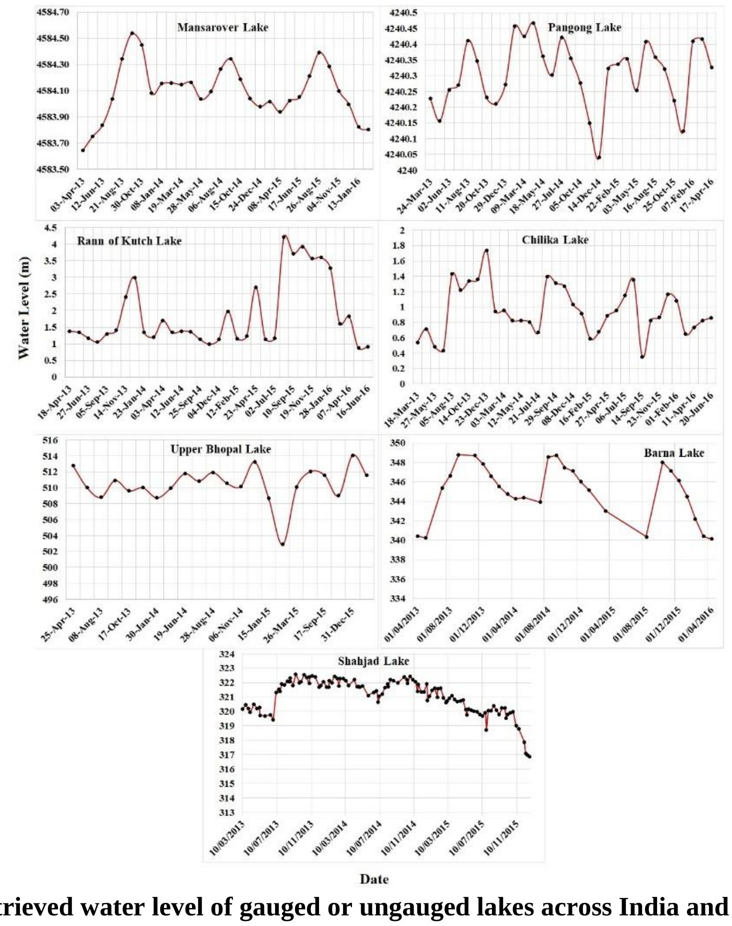

Figure 3. The retrieved water level of gauged or ungauged lakes across India and its surroundings

In continuation of this analysis, the water level of different water bodies mainly across Asia was retrieved using SARAL AltiKa datasets for all available cycles and tracks mentioned above. The water level derived for 16 different lakes and reservoir of China was shown in Figure 4. Again, it can be observed that the retrieved water level followed the natural trend of water level in a water body. It can be noticed that the Boston Lake is showing increase in water level over the selected period. It was verified from the literature that the lake has shown increasing trend of 0.575 m per year during 2013–2016 (Yao et al., 2018). It is also reported that the lowest water level of 1045 m was recorded in the year 2013. The same was depicted, in the present study.

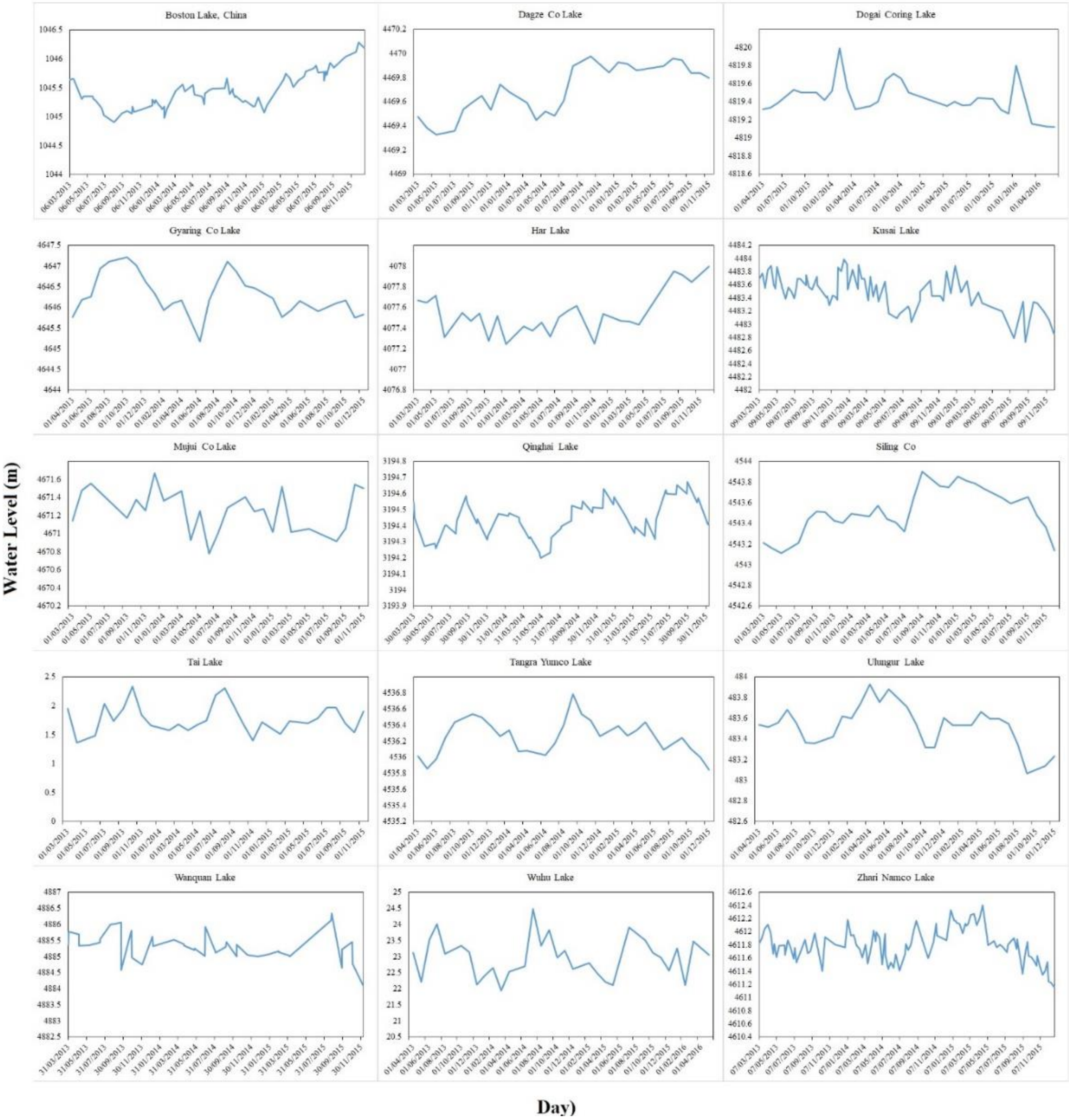

Figure 4. The retrieved water level of lakes and reservoirs selected across China

The water level derived for different lakes/reservoirs of other countries is presented in Figure 5. A very low variation of 0.8 m (1900 – 1900.8 m) in lake Sevan, Armenia was noticed. It is reported that the level of water in the lake has not exceeded 1901 m since 1960s (Nazaretyan 2021). The retrieved water level of Sevan Lake was compared with the observed data at Arpa-Sevan OJSC (Source: arpa-sevan.am), as shown in Figure 6. It was found that the coefficient of correlation between the estimate and observed water level was 0.902. The analysis showed the higher accuracy in estimation of water level using SARAL AltiKa space based altimeter data. It is also reported that attributing to low precipitation and recurrent droughts in the region, the annual average water level of Razazza Lake, Iraq reduced from 23.05 to 20.81 m.a.s.l. It has caused a decrease in the average annual capacity storage of the lake from 2.418 to 1.042 MCM and the top surface area shrunk from 742.55 to 483.66 km^2 (Al-Anbari and Mulahasan, 2022). However, the average water level of 21.02 m was estimated, in the present study, for selected analysis period.

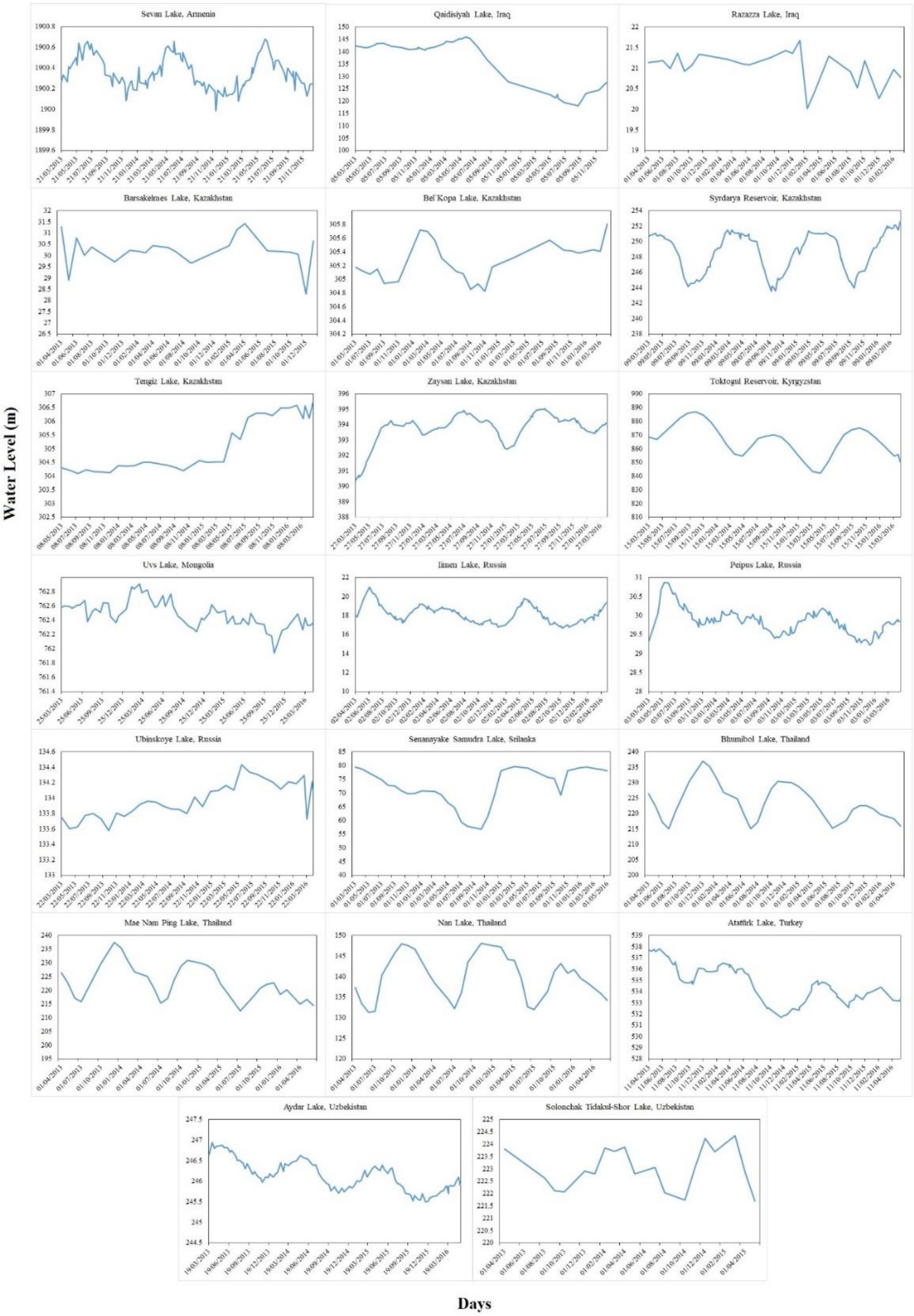

Figure 5. The time series of water level retrieved for other Asian Countries

The main source of recharge of Tengiz Lake, Kazakhstan is inflow from snow-melt in spring season. Further, the precipitation has increased and temperature decreased in the region during the period of analysis. Therefore, it was reported that the lake area enlarged from 2013 to 2015 (Liu et al., 2019). The increase in inflow and water spread were consistent with our study showing increasing trend in water level. According to the Tiirikoja/Mustvee hydrometric station the reference water level of Peipus Lake Russia is 30 m a.m.s.l. (Kapanen, 2018). The reported annual variation of the water level in the Atatürk Dam Reservoir, Turkey was in the range of 30 m, between 513 m and 542 m above sea level (Büyükakpınar et al. 2021). In the present study, the retrieved water level in Uvs Lake, Mongolia was in the range of 761.946 – 762.91 m, however, the recorded water level of the lake is 759 m, in the year 2021. It is also reported that the lake water level was showing decreasing trend since 2002 by −0.6172 cm/yr (Zhang et al., 2021). The higher accuracy in retrieving water level of different water bodies by SARAL AltiKa was also supported by Thakur et al. (2021).

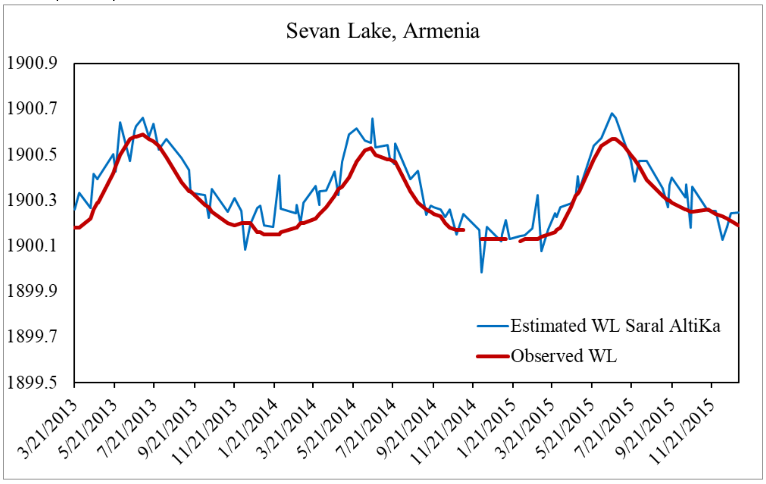

Figure 6. The comparison of estimated and observed water level of Sevan Lake, Armenia

5. CONCLUSIONS

The study depicted that the space based altimeters are very much capable of retrieving water level of inland water bodies. The higher frequency (Ka band) sensors like SARAL AltiKa play crucial role in estimating the water level of smaller/narrower water bodies attributing to their reduced altimeter footprint. The sensors have near global coverage, it helps hydrologist to understand the dynamics of transboundary water bodies, as well. However, SARAL AltiKa which was launched in February 2013, is now operating in the drifting orbit, since July 2016. Therefore, the systematic repeated observation over all reservoirs not possible. However, researchers have attempted to use the drifting orbit SARAL AltiKa data to retrieve the water level of selected water bodies. Further, the Jason – 3, Sentinel 3A/B, Sentinel – 6, Jason – 6 ensure the continuity of space based altimeter datasets for the water level estimation of different water bodies.

The researchers have used the altimeter retrieved water level with earth observation satellite derived water spread area to calculate the water body’s capacity, as well. The space based altimeter data is extensively used to establish the virtual gauge across the large rivers. The virtual gauges are established at the location of the pass of satellite altimeter, by simulating the discharge at the particular virtual gauge adapting hydrodynamic modelling approach, the rating curves for discharge estimation were generated. The upcoming SWOT altimeter mission promises the future continuity and will provide directly the discharge product for large reservoirs.

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