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Estimating and Assessing Monthly Water Level Changes of Reservoirs and Lakes in Jiangsu Province Using Sentinel-3 Radar Altimetry Data

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Abstract: Generating accurate monthly estimations of water level fluctuations in reservoirs and lakes is crucial for supporting effective water resource management and protection. The dual-satellite configuration of Sentinel-3 makes it possible to monitor water level changes with great coverage and short time intervals. However, the potential of Sentinel-3's Synthetic Aperture Radar Altimetry (SRAL) data to enable operational monitoring of water levels across Jiangsu Province on a monthly basis has not yet been fully explored. This study demonstrated and validated the use of Sentinel-3's SRAL to generate accurate monthly water level estimations needed to inform water management strategies. The monthly water levels of lakes and reservoirs from 2017 to 2021 were produced using Sentinel-3 level-2 land products. Results showed that, compared with in situ data across eight studied lakes, all lakes presented R (Pearson correlation coefficient) values greater than 0.5 and Root Mean Square Error (RMSE) values less than 1 m. Notably, water level estimates for Tai Lake, Gaoyou Lake, and Luoma Lake were particularly accurate, with R above 0.9 and RMSE below 0.5 m. Furthermore, the monthly water level estimates derived from the Sentinel-3 data showed consistent seasonal trends over the multi-year study period. The annual water level of all lakes did not change significantly, except for Shijiu Lake, of which the difference between the highest and lowest water level was up to about 5 m. Our findings confirmed the water level observation ability of Sentinel-3. The accuracy of water level monitoring could be influenced by internal water level differences, terrain features, as well as the area and shape of the lake. Larger lakes with more altimetry sampling points tended to yield higher accuracy estimates of water level fluctuations. These results demonstrate that the frequent, wide-area coverage offered by this satellite platform provides valuable hydrological information, especially across remote regions lacking in situ data. Sentinel-3 has immense potential to support improved water security in data-scarce regions.

Keywords: satellite altimetry; Sentinel-3; SRAL; lakes and reservoirs; Jiangsu Province

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Citation: Xu, J.; Xia, M.; Ferreira, V.G.; Wang, D.; Liu, C. Estimating and Assessing Monthly Water Level Changes of Reservoirs and Lakes in Jiangsu Province Using Sentinel-3 Radar Altimetry Data. *Remote Sens.* **2024**, *16*, 808. https://doi.org/10.3390/rs16050808

Academic Editors: Xiaoli Deng, Stelios Mertikas and Jérôme Benveniste

Received: 20 December 2023
Revised: 8 February 2024
Accepted: 20 February 2024
Published: 26 February 2024

1. Introduction

Lakes and reservoirs cover only about 2% of the Earth's land surface. However, they play an important role in the development of the national economy, such as regulating river runoff, developing irrigation, providing industrial and drinking water sources, breeding aquatic organisms, improving the regional ecological environment, and shipping [1,2]. They are quite vulnerable to human activities like industry, agriculture, aquaculture, and climate change [3–5]. Under the influence of natural and anthropogenic factors, lakes and reservoirs may change considerably, and even the water bodies may disappear [6,7]. Water levels can clearly show the changing trends under those factors. Therefore, it is essential to protect and rationalize water resources by accurately collecting information on fluctuations in lakes and reservoirs water levels and studying their spatio-temporal changes in different periods.

However, conventional approaches to measuring water levels rely primarily on in situ data from hydrological stations. It might be challenging to collect accurate data on water levels because of the uneven and limited distribution of hydrological stations. Altimetry has shown some promising results in monitoring inland water levels due to the advancement of satellite altimeters. For instance, several studies have used altimetry data from T/P, Jason-1/2/3, EnviSat, CryoSat-2, and ICESat-1/2 to retrieve water level fluctuation (see, e.g., [8–17]). Xu et al. [18] used the ICESat-2 ATL13 product to monitor 13,843 lakes and reservoirs worldwide with areas greater than 0.1 km^2. These authors showed that the absolute mean difference and standard deviation can reach a decimeter level compared to in situ data. Light Detection and Ranging (LiDAR) altimeters, like ICESat-1/2 and GF-7, and microwave altimeters, such EnviSat, T/P, Jason-1/2/3, CryoSat-2, and Sentinel-3, are the two primary categories of spaceborne altimeters now in use [19]. The small footprint of the LiDAR altimeter is advantageous for monitoring small and medium-sized water bodies [20]. However, its revisit time interval is too long for high temporal water level monitoring. The microwave altimeter, on the other hand, has a shorter revisit duration, which makes regular observation more feasible.

In February 2016 and April 2018, Sentinel-3A and Sentinel-3B were successfully launched, adding another trustworthy data source for inland water monitoring. Together, they offer a 140° in-plane separation, the repetition cycle is the same (27 days), but the SRAL coverage is increased, allowing for the monitoring of more water bodies. The two operating modes of Sentinel-3 are the LRM (low-resolution mode) and SAR (synthetic aperture radar). It maintains LRM as a backup operational mode while providing 100% SAR altimetry coverage. The along-track and across-track resolutions in SAR mode are approximately 0.3 km and 1.63 km, respectively, and the footprint interval is 320 m [21]. Compared to EnviSat, ERS, and SARAL, its resolution is significantly higher and is primarily less impacted by coastal terrain. After one complete cycle with two satellites in operation, the inter-track spacing at the equator decreases from 104 km to 52 km, giving global coverage of mesoscale topography data [22]. The dual-satellite configuration means that Sentinel-3 can be used to monitor more lakes, and water level series with shorter intervals can be acquired. Nielsen et al. [23] evaluated the performance of Sentinel-3A in more than 100 lakes in the United States and Canada based on the official Level 2 product. Song et al. [24] assessed the performance of the Sentinel-3 SRAL SAR tracker on 15 lakes located in the Northern Hemisphere. Sentinel-3 has undergone suitability assessments globally, across all of China, and specifically in the southwestern mountainous regions [25]. Despite the vast number of studies that have used Sentinel-3 products to monitor water levels in inland lakes, most have only targeted a small subset of lakes, particularly large lakes with an area larger than 100 km^2 [23,26,27]. Jiangsu Province, which has 137 lakes and 908 reservoirs, has the most concentrated distribution of freshwater lakes. Therefore, it is necessary to investigate whether water level data derived from Sentinel-3's SRAL can accurately depict the fluctuations in lake and reservoir water levels. Additionally, an exploration into the factors influencing the accuracy of water level monitoring is warranted.

This study aims to demonstrate and validate the use of Sentinel-3A/B SRAL data for monitoring water level changes across reservoirs and lakes in Jiangsu Province. The specific objectives are: (1) to statistically validate the Sentinel-3-derived water level estimates against in situ gauge data; (2) to generate a complete time series of monthly water levels for the major lakes and reservoirs in Jiangsu Province from 2017 to 2021 using only Sentinel-3 data and analyze the spatiotemporal variations; and (3) to explore the potential factors that may influence the accuracy of water level retrieval. This study will help determine the efficacy of using Sentinel-3 SRAL for operational monitoring of reservoirs and lake water levels across Jiangsu Province to support improved water resource management.

2. Study Area and Datasets

2.1. Study Area

Jiangsu Province is situated along the coast of eastern China, between latitudes 30°45′ and 35°08′N and longitudes 116°22′ and 121°55′E. The Yangtze River, Tai Lake, Huaihe River, and Yishusi River systems are all part of the Jiangsu River System, which is separated into the Yangtze River basin and the Huaihe River basin. In Jiangsu, there are several lakes and extensive river systems. The lakes cover an area of 6260 km^2, accounting for 6% of Jiangsu's total area and ranking highest in China [28].

We utilized ArcGIS to count the number of water bodies; according to the HydroLAKES database [29], Jiangsu Province has 1190 lakes and reservoirs with an area larger than 0.1 km^2, of which 29 are larger than 10 km^2. Overall, 17 of the 29 water bodies can be covered by Sentinel-3. Out of the 17 lakes considered, Nvshan Lake is predominantly located within Anhui Province and falls under its jurisdiction. Consequently, we did not include it as a subject of our research and directed our attention to the remaining 16 lakes. Their geographical position is depicted in Figure 1. They are dispersed over northern, central, and southern Jiangsu and have a strong regional representation.

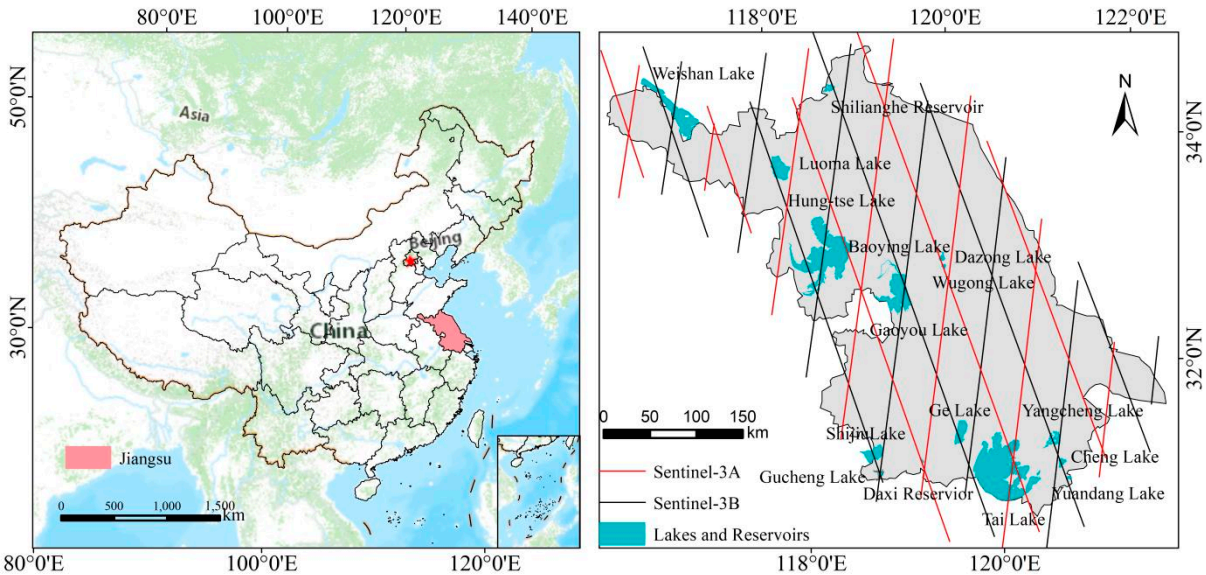


Figure 1. Geographical location of Jiangsu Province and the distribution of lakes and reservoirs.

2.2. Datasets

2.2.1. Sentinel-3 Altimetry Data

With an orbital inclination of 98.65° and a reference height of 814.5 km, the Sentinel-3 topography mission is primarily employed for the research of marine topography and terrestrial topography, encompassing land-ice, land, and inland waterways, respectively [30]. The satellites carry a dual-frequency advanced synthetic aperture radar altimeter (Ku and C-band). The Ku band is used for ranging, while the c band is employed to determine ionospheric errors. The orbital cycle of a single satellite is 27 days, encompassing 385 orbits per cycle, with a track spacing of approximately 87 km at 33°N. In this study, Level 2 NTC (non-time critical) land standard data products from 2017 to 2021 for Sentinel-3A and from 2019 to 2021 for Sentinel-3B were utilized for water level extraction. These data were downloaded from https://dataspace.copernicus.eu (accessed on 27 January 2024). The products contained longitude, latitude, altitude, measurement time and some necessary geophysical correction parameters. The information about the data used is displayed in Table 1. It is worth noting that the B046 and B052 tracks of Gaoyou Lake transited on the same day, as did the B374 and B380 tracks of Hung-tse Lake.

Table 1. The information on the lakes/reservoirs and the altimetry data used in this study. The asterisk (*) in the lake names indicates the presence of in situ data. The average depth was provided by HydroLAKES database; the area was provided by HydroLAKES and Jiangsu Hydraulic Research Institute; and the transit time was extracted from Sentinel-3 radar data.

Lake Names	Water System	Lake Area (km^2)	Average Depth (m)	Track	Number of Tracks	Transit Time (UTC + 8:00)
Baoying Lake *	Huaihe River	40.28	1.13	B052	41	21:39–21:40
Dazong Lake	Huaihe River	32.25	1	A052	68	21:38
Gaoyou Lake *	Huaihe River	655.942	7.9	B046	36	10:24
				B052	41	21:39–21:40
Hung-tse Lake *	Huaihe River	1786.75	9.8	A380	68	21:42
				B374	40	10:28
				B380	41	21:43–21:44
Wugong Lake	Huaihe River	15.33	1	A052	68	21:38
Cheng Lake	Tai Lake	42.26	1.9	B109	40	21:35
Ge Lake *	Tai Lake	196.07	2.9	B052	41	21:39
Tai Lake *	Tai Lake	2341.04	2.2	A052	68	21:37
				A103	66	10:19
Yangcheng Lake	Tai Lake	124.24	1.7	B109	40	21:35–21:36
				B160	37	10:17–10:18
Yuandang Lake	Tai Lake	12.93	1.7	B109	24	21:35
Gucheng Lake *	Yangtze River	30.29	1	B046	36	10:25
				B380	41	21:43
Shijiu Lake *	Yangtze River	212.16	3.7	B046	33	10:25
				B380	41	21:43
Luoma Lake *	YiShuSi River	296.662	3.9	B380	41	21:43–21:44
Weishan Lake	YiShuSi River	690.59	3	B260	38	10:35
				B323	41	21:47–21:48
Daxi Reservoir	Tai Lake	11.29	0.9	A380	67	21:41
Shilianghe Reservoir	YiShuSi River	52.22	7.7	B052	41	21:40

2.2.2. Water Mask Data

The water masks of lakes and reservoirs were offered by Jiangsu Hydraulic Research Institute and the HydroLAKES database. The current version of the HydroLAKES database covers 1,427,688 water bodies, including all lakes with an area larger than 0.1 km^2. The water masks for Yangcheng Lake, Cheng Lake, Dazong Lake, Wugong Lake, and Yuandang Lake were gathered from the HydroLAKES database, and Jiangsu Hydraulic Research Institute provided the rest.

2.2.3. In Situ Data

The in situ data from 2017 to 2020 were sourced from the Hydrological Yearbook of the People's Republic of China [31–36]. The primary device for gauging the in situ water level is an automatic monitoring water level gauge, which is manually calibrated daily at 8:00 am. At certain stations, technicians also take manual water level measurements at least twice a day, in conjunction with the automated gauging. Any significant changes in the water level will cause the number of observations to increase to control the changing process. For lakes and reservoirs with multiple hydrological stations, the in situ water level on a given day is calculated by averaging the data from all stations.

3. Methods

3.1. Principle of Satellite Altimetry

The basic principle of satellite altimetry is that the pulse signal transmitted by the radar altimeter is reflected when it comes into contact with the Earth's surface, with the receiver detecting the echo pulse reflected from the surface. In theory, the distance between the satellite and the water surface can be determined by the speed of signal propagation and the interval between signal transmission and reception. However, due to the influence of terrain, the reflected echo waveform may become contaminated, resulting in distance divergence. To address this issue, waveform retracking algorithms are employed for

correction. Sentinel-3 altimetry data offer various waveform retracking algorithms, which are discussed in detail in Section 4.1. In addition, the effects of signal propagation errors must also be considered, collectively referred to as geophysical corrections [37]. The corrections processing criteria are based on ocean data. The inland water surface is so tiny compared to the sea surface that the effects of sea tide, inverse barometric effect, and tidal pressure can be disregarded [38,39]. As a result, the following equation is used to build the specific error corrections:

$$cor = dry + wet + iono + solid + pole \tag{1}$$

where *cor* is the total error correction, *dry* is the dry troposphere correction, *wet* is the wet troposphere correction, *iono* is the ionosphere correction, *solid* is the solid Earth tide correction, and *pole* is the polar tide correction. Therefore, the water level based on the EGM2008 geoidal model is constructed as follow:

$$h = h_{alt} - h_{ran} - cor - N \tag{2}$$

where N is the geoidal undulation based on the EGM2008, h_{alt} is the distance between the altimeter and the WGS84 reference ellipsoid, and h_{ran} is the distance between the altimeter and the water surface after waveform retracking.

Figure 2 shows the basic principle of satellite altimetry. The geophysical correction parameters are provided at a 1 Hz data rate, whereas the latitude, longitude, and altitude are available at both 1 Hz and 20 Hz data rates (where the 1 Hz measurement is interpolated from the 20 Hz measurement). The specific indexes 'index_1hz_meas_20_ku' and 'index_first_20hz_meas_01_ku' relate all 1 Hz to 20 Hz data.

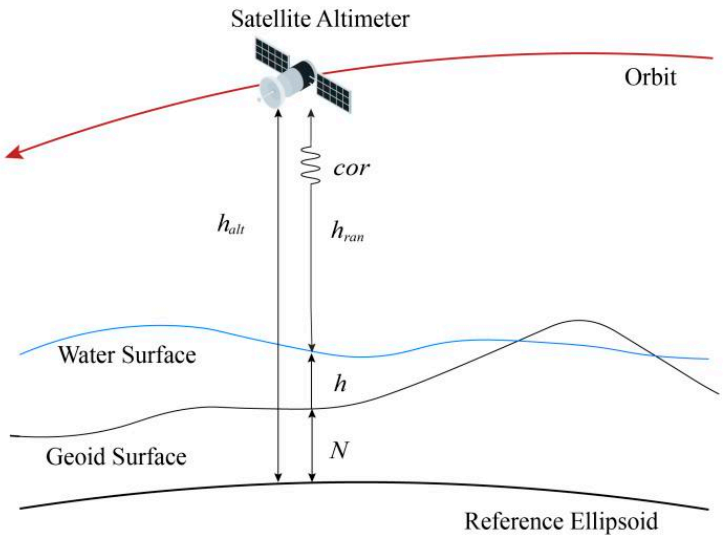


Figure 2. Schematic diagram of the satellite altimetry.

3.2. Extraction of Water Level Information

The extraction framework is described in Figure 3. The elevation points' orthometric heights based on EGM2008 are determined using Equations (1) and (2). Before the water level extraction, filtering out elevation points outside the water surface according to the water masks is needed, only keeping the points of interest inside the lake. In this study, the extraction procedure mainly includes three steps: (1) data quality grading, (2) vertical datum conversion and deviation correction, (3) calculation of monthly water level.

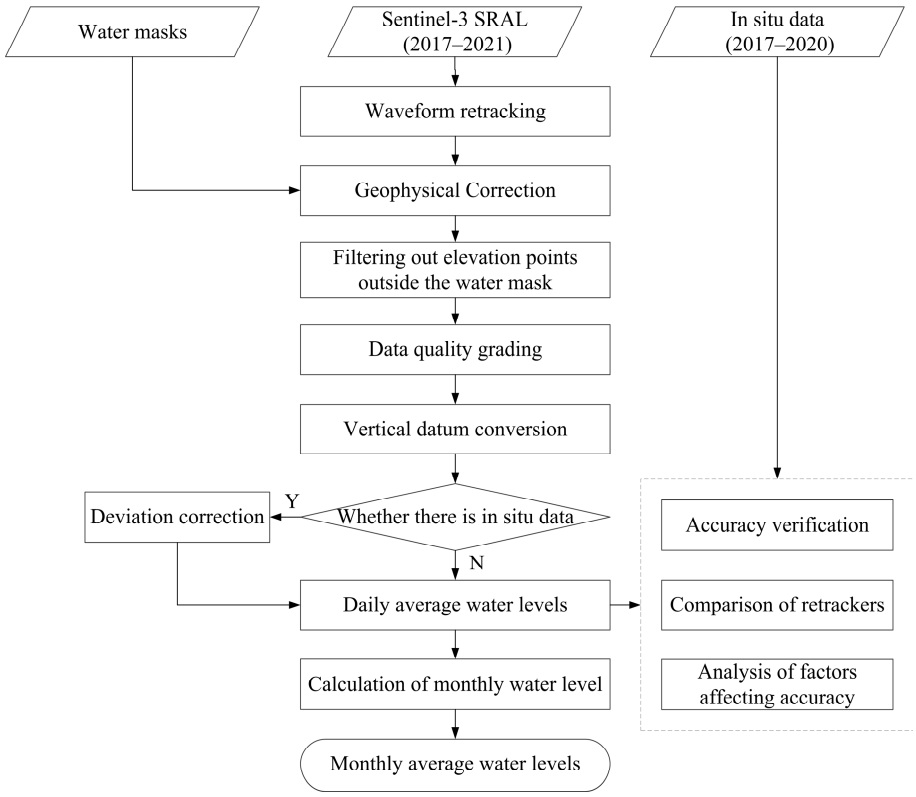


Figure 3. Workflow of water level extraction.

3.2.1. Data Quality Grading

In 2018, Wen et al. proposed a method for extracting water levels based on data quality grading and evaluation [40]. The method consists of removing the elevation points outside the water mask, then the reserved locations are arranged according to the latitude. A subset of points that satisfies the following criteria constitutes a continuous, high-quality point group: there must be at least three points; elevation fluctuation must be slight, with no more than 0.3 m between each point and the average of all points in the group. We assume that, for a given moment, the water level across a calm surface remains static. During the same timeframe, most lakes in Jiangsu undergo a slight water level decrease, commonly limited to within 0.3 m.

In this study, when multiple continuous, high-quality point groups were available on the same day, the point group with the highest quantity and the lowest Root Mean Square Error (RMSE) was selected. If the difference between the mean of one group and the chosen group was less than 1 cm, they were combined to generate the final point group. The proportion of the points in the continuous, high-quality point group to the total number of points in the water surface was calculated. The data were categorized into grades one, two, and three based on the proportion interval values of 66.67% and 33.33%. If a pass lacked group falling within between grade one and three range, it was categorized as grade four, and no measurement was assigned for that specific pass. Finally, the PauTa Criterion (also called the 3σ Criterion) was used to remove the large errors, and the average of the remaining points was determined as the daily altimetry water level.

Figure 4 shows an example of water level observations in Shijiu Lake with the Sentinel-3B track 380. The points in the figure represent elevation points within the Shijiu Lake water surface range, and the red box depicts the continuous, high-quality point group we selected. Non-water surface reflections could skew the altimetry result, particularly in the shoreside region and middle island. Before determining the water level, these outliers were eliminated using the data quality grading method.

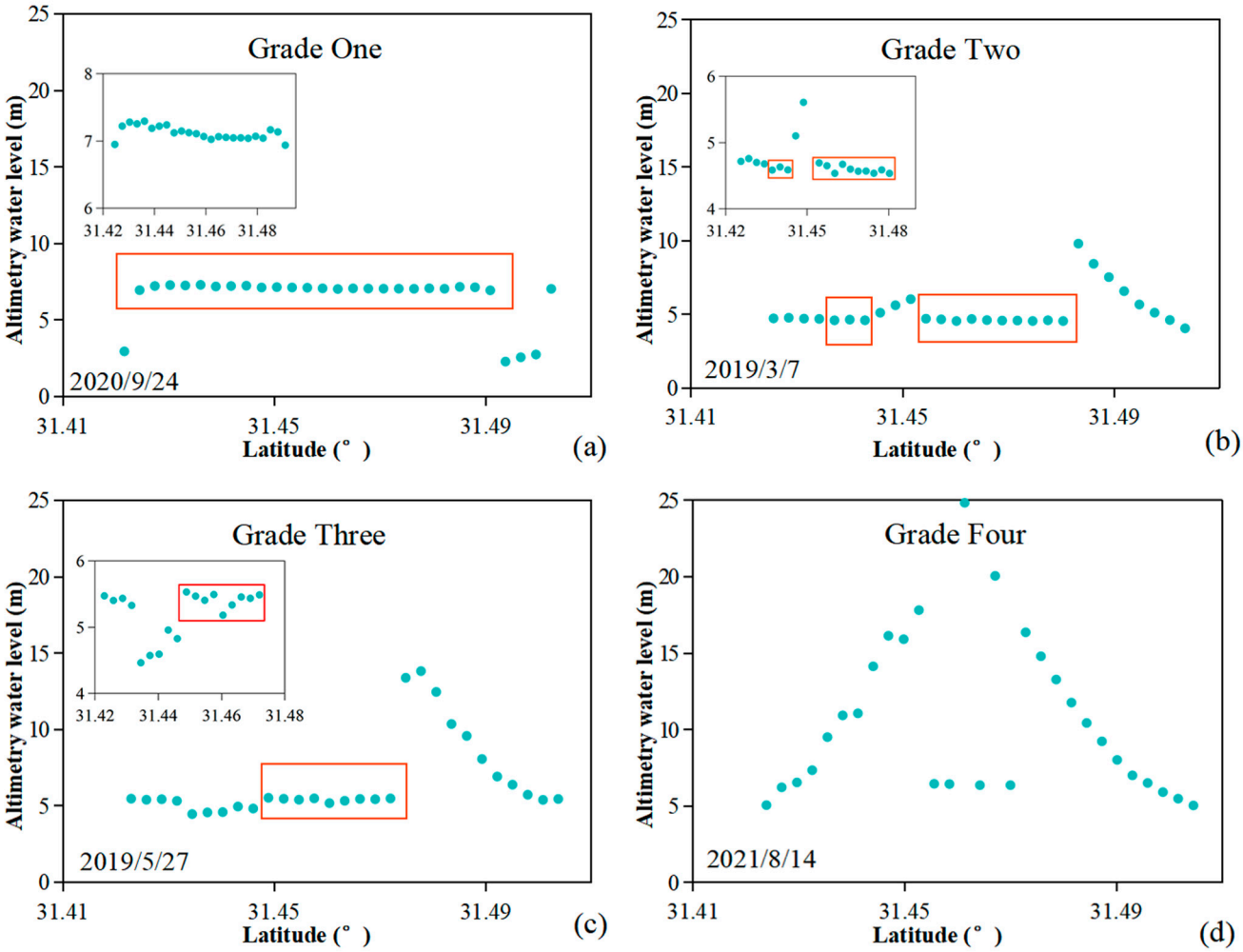


Figure 4. Data quality grading of Shijiui Lake. (**a**–**d**) depict data samples for grade one through grade four.

3.2.2. Vertical Datum Conversion and Deviation Correction

A comparison was conducted between altimetry observations and in situ water levels for eight lakes that had available in situ data. Vertical datum conversion was necessary since the altitude references for in situ data (National Vertical Datum 1985) and altimetry data (EGM2008 geoid) were different. There was a 0.32 m discrepancy between the two references [41]. Some divergence remained even after altimetry levels were adjusted by subtracting a constant of 0.32 m to make them compatible with in situ data [23]. We computed the RMSE and correlation coefficients after subtracting the average deviation in order to improve accuracy. Since certain lakes lacked in situ data, deviation correction was only included in the accuracy verification step (Section 4.2).

3.2.3. Calculation of Monthly Water Level

Finally, to calculate the water levels of lakes and reservoirs, the daily average water level was determined by taking the average of all data points within a final continuous high-quality group. Subsequently, the monthly average water level was computed by averaging all the daily average water levels for each respective month.

4. Results

4.1. Comparison of Four Different Retracking Algorithms

The different retrackers can be more suited to a specific surface. The Ocean, OCOG (Offset Center Of Gravity) [42,43], Ice sheet, and Sea ice retracking algorithms of Sentinel-3

SAR mode are designed, respectively, for open ocean and coastal zones, sea-ice margins, ice-sheet margins, and sea ice. Figure 5 shows the comparison between the water level time series obtained by the four retrackers of Tai Lake (track A052) and the in situ measurements. It was found that from January 2017 to December 2020, the RMSE of the OCOG algorithm can reach 0.31 m with the R of 0.963, which is better than the other three trackers.

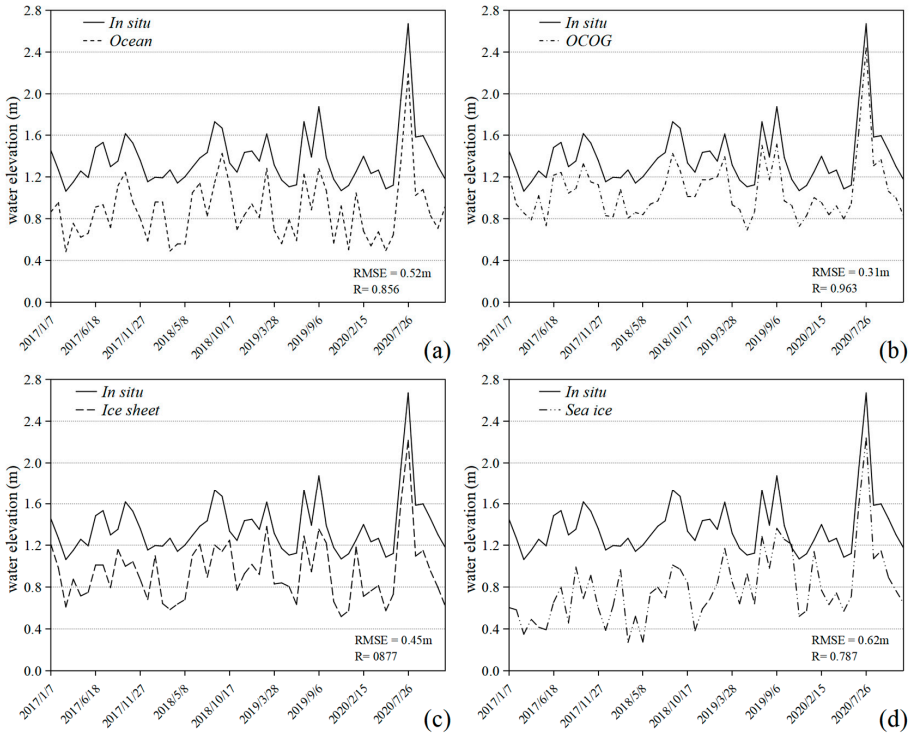


Figure 5. Time series of water level derived from Sentinel-3A retracker across Tai Lake with track A052 and compared with in situ measurements. The solid lines stand for in situ water level measurements; dash lines represent water levels derived from the Ocean (**a**), OCOG (**b**), Ice sheet (**c**), and Sea ice (**d**) retrackers.

The performance of these four retrackers was also calculated in several other lakes, including Tai Lake (track A052, A103), Hung-tse Lake (A380), Gucheng Lake (B046), Gehu Lake (B052), Gaoyou Lake (B052), Baoying Lake (B052), Shijiu Lake (B380), and Luoma Lake (B380). As shown in Table 2, in comparison to other retrackers, OCOG has the lowest RMSE and highest R. The findings support Frappart's and Medina's assertions that the OCOG retracker, also known as Ice-1, is better suited for collecting inland water level [37,43]. Therefore, the altimetry water levels for all lakes and reservoirs were extracted using the OCOG retracker in this study.

Table 2. Comparison between different retrackers. Note that observations with final altimetry heights less than three are considered invalid.

Lake	Track	RMSE (m)				R				Number of Invalid Observations			
		OCOG	Ocean	Ice Sheet	Sea Ice	OCOG	Ocean	Ice Sheet	Sea Ice	OCOG	Ocean	Ice Sheet	Sea Ice
Tai	A052	0.31	0.52	0.45	0.62	0.963	0.856	0.877	0.787	0	0	0	0
	A103	0.23	0.52	0.43	0.64	0.977	0.975	0.979	0.864	0	0	0	0
Hung-tse	A380	0.75	1.21	0.92	1.99	0.838	0.362	0.592	0.328	0	0	0	2
Ge	B052	0.53	0.83	0.90	0.48	0.716	0.671	0.595	0.759	0	0	0	2
Gucheng	B046	1.16	3.63	0.42	1.18	0.688	0.429	0.954	0.529	2	2	14	4
Shijiu	B380	0.54	0.59	0.48	0.52	0.996	0.996	0.990	0.991	0	0	3	2
Luoma	B380	0.30	0.21	0.26	0.23	0.987	0.966	0.907	0.932	0	0	0	0
Gaoyou	B052	0.45	0.27	0.14	0.20	0.996	0.995	0.994	0.985	0	0	0	0
Baoying	B052	0.56	0.36	0.25	0.30	0.865	0.876	0.912	0.877	9	9	9	9
Total		0.56	0.88	0.58	0.99	0.998	0.994	0.998	0.992	11	11	26	17

4.2. Validation of Altimetry Water Level Using In Situ Data

When two or more tracks passed through a lake on the same day, we selected the continuous group of high-quality points with the highest quantity and the least RMSE and calculated its average to represent the water level of the day. The correction of height level deviations can only be performed on the premise of the existence of field data. Table 3 shows the values of R and RMSE before and after deviation correction. The RMSE values of eight lakes were improved to some extent, especially Baoying Lake. Figure 6 displays the correlation coefficient between altimetry water level and in situ water level after deviation correction. With R exceeding 0.5 and RMSE under 1 m, the Sentinel-3 satellite achieved effective capabilities for monitoring lake water levels across a range of study sites. For example, demonstrating superior performance, accuracy metrics in Tai Lake, Gaoyou Lake, and Luoma Lake surpassed 0.9 for R and fell below 0.1 m in RMSE terms. It is important to note that the scatter plot contains a few apparent, significant inaccuracies. Correlation analysis may, therefore, understate their consistency.

Table 3. Comparison of R and RMSE in 8 lakes before and after deviation correction.

Lake Name		Baoying	Gaoyou	Ge	Gucheng	Hung-tse	Luoma	Tai	Shijiu
Before deviation correction	R	0.865	0.995	0.716	0.805	0.971	0.987	0.961	0.929
	RMSE (m)	0.56	0.40	0.53	0.84	0.50	0.30	0.26	0.99
After deviation correction	R	0.865	0.995	0.716	0.805	0.971	0.987	0.961	0.929
	RMSE (m)	0.16	0.06	0.31	0.66	0.15	0.09	0.07	0.77

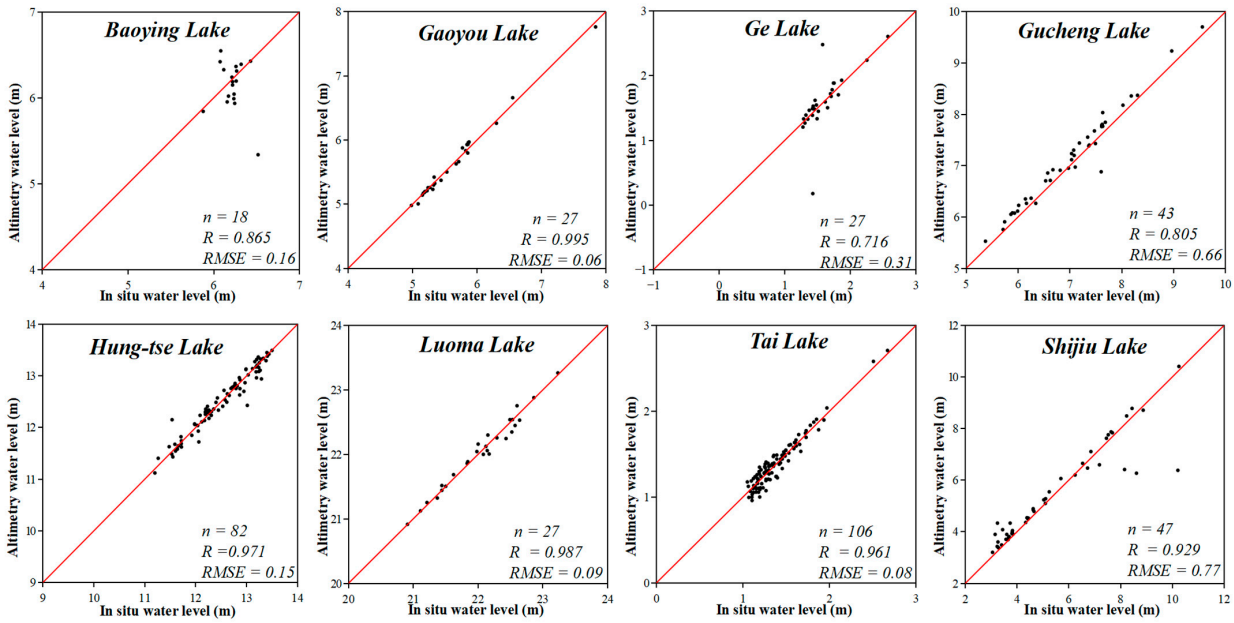


Figure 6. Validations of altimetry water levels after deviation correction using in situ data. The red dash line represents the 1:1 line. Note: All valid observations for 2017/2019–2020 are shown in this figure, that is, data for 2021 and invalid observations are not included.

4.3. Monthly Water Level Changes of Lakes and Reservoirs

Despite the short revisit period of Sentinel-3 satellite, Yuandang Lake has only 24 available cycles for track B109 between 2019 and 2021 due to its small area. This limited availability makes it challenging to ensure at least one piece of data per month, thus complicating the analysis of monthly water level changes for Yuandang Lake. Therefore, we only analyzed the water level changes of 13 lakes and 2 reservoirs in Jiangsu Province. Figure 7 shows the trend of monthly water level changes.

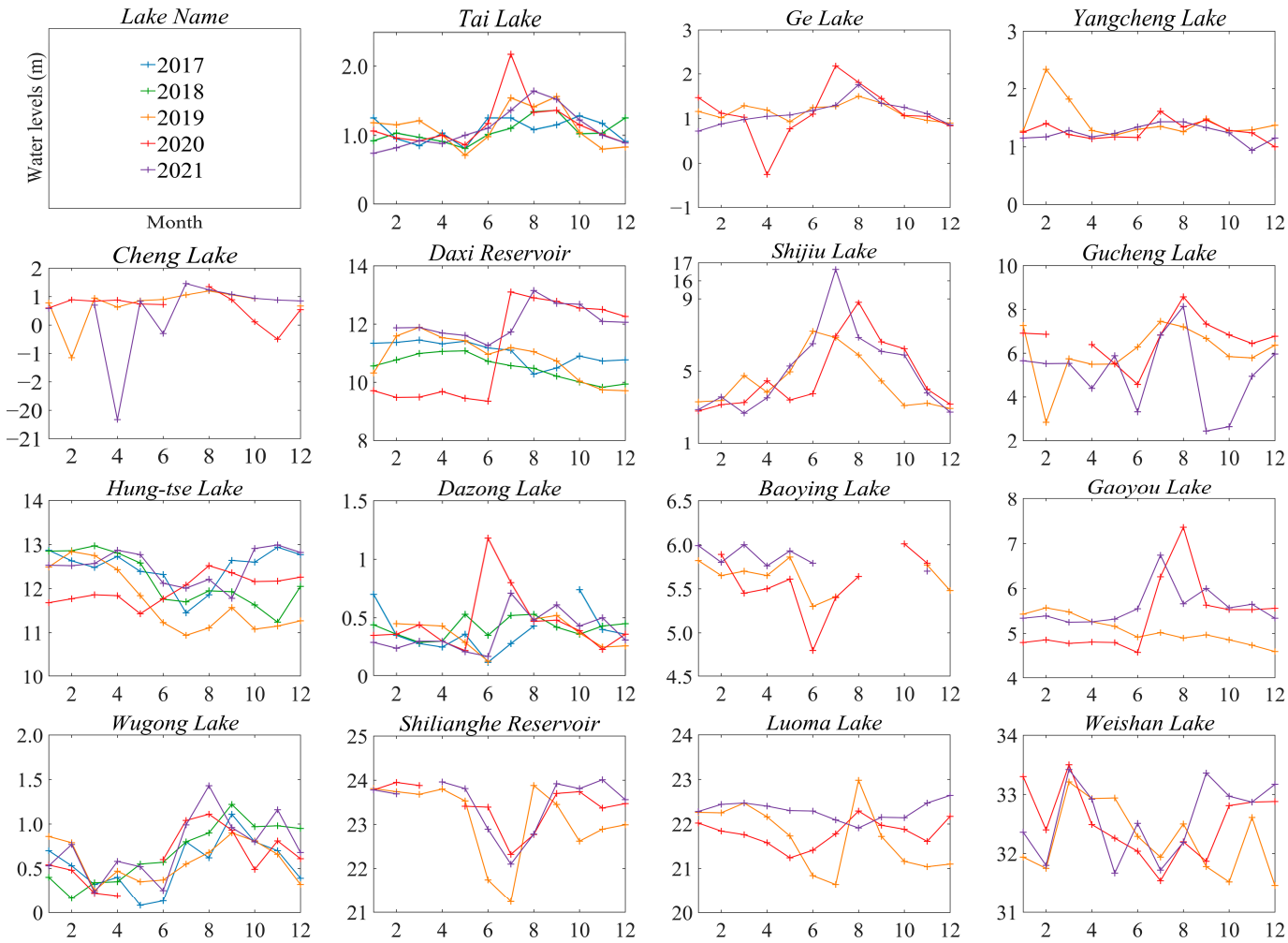


Figure 7. Monthly water level changes of 13 lakes and 2 reservoirs. In the line chart depicting Chenghu Lake and Shijiu Lake, it is imperative to note that a non-uniform spacing ordinate system was employed.

The flood season in Jiangsu Province typically spans from 1 May to 30 September each year, with June to July considered the plum rain season. During this period, there is usually higher precipitation, leading to significant changes in lake water levels. Most lakes in Jiangsu Province exhibited seasonal changes in water level. In most cases, water level changes could be constructed accurately, especially for lakes with large areas, such as the Tai Lake, Hung-tse Lake, Gaoyou Lake, etc. (refer to Figure 7).

As shown in Figure 7, the water level of Tai Lake changed slightly, with the maximum water level typically occurring from July to October. The difference between the maximum and minimum water levels was generally less than 1 m (except in 2020). Similarly, the water levels of Ge Lake, Yangcheng Lake, and Cheng Lake also exhibited slight fluctuations throughout the year. From 2017 to 2019, the water level of Daxi Reservoir showed a rising trend in the spring, followed by a gradual decrease. However, in 2020 and 2021, its water level showed a relatively apparent rising trend in June (rising by nearly 4 m in 2020). Shijiu Lake and Gucheng Lake, located in the Yangtze River Main Stream Water System, exhibited distinct seasonal patterns in water level changes from 2019 to 2021. Shijiu Lake, in particular, is the only lake directly connected to the Yangtze River in the lower reaches, leading to significant fluctuations in its water level. Usually, the difference between the maximum and minimum water levels could reach up to 5 m. The water level of Hung-tse Lake changed slightly from January to April annually, followed by a rapid decline from April to June. Subsequently, during the main flood season, the water level began to rise

gradually. The water levels of Dazhong Lake and Baoying Lake tended to remain relatively stable throughout the year, with minimal fluctuations. The water level of Gaoyou Lake decreased slowly in 2019. However, in 2020 and 2021, its water level changed significantly from June to September. The water level of Wugong Lake has been rising since May, reaching its peak in September, followed by a decrease in water level. The water level of Shilianghe Reservoir significantly decreased from May to July, followed by a rapid increase from July to September, and then gradually leveled off. The water level of Luoma Lake exhibited different trends from 2019 to 2021. In 2019, the water level dropped rapidly from March to July, increased rapidly from July to August, and then gradually decreased. Conversely, in 2020, it decreased steadily from January to May, gradually increased from May to August, and began to decline again from August to November. In 2021, compared to the previous two years, the water level changed more slowly, declining from January to August, and then gradually rising. The difference in water level between the two parts was approximately 2 m. The water level of Weishan Lake fluctuated between 31 m and 34 m, experiencing several rises throughout the year, with no discernible consistent pattern of change.

The changing trend of lakes and large reservoirs can be effectively reflected by the water levels derived from satellite altimeters, and it also has good performance during periods with significant fluctuations. For example, in late June 2019, the Jiangsu Province Hydrology and Water Resources Investigation Bureau issued a blue alert for a low water level. The water level of Luoma Lake experienced a rapid drop due to the combined impact of reduced rainfall and agricultural water consumption. In early July 2019, the water level of Hung-tse Lake and Shilianghe Reservoir also dropped rapidly due to the same reason. Furthermore, in 2020, it was evident that the water level of some lakes rose sharply in July and surpassed that of previous years, especially the lakes within the Tai Lake system. According to the annual report on water regime in the Tai Lake basin, in 2020, a severe flood occurred basin-wide, characterized by frequent heavy rainfall. The highest water level of Tai Lake was recorded on July 20, marking the third-highest level since in situ data became available in 1954. Subsequently, the water level gradually decreased due to the impact of high-temperature weather and little rainfall.

5. Discussion

5.1. Analysis of Factors Influencing Altimetry Water Level Measurement Accuracy

Numerous factors contribute to the precision of altimeter satellite water level monitoring. These factors encompass both internal considerations, such as sensor performance and instrument resolution, and external elements like atmospheric influence, terrain characteristics, and the shape and size of the lake. This section specifically concentrates on exploring water level differences, terrain features, and the area and shape of the lake.

The precision of altimetry water level is influenced by internal variations in water levels across expansive lake. Taking Weishan Lake as an example, the northern part of Weishan Lake connects with Zhaoyang Lake, Dushan Lake, and Nanyang Lake, collectively known as Nansi Lake or Weishan Lake. Extending from northwest to southeast, Weishan Lake is divided into upper and lower lakes by a dam at its narrowest point. The upper lake maintains a water level approximately 2 m higher than the lower lake, as shown in Figure 8. The disparate distribution of satellite footprints over the upper and lower lakes induces substantial variations in the altimetry water level of the lake. Independent calculations of water levels for the upper and lower lakes show consistent trends, with a decline from April to June and a significant rise from June to September. Furthermore, discrepancies may occur between altimetry and in situ water levels, as the former represents instantaneous values, while the latter averages data from various stations and time periods.

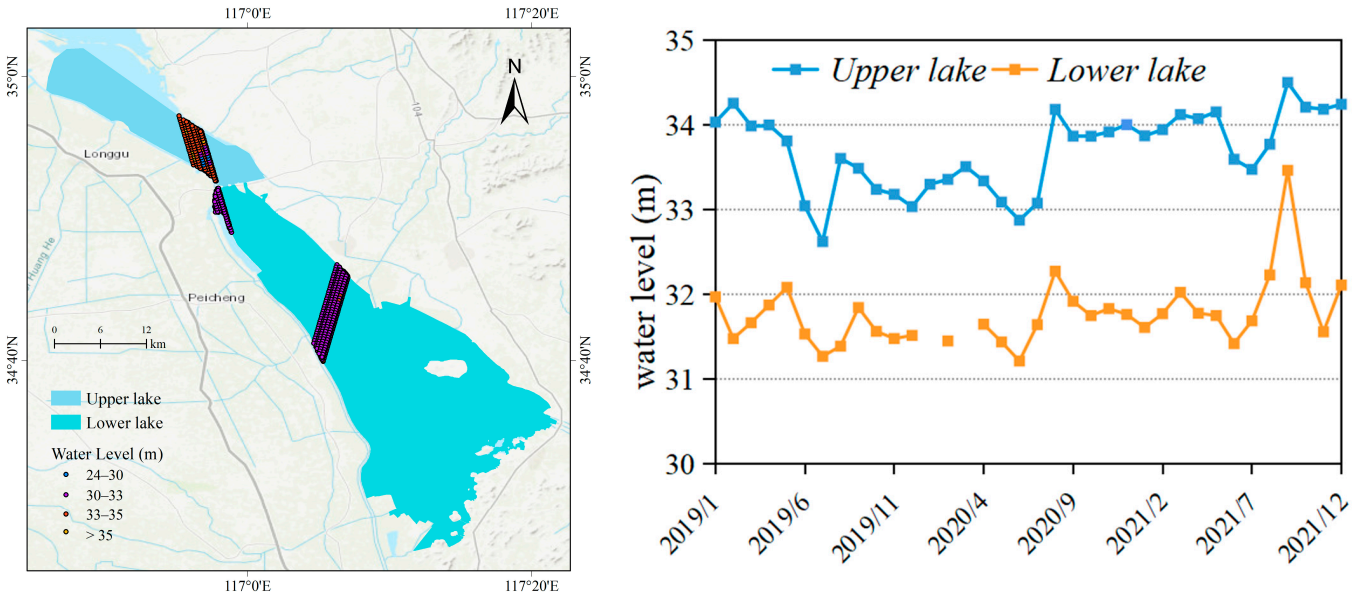
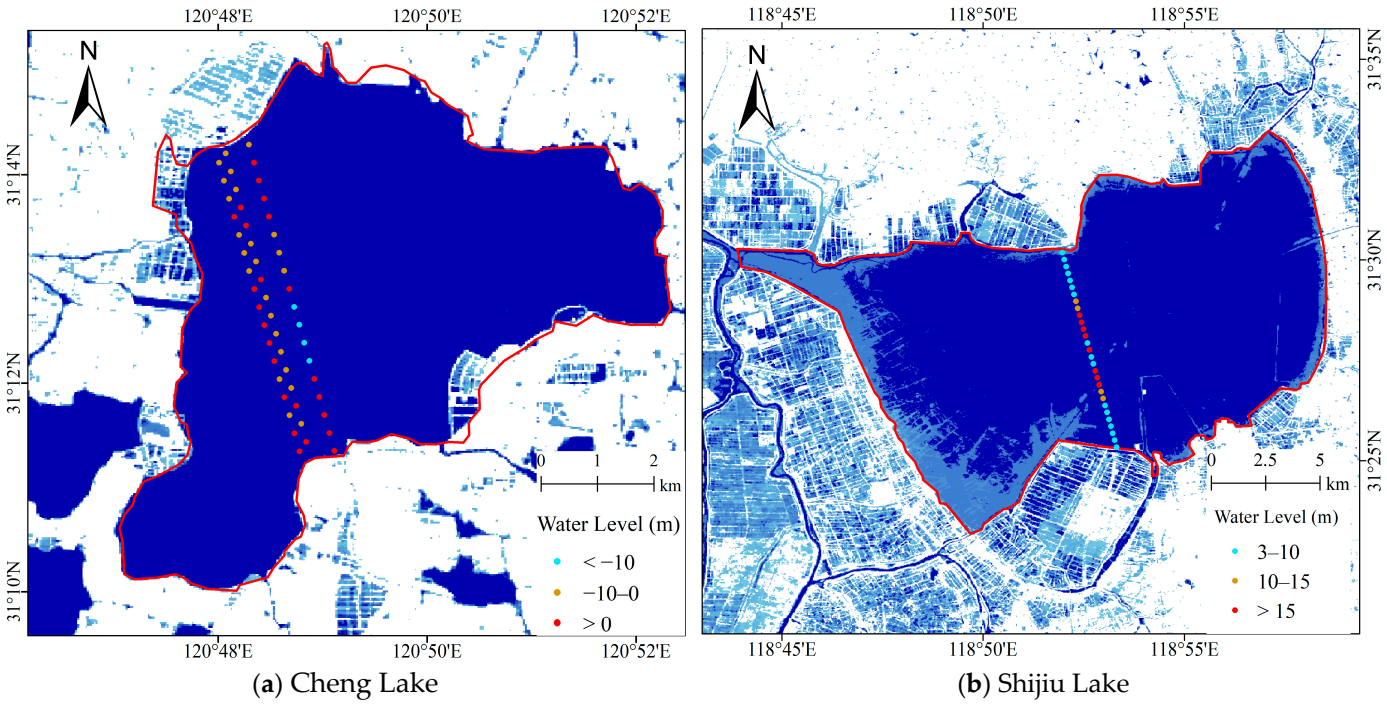


Figure 8. Water level difference between the upper and lower lakes of Weishan Lake.

The SAR altimeter has a big footprint, and its measurement accuracy is susceptible to topographic conditions. In regions near the shore or islands situated in the middle of lakes, radar signals are susceptible to contamination upon interaction with the land, which increases the likelihood of a significant number of outliers. In Jiangsu Province, the majority of lakes are characterized by shallow depths. Consequently, even a slight decrease in water levels leads to notable reduction in water area, revealing the underlying land. Figure 9, featuring Shijiu Lake, serves as an illustrative example of this phenomenon. The hydrological station Beixucun (II) of Shijiu Lake is frequently dry from October to February of the following year. There are a total of 52 dots in Figure 9a, of which 28 dots have water levels below 0 m and even four dots (blue dots) have water levels below −10 m. Figure 7 further accentuates this issue, displaying improbable negative readings for Cheng Lake: the water level was −1.15 m in February 2019, −0.50 m in November 2020, −20.33 m in April 2021, and −0.30 m in July 2021. In Figure 9b, there are 29 dots, 12 of which have water levels greater than 10 m. Shijiu Lake's water level in July 2019 and 2020 was 6.85 m and 6.94 m, respectively, while in July 2021, it reached 16.63 m, which was almost 10 m higher than the normal water level.

Another factor influencing altimetry accuracy is the shape and area of the lake. Baoying Lake, Gucheng Lake, and Ge Lake, which have smaller surface areas, exhibit lower accuracy compared to other lakes (Table 4). The shape also plays a significant role in influencing the trajectory of a satellite as it crosses the lake. As depicted in Figure 10, the lake's shape and the spatial distribution of tracks are illustrated. For Hung-tse Lake, where three orbital tracks intersect, the accuracy of water level derived from track B374, which passes through the lake's center, is superior to the other two tracks. Similarly, for Shijiu Lake, the water level accuracy derived from track B380 surpasses that of track B046. The number of altimetry points reflects the size and shape of the lake to some extent. As illustrated in Table 4 and Figure 11, a greater number of altimetry points correlate with an increased likelihood of achieving a larger R and a lower RMSE in the derived water level. This implies that augmenting the number of sampling points will bolster the reliability of altimetry water level measurements.



(**a**) Cheng Lake (**b**) Shijiu Lake

Figure 9. Outliers in Cheng Lake (**a**) and Shijiu Lake (**b**). The base map was the seasonality map of global surface water in 2021 (Source: EC JRC/Google). The permanent water is represented in dark blue, and areas of seasonal water are shown in lighter blue. The dots represent water levels obtained from altimeter. The acquisition dates for water levels of Cheng Lake from left to right are 26 February 2019, 25 November 2020, and 9 April 2021, and the date for Shijiu Lake is 18 July 2021.

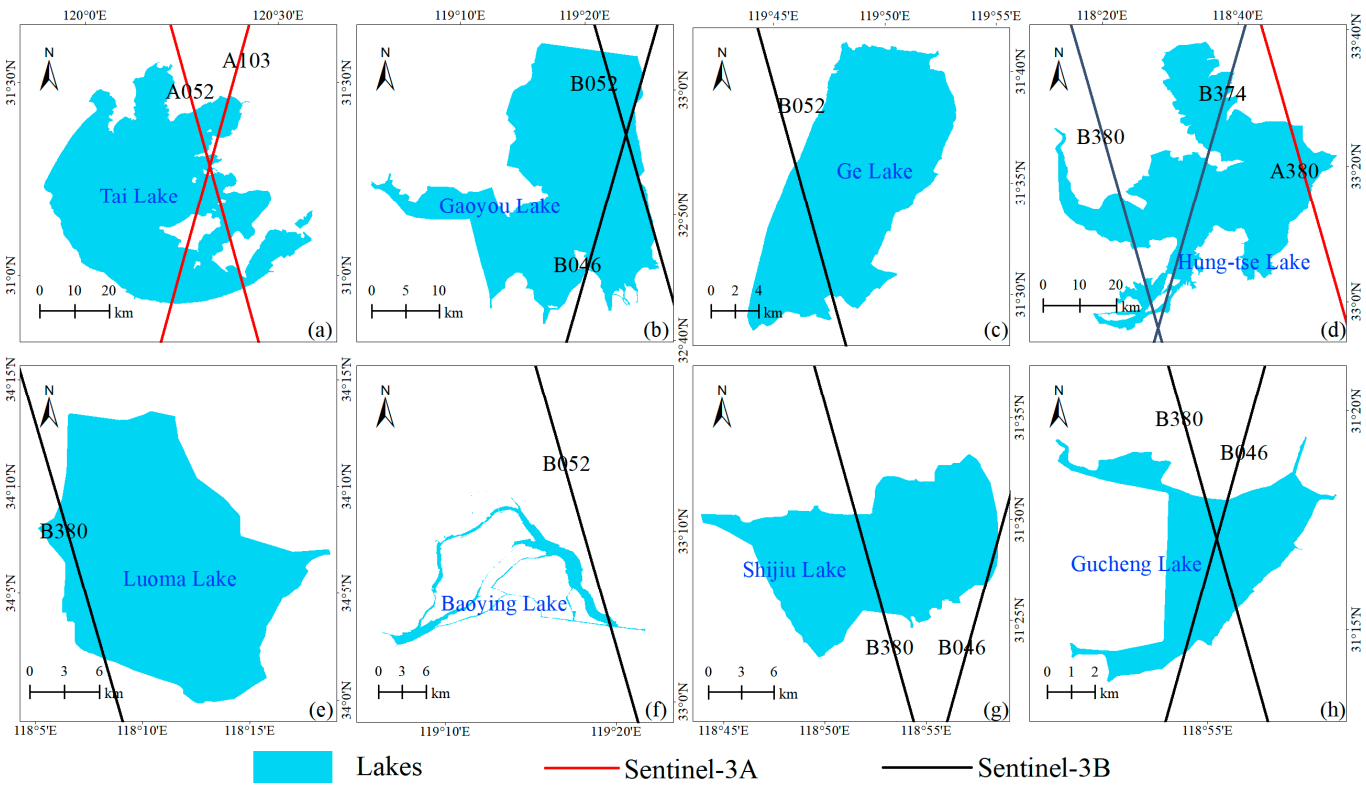


Figure 10. Sentinel-3A orbits and Sentinel-3B orbits crossing lakes. (**a**–**h**) illustrate the trajectories of Sentinel-3A/B over eight distinct lakes.

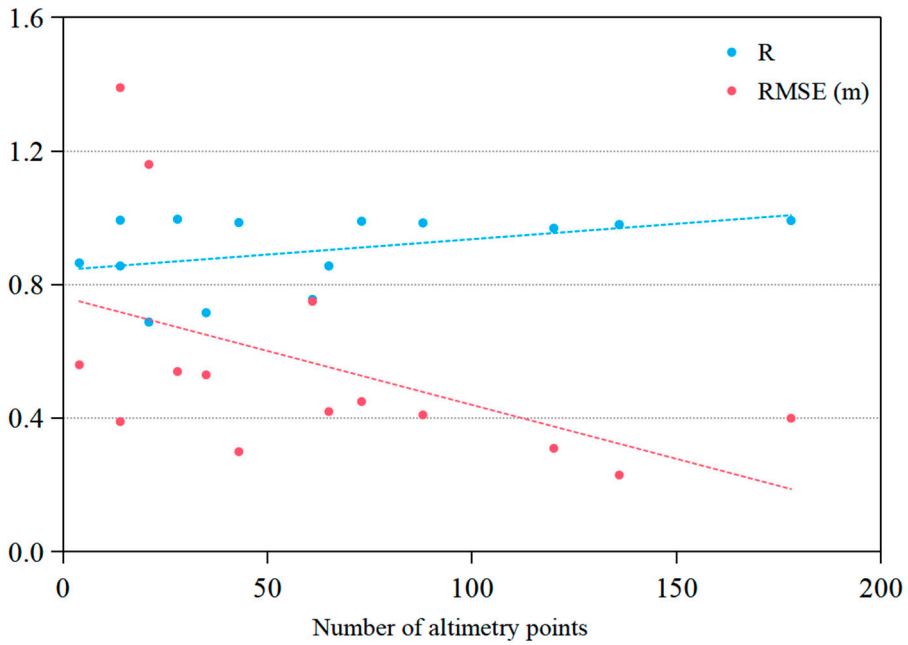


Figure 11. Scatter plot of R, RMSE, and the number of altimetry points. The line segments in the figure are fitted lines.

Table 4. The information and accuracy of the water levels in the lakes.

Names	Track	Number of Altimetry Points	R	RMSE (m)
Tai Lake	A052	120	0.969	0.31
	A103	136	0.980	0.23
Hung-tse Lake	A380	61	0.756	0.75
	B374	178	0.992	0.40
	B380	65	0.856	0.42
Gaoyou Lake	B046	88	0.985	0.41
	B052	73	0.990	0.45
Luoma Lake	B380	43	0.986	0.30
Shijiu Lake	B046	14	0.856	1.39
	B380	28	0.996	0.54
Baoying Lake	B052	4	0.865	0.56
Gucheng Lake	B046	21	0.688	1.16
	B380	14	0.993	0.39
Ge Lake	B052	35	0.716	0.53

5.2. Characteristics of Lakes/Reservoirs That Can Be Monitored by Sentinel-3

Whether the altimeter can track lakes depends on the geographical coverage and resolution of altimeter, as well as the area and distribution of the lakes. The HydroLAKES database contains 1,427,688 lakes larger than 0.1 km^2, and 125,032 of these can be covered by Sentinel-3 with a coverage rate of about 8.76%. We often require the elevation points on a single day to be larger than or equal to three in order to calculate the water level. As a result, it is preferable that the intercept of the lake under observation along the track direction (in the north-south direction) be greater than 1000 m. Additionally, Table 5 shows that a lake's probability of being covered by Sentinel-3 decreases as its size decreases. Even with orbital coverage, there is a good chance that the water level cannot be established or that the results are not accurate when the area of lake is too small. The likelihood of Sentinel-3 covering a lake increases with the size of the lake, resulting in a denser time series of water levels.

Table 5. The number of lakes/reservoirs covered by Sentinel-3.

Area Categories		>1000 km²	>100 km²	>10 km²	>1 km²	>0.1 km²
Number of Lakes in HydroLAKES	Global	178	1708	16,689	185,181	1,427,688
	Jiangsu	2	9	29	249	1190
Number of Lakes covered by Sentinel-3A	Global	173	1237	5879	23,348	64,686
	Jiangsu	2	3	6	15	25
Number of Lakes covered by Sentinel-3B	Global	171	1220	5766	23,102	64,644
	Jiangsu	1	6	12	32	52
Number of Lakes covered by Sentinel-3	Global	178	1549	9550	43,097	125,032
	Jiangsu	2	8	17	46	76
Coverage rate by Sentinel-3	Global	100%	90.69%	57.22%	23.27%	8.76%
	Jiangsu	100%	88.89%	58.62%	18.47%	6.39%

Jiangsu Province is traversed by 12 Sentinel-3A tracks and 12 Sentinel-3B tracks. Out of the 1190 water bodies in total, approximately 76 are covered by Sentinel-3, resulting in a coverage rate of roughly 6.39 percent. The majority of the lakes in Jiangsu Province, especially the tiny ones with an area from 0.1 to 10 km^2, may not be covered by Sentinel-3 products due to limitations imposed by the factors mentioned earlier. The only lake simultaneously covered by both Sentinel-3A and Sentinel-3B is Hung-tse Lake. Only 30 of the 1161 lakes and reservoirs under 1 km^2 are covered by Sentinel-3. Sentinel-3B has the capacity to monitor more lakes in Jiangsu Province than Sentinel-3A due to differences in their orbits and coverage patterns, which may result in better spatial coverage for certain lakes.

5.3. Uncertainties and Limitations of This Study

It is worth noting that, without deviation correction, the altimetry water levels obtained tended to be lower than the in situ water levels, as observed in both the analysis of four retracking algorithms. Furthermore, with typically only one or a limited set of monthly altimetry observations, computing a monthly average water level from these data incorporates additional uncertainty. When averaged, the temporally sparse altimetry measurements are likely to deviate to some extent from the ground truth monthly mean value derived from continuous monitoring.

6. Conclusions

In this study, taking 16 lakes and reservoirs in Jiangsu Province as the research objects, Sentinel-3 Level-2 land products were processed to derive monthly water levels from 2017 to 2021 using a data quality grading method. The following conclusions were drawn:

(1) Taking the track A103 of Tai Lake as an example, it showed that the OCOG algorithm is more suitable than the other three algorithms (i.e., Ocean, Ice sheet, and Sea ice), for extracting the water level of inland water bodies. By comparing the altimetry-derived water levels with in situ data, it was found that Sentinel-3 has good performance in water level monitoring. The R of all lakes was greater than 0.5, and the RMSE was less than 1 m. Among the eight lakes with in situ data, Tai Lake, Gaoyou Lake, and Luoma Lake had better measurement accuracy, with R > 0.9 and RMSE < 0.1 m.

(2) The variation of monthly water level in the 15 lakes mostly has a certain regularity. The water level may rise slightly several times throughout the year, and the highest water level of the lake mainly occurs during the flood season. The monthly variation in water level at Shijiu Lake is the most pronounced. In 2020, frequent rainfall in the Tai Lake basin led to significant regional floods, causing a rapid rise in water levels across many lakes in July 2020.

(3) Internal water level differences, terrain features, and the area and shape of the lake may influence the accuracy of altimetry water levels. The geographical location and distribution of lakes determine whether altimeter products can cover them. Specifically, the larger the lake area is, the greater the number of altimetry points

within the water surface is, resulting in higher values of R and smaller values of RMSE for the altimeter water level.

Altimetry products are of tremendous value for calculating lake water levels in places without in situ data since they can provide accurate water level information. The storage capacity of lakes and reservoirs can be calculated using the appropriate models by measuring the area of lakes using remote sensing images and collecting water levels from altimetry data. Sentinel-3 has immense potential to support improved water security in data-scarce regions. And the long-term water levels of water bodies of various sizes can be derived by combining the various satellite products from the ICESat-2, T/P, Jason series, and Sentinel-3. It can provide scientific insights for realizing water resource distribution and spatiotemporal variation.

Author Contributions: Methodology, J.X.; software, M.X. and V.G.F.; validation, M.X. and C.L.; writing—original draft preparation, J.X., M.X. and V.G.F.; writing—review and editing, V.G.F.; supervision, C.L.; project administration, J.X. and D.W.; funding acquisition, J.X. and D.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Key Laboratory of Land Satellite Remote Sensing Application, Ministry of Natural Resources of the People's Republic of China (Grant No. KLSMNR-K202209), Joint Research, Development and Application Demonstration of Remote Sensing Monitoring Technology for Typical Natural Resources Features (Grant No. 2023YFE0207900), the Fundamental Research Funds for the Central Universities (Grant No. B220202052), and the Research Funds of Jiangsu Hydraulic Research Institute (Grant No. 2020z025).

Data Availability Statement: Publicly available datasets were analyzed in this study. Sentinel-3 data can be freely downloaded from European Space Agency (ESA) (https://scihub.copernicus.eu/dhus/, accessed on 20 June 2023). HydroLAKES water mask are available from the website https://www.hydrosheds.org/products/hydrolakes (accessed on 20 June 2023).

Acknowledgments: We thank European Space Agency for distributing the Sentinel-3 data and thank the World Wildlife Fund US for providing the HydroLAKES database.

Conflicts of Interest: The authors declare no conflicts of interest.

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