

Dynamic Monitoring of Lake Balkhash (1970-2020) Using Multi-Source Remote Sensing Data: Postprint

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Abstract

Using ICESat-1 and CryoSat-2 altimetry data along with in-situ hydrological station measurements, this study analyzed the water level variation characteristics of Lake Balkhash from 1970 to 2020. Combined with MOD09A1 data and related materials, the long-term time series changes in lake area and water volume were examined, and irrigation data from the Lake Balkhash basin together with meteorological data from the Climatic Research Unit (CRU) were utilized to briefly investigate the impacts of climate change and human activities on the long-term lake dynamics. The results indicate that the water level of Lake Balkhash exhibited an overall trend of first decreasing then rising with fluctuations during the study period, reaching its lowest value in 1987 (340.64 m). Intra-annual water level increases primarily occurred from late February to early June, and water level fluctuations were more pronounced during the warm season (April-October) than during the cold season (November-March). From 1970 to 2020, the area of Lake Balkhash decreased from 19996 km² to 16641.93 km², representing a reduction of approximately 16.77% in lake surface area; during this period, the water volume loss of Lake Balkhash was approximately 12.33 km³. The dynamic changes of the lake resulted from the combined effects of multiple factors; the lake dynamics from 1970 to 1987 were primarily caused by human activities such as water impoundment in the Kapchagay Reservoir and expansion of irrigated cropland within Kazakhstan. Temperature and precipitation showed no significant correlation with the lake's dynamic changes in terms of overall trends, and quantitative discussion of the impacts of various factors on lake dynamics requires further research.

Full Text

Introduction

Lakes are extremely sensitive to climate and environmental changes [?, ?] and play a crucial role in maintaining regional ecological balance [?]. Variations in lake water level, area, and volume are closely related to regional temperature, precipitation, evaporation, and human activities [?, ?]; thus, their dynamic changes can indirectly reflect regional climate change and the impact of human activities on lake ecological environments [?]. Balkhash Lake, the third largest water body in the arid region of Central Asia, has experienced severe ecological damage since the 1960s due to unreasonable human activities in its basin, leading to significant declines in water level, lake area shrinkage, and reduced land productivity [?]. In 2004/5, the UNEP GEO Yearbook reported that Balkhash Lake faced the possibility of completely drying up [?], and its ecosystem has continued to attract public attention, making long-term monitoring of the lake and its environment essential.

Traditional lake water level monitoring relies on measurements from hydrological stations. While this method offers high accuracy, it consumes substantial manpower and material resources [?] and is limited by natural conditions and spatial distribution factors, making it difficult to obtain long-term continuous observation data for remote inland lakes. Additionally, traditional water level monitoring suffers from low data sharing, which increases the difficulty of data acquisition [?]. Satellite altimetry, as a space geodetic technique, is now widely used for water level monitoring of inland lakes and analyzing their environmental responses [?, ?]. Compared with conventional water level monitoring methods, satellite altimetry enables large-scale, periodic monitoring of various dynamic changes in terrestrial water bodies [?, ?], and numerous studies have demonstrated its effectiveness in monitoring lake water level dynamics [?, ?].

Satellite altimetry data are primarily derived from two types of altimeters: laser and radar. ICESat-1, the world's first spaceborne laser altimetry satellite, utilizes the Geoscience Laser Altimeter System (GLAS) to measure global surface elevations [?]. Its ground footprint diameter is approximately 70 m, with adjacent footprint spacing of about 172 m along the track, enabling high-precision lake water level measurements. CryoSat-2, launched by the European Space Agency in 2010, carries the Synthetic Aperture Interferometric Radar Altimeter (SIRAL) [?]. The along-track adjacent footprint spacing is approximately 0.369 km, and compared with traditional radar altimeters such as ERS-1/2, Envisat, and Jason-1/2, CryoSat-2 has denser orbital coverage and smaller footprint spacing, allowing it to monitor more small inland lakes [?]. The operational period of ICESat-1 was 2003–2009, while CryoSat-2 continues to operate to the present, enabling several studies to combine data from both satellites to construct long-term time series. For example, Song et al. [?] combined ICESat-1 and CryoSat-2 data to construct a long-term water level sequence for Qinghai Lake from 2003–2014, analyzing both long-term and seasonal water level varia-

tions. Li et al. [?] used the same combination to monitor water level trends in Namco Lake on the Tibetan Plateau.

Previous studies on Balkhash Lake have primarily focused on recent hydrological changes using single remote sensing data sources combined with meteorological data [?, ?, ?, ?, ?, ?, ?, ?]. However, comprehensive and systematic analysis of long-term continuous changes in lake area, water level, and volume is lacking. Most water level studies have relied on measured data from hydrological stations or Jason-1 altimetry data, which are insufficient in terms of data precision and temporal scale [?, ?]. Data sources have been relatively single, without integrating traditional data, laser, and radar altimetry data to obtain more continuous and complete long-term observations. Therefore, this study utilizes ICESat-1 and CryoSat-2 altimetry data and hydrological station measurements to construct a water level sequence for Balkhash Lake, analyzing its long-term and seasonal variation characteristics. Combined with MOD09A1 data and related materials, we analyze the long-term area and water volume changes of Balkhash Lake and briefly explore the impacts of climate change and human activities on the lake's dynamics, providing a scientific basis for long-term monitoring, rational water resource utilization, and ecosystem protection of Balkhash Lake.

1 Study Area

Balkhash Lake (45°21'–46°30' N, 73°45'–79°30' E) is located in southeastern Kazakhstan [?] and is a typical terminal lake on a plain. The lake has a vast area of approximately 1.83×10^4 km², with a maximum width of about 71 km and a length of about 600 km [?]. The Ili River, as the main water artery, flows into the western part of the lake through the Ili River delta, contributing approximately 80% of the inflow [?]. The eastern part of the lake has minimal inflow, high evaporation rates, and consequently significantly higher mineralization than the western part [?]. The northern shore has few water bodies, higher terrain, and is mostly rock-covered, while the southern shore has numerous small lakes and marshes, lower terrain, and is mostly sandy [?]. The Ili-Balkhash Lake Basin is one of the world's largest lake ecosystems [?], with main tributaries including the Ili River, Karatal River, Lepsy River, and Ayağoz River. Due to warm and moist airflows from the Indian and Pacific Oceans being unable to penetrate deep into the Eurasian continent where the basin is located, the Balkhash Lake basin exhibits a temperate continental climate with dryness and low precipitation.

2 Data and Methods

2.1 Data Sources

2.1.1 ICESat-1 Altimetry Data The ICESat-1/GLAS (Geoscience Laser Altimeter System) emits laser signals to the nadir point and calculates the distance between the satellite and nadir point based on the round-trip time of the laser signal, thereby obtaining the elevation of the nadir point [?]. The data

acquisition period for this satellite was 2003–2009, with observation cycles of approximately 91 days [?]. The GLAS data products include 15 types; this study uses the GLA14 global altimetry data product, which contains laser footprint geolocation, elevation, and various correction parameters.

Data preprocessing for ICESat-1 altimetry includes ellipsoid conversion and saturation correction. Since ICESat-1 and CryoSat-2 data are based on different reference ellipsoids, the ICESat-1 data reference ellipsoid (TOPEX/Poseidon ellipsoid) must be converted to the WGS84 ellipsoid to eliminate ellipsoid differences [?]. Additionally, ICESat-1 may experience waveform saturation during elevation measurements, causing measured footprint elevations to be lower than actual values, thus requiring saturation correction. The footprint elevation calculation principle is shown in Equation (1):

$$H = h_{\text{sat}} - d_{\text{deltaEllip}} + d_{\text{satElevCorr}} - N \quad (1)$$

where H is the orthometric height based on the EGM96 geoid; h_{sat} is the elevation based on the WGS84 ellipsoid; $d_{\text{deltaEllip}}$ is the difference between the TOPEX/Poseidon and WGS84 ellipsoids; $d_{\text{satElevCorr}}$ is the saturation correction parameter obtainable from the dataset; and N is the local geoid undulation, which can be calculated using the MATLAB geoidheight function.

2.1.2 CryoSat-2 Altimetry Data CryoSat-2 was launched on April 8, 2010, with measurement modes including Low Resolution Mode (LRM), Synthetic Aperture Radar mode (SAR), and Synthetic Aperture Radar Interferometric mode (SARIn) [?]. The study uses Level-2 GDR data products, which include measurement time, geographic location, and height information after instrument correction, transmission delay correction, geometric correction, and geophysical correction. These are standalone global full-orbit data that integrate measurement results from all three modes through different processing procedures in chronological order to produce uniformly formatted data records.

The three modes employ different waveform retracking algorithms to obtain height values: Refined OCOG and Refined CFI [?]. By comparing the number of height anomaly values obtained within the Balkhash Lake area using both algorithms, this study selects the Refined OCOG retracking algorithm to extract Balkhash Lake water levels from 2011 to 2020.

CryoSat-2 altimetry data preprocessing includes various bias corrections. During propagation, satellite radar pulses may experience scattering or refraction that affects propagation speed, causing delays in observed signal round-trip times. Additionally, various natural factors can introduce biases in distance estimates, requiring corrections [?]. The lake water level calculation formula is as follows:

$$H = H_{\text{alt}} - R_{\text{range}} - \Delta R \quad (2)$$

where H is the orthometric height based on the EGM96 geoid; H_{alt} is the satellite altitude from the satellite center of mass to the reference ellipsoid; R_{range} is the distance from satellite to lake surface; ΔR is the sum of various error corrections ($\Delta R = R_{\text{Dry}} + R_{\text{Wet}} + R_{\text{Ion}} + R_{\text{Sol}} + R_{\text{Pol}}$), where R_{Dry} is dry troposphere correction, R_{Wet} is wet troposphere correction, R_{Ion} is ionosphere correction, R_{Sol} is solid tide correction, and R_{Pol} is pole tide correction.

2.1.3 Lake Area Data The Moderate Resolution Imaging Spectroradiometer (MODIS) is an important sensor aboard the TERRA satellite for global dynamic measurements, providing multiple detection bands with relatively high resolution. It is widely used for water body feature extraction, with numerous studies demonstrating its high precision for lake area monitoring [?]. MODIS data products are extensive, with MOD09A1 being an 8-day composite Level-2 surface reflectance product at 500 m spatial resolution. This study uses MOD09A1 data to extract lake boundaries and calculate area. For 1975–2000, lake area data are derived from relevant literature [?, ?, ?, ?, ?, ?, ?, ?], while annual remote sensing image areas from 2001–2020 are calculated based on MOD09A1 data.

The Normalized Difference Water Index (NDWI) proposed by Mcfeeters [?] is used to extract water body information, reducing interference from surface soil and vegetation for effective threshold segmentation [?]:

$$\text{NDWI} = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}} \quad (3)$$

where Green is the green band (MOD09A1 Band 4) and NIR is the near-infrared band (MOD09A1 Band 2).

2.1.4 Meteorological Data Meteorological data are selected from the Climatic Research Unit (CRU) Time Series version 4.05 (CRUTS v4.05) dataset, available at https://crudata.uea.ac.uk/cru/data/hrg/cru_{ts}4.05/. This dataset integrates materials from multiple databases to reconstruct a high-resolution, continuous surface climate 要素 dataset covering the global range [?]. With a spatial resolution of 0.5°, studies have shown this data can be used to discuss climate change in Central Asia [?]. Since meteorological data from stations near Balkhash Lake are incomplete, this dataset is used as the primary meteorological factor to analyze the lake's water level response to climate change, including temperature and precipitation data. Additionally, some station data are selected from the Global Weather Station Data website (<https://www.climate.gov/maps>).

2.1.5 Other Data Balkhash Lake vector boundary data are derived from the Global Lakes and Wetlands Database (GLWD) [?]. Measured water level data from 1970 onward are obtained from the HYDROLARE website (<http://hydrolare.net/>), though some monthly data are missing for certain years. Irrigation area data for the Balkhash Lake basin are sourced from the Food and

Agriculture Organization of the United Nations (FAO) AQUASTAT database (<http://www.fao.org/aquastat/zh/countries/basins/regional/overviews/central-asia/>), with data available through 2006 (2017 data not yet released). Glacier data are from China's Second Glacier Inventory.

2.2 Research Methods

The technical workflow is shown in Figure 2. First, ICESat-1 GLA14 altimetry data are preprocessed to extract satellite footprint elevations, screening those within the Balkhash Lake boundary range. CryoSat-2 GDR data are similarly preprocessed to extract lake area footprints, eliminating anomalous elevation points to calculate satellite-derived water levels for 2010–2020. These are validated against measured water level data. Combined with MOD09A1-derived lake area data and literature data, long-term time series of lake area are obtained. Finally, water volume changes are estimated using the appropriate equations.

2.2.1 Water Level Data Extraction (1) Satellite altimetry data preprocessing. ICESat-1 altimetry data preprocessing primarily includes ellipsoid conversion and saturation correction. Since ICESat-1 and CryoSat-2 data are based on different reference ellipsoids, ICESat-1 data must be converted from its reference ellipsoid (TOPEX/Poseidon ellipsoid) to the WGS84 ellipsoid to eliminate ellipsoid differences [?]. Additionally, ICESat-1 may experience waveform saturation during elevation measurements, causing measured footprint elevations to be lower than actual values, requiring saturation correction.

After data preprocessing, all water level values are processed to extract the lake water level sequence through the following outlier removal steps [?, ?, ?]:

Step 1: Create a 200 m buffer zone from the lake boundary toward the lake center. Screen satellite footprint points using this buffer to ensure data points fall completely within the lake, reducing interference from elevation points potentially contacting the shoreline on single-day water level data.

Step 2: Conduct visual interpretation of the obtained water level data points, eliminating extreme outliers that deviate by tens or even hundreds of meters from most water level values.

Step 3: Apply the 3σ criterion to remove anomalies from single-day water level data, then average the remaining valid water level values as the daily mean water level. The specific discrimination method for the 3σ criterion is shown in Equation (4): For collected data samples $(x_1, x_2, \dots, x_n)$, calculate the arithmetic mean $\bar{x}$ and residual error v_i , then compute the root-mean-square deviation σ :

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i, \quad v_i = x_i - \bar{x}, \quad \sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n v_i^2} \quad (4)$$

If $|x_i - \bar{x}| > 3\sigma$, the error is relatively large and x_i should be discarded. The probability of observation data exceeding 3σ is only 0.27%.

Step 4: For all daily mean water levels, first visually interpret and eliminate obvious outliers, then apply the 3σ criterion to further remove anomalies, and finally calculate monthly and annual mean water levels.

(2) Data conversion. As shown in the technical workflow (Figure 2), ICESat-1 data use the EGM2008 reference system, CryoSat-2 data use the WGS84 reference system, while hydrological station measured data use the Baltic (EGM96) height system. Since these three datasets employ different vertical datums, they must be unified before constructing the water level sequence. In this study, ICESat-1 and CryoSat-2 data are first converted to the same reference system. After outlier removal, the annual mean water level sequence for Balkhash Lake from 2003–2020 is obtained. Based on the mean difference between this altimetry-derived sequence and corresponding years of measured water levels, the altimetry water levels are adjusted by subtracting the mean difference to convert them to the same datum as the measured water levels [?, ?], yielding the final Balkhash Lake water level sequence.

(3) Accuracy validation. Following previous methods [?, ?], correlation coefficient (r), significance value (P), mean absolute error (MAE), and root mean square error (RMSE) are calculated to evaluate the agreement between radar altimeter-derived lake water levels and corresponding measured water levels. The correlation coefficient (r) reflects the degree of correlation between variables:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (5)$$

where r is the correlation coefficient; x_i is the altimeter-derived water level value; $\bar{x}$ is the mean of altimeter-derived values; y_i is the measured water level value; $\bar{y}$ is the mean of measured values; and n is the sample size. When $r > 0$, variables are positively correlated; otherwise negatively correlated. The absolute value of r approaching 1 indicates stronger correlation. The significance value (P) reflects the probability of an event occurring. $P < 0.05$ indicates significance, while $P < 0.01$ indicates high significance, showing that differences between samples are unlikely due to sampling error. Mean absolute error (MAE) represents the average of absolute differences between extracted and measured values, while root mean square error (RMSE) represents the square root of the average squared deviations. Both metrics effectively reflect differences between extracted and measured values [?, ?].

2.2.2 Lake Area Extraction Annual area data for 1975–2000 are derived from relevant literature [?, ?, ?, ?, ?, ?, ?, ?]. Annual remote sensing image areas from 2001–2020 are calculated based on MOD09A1 data. The Normalized

Difference Water Index (NDWI) proposed by Mcfeeters [?] is used to extract lake boundaries:

$$\text{NDWI} = \frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}} \quad (6)$$

where Green is the green band (MOD09A1 Band 4) and NIR is the near-infrared band (MOD09A1 Band 2). MOD09A1 can extract water body information, reducing interference from surface soil and vegetation, enabling effective threshold segmentation [?] to clearly distinguish water from vegetation and soil.

2.2.3 Water Volume Change Estimation Based on the water balance of inland lakes, water volume change is determined by both lake area and water level. The following equation is used to estimate water volume change [?]:

$$\Delta V = \Delta H \times S \quad (7)$$

where ΔV is water storage change between two periods; ΔH is water level change between two periods; and S is the lake area during the period.

3 Results

3.1 Water Level Variation Characteristics of Balkhash Lake

Using ICESat-1 and CryoSat-2 altimetry data and hydrological station measurements, the water level changes of Balkhash Lake from 1970-2020 were obtained (Figure 5). During the study period, lake water level showed an initial decline followed by a fluctuating upward trend. From 1970-1987, lake water level decreased significantly ($P < 0.01$) at a rate of approximately $-0.021 \text{ m} \cdot \text{a}^{-1}$, with a total decline of about 2.21 m, reaching its lowest value (340.64 m) in 1987. From 1987-2020, lake water level showed an overall upward trend ($P < 0.01$) at a rate of approximately $0.039 \text{ m} \cdot \text{a}^{-1}$. During this period, several short-term oscillations were observed, with increasing intervals from 1987-1995, 1998-2005, and 2010-2020. In other periods, Balkhash Lake water level showed a slight decreasing trend. Notably, the upward trend after the 1990s represents the most significant rising period, with the longest duration of continuous increase. The highest rising rate occurred during 2010-2020 at $0.166 \text{ m} \cdot \text{a}^{-1}$, with a local peak reaching 342.66 m.

To further monitor intra-annual dynamic changes, monthly water levels were analyzed (Figure 6). Results show that Balkhash Lake water level changes have distinct seasonal characteristics. Multi-year mean monthly water levels from April to October show an upward trend ($P < 0.01$), peaking in June at approximately 341.99 m, after which water levels decline ($P < 0.01$). After July, the fluctuation amplitude of monthly mean water levels gradually decreases and stabilizes, with mean water levels ranging between 341.65-341.70 m. This

indicates that annual water level growth mainly occurs from late February to early June, with more dramatic fluctuations in the warm season (April–October) than in the cold season (November–March). Multi-year average water levels are highest in spring and lowest in autumn.

3.2 Area Variation Characteristics of Balkhash Lake

Long-term area changes of Balkhash Lake are shown in Figure 7. From 1970–2020, Balkhash Lake area decreased from 19,996 km² to 16,641.93 km², a reduction of approximately 16.77%. The maximum area (19,996 km²) occurred in 1970, while the minimum (16,638.87 km²) occurred in 1987, with a mean change rate of $-65.77 \text{ km}^2 \cdot \text{a}^{-1}$. From 1970–1987, lake area decreased dramatically at a rate of $-159.86 \text{ km}^2 \cdot \text{a}^{-1}$. From 1987–1995, area recovered slightly, increasing from 16,638.87 km² to 16,896.44 km² at a rate of $32.19 \text{ km}^2 \cdot \text{a}^{-1}$. After 1995, lake area showed a fluctuating decreasing trend with a shrinkage rate of $-21.31 \text{ km}^2 \cdot \text{a}^{-1}$.

3.3 Water Volume Variation Characteristics of Balkhash Lake

Based on Balkhash Lake area and water level data, multi-year water volume changes were calculated (Figure 8). From 1970–2020, Balkhash Lake lost approximately 12.33 km³ of water. From 1970–1987, lake water storage decreased continuously at a rate of $-0.725 \text{ km}^3 \cdot \text{a}^{-1}$, with a cumulative change of -12.33 km^3 . From 1987–1995, water volume increased substantially by 1.84 km³ at a rate of $0.23 \text{ km}^3 \cdot \text{a}^{-1}$. Subsequently, water volume showed fluctuating decreases, with the fastest reduction rate of $-0.265 \text{ km}^3 \cdot \text{a}^{-1}$ during 1995–2005, cumulatively decreasing by 2.65 km³. After 2005, water volume continued to decline at a rate of $-0.059 \text{ km}^3 \cdot \text{a}^{-1}$, with a cumulative reduction of 0.59 km³.

3.4 Water Level Data Accuracy Validation

Satellite observation data and measured water level data overlap partially during 2003–2009 for ICESat-1 and 2011–2020 for CryoSat-2. Specifically, ICESat-1 has 23 coincident values with measured data, while CryoSat-2 has 60 coincident values starting from April 2011. To verify the accuracy and reliability of satellite altimetry data, correlation analysis was performed between satellite observations and measured water level data. Results show (Figure 9) that ICESat-1-derived water levels correlate significantly with hydrological station measurements ($r = 0.92$, $P < 0.01$), with MAE = 0.07 m and RMSE = 0.08 m. CryoSat-2-derived water levels also show significant correlation ($r = 0.89$, $P < 0.01$), with MAE = 0.11 m and RMSE = 0.13 m. These results demonstrate the feasibility of using both satellite altimetry datasets for long-term water level change monitoring of Balkhash Lake.

3.5 Discussion

3.5.1 Climate Change Meteorological data published by hydrological stations within the Balkhash Lake basin are incomplete, with only annual temperature and precipitation data for 1936–2005. To verify the applicability of the CRUTS v4.05 dataset in the Balkhash Lake basin, correlation analysis was performed between station data and CRUTS v4.05 data. Results show (Figure 10) that temperature and precipitation data from meteorological stations correlate significantly with the CRUTS v4.05 dataset ($r = 0.91$ and 0.85 respectively, both $P < 0.01$), indicating that the CRUTS v4.05 dataset can be used to discuss climate change conditions in the Balkhash Lake basin.

Analysis of temperature and precipitation changes in the Balkhash Lake basin and their correlation with lake water level, area, and volume shows no significant correlation in long-term trends. From 1970–2020, the multi-year average temperature in the basin was 6.02°C , with an overall significant warming trend at a rate of $0.39^{\circ}\text{C} \cdot (10\text{a})^{-1}$ (Figure 11a). The Mann-Kendall test indicates a temperature mutation in 1979, after which warming became significant. Multi-year average precipitation was 280.584 mm , with a change rate of $0.06\text{ mm} \cdot (10\text{a})^{-1}$ (Figure 11b). The Mann-Kendall test shows multiple precipitation mutation points, with large fluctuations before 1990, increases after 1990, and significant increases after 2000.

Segmented correlation analysis between lake dynamics and climate factors shows no correlation between water level, area, and volume changes with temperature and precipitation from 1970–1987. From 1987–1995, only water level correlates positively with temperature ($r = 0.72$, $P < 0.01$). Thus, the overall trend of Balkhash Lake dynamics shows no obvious correlation with climate change during the study period, and quantitative discussion of their relationship requires further research.

3.5.2 Human Activities The dynamic changes of Balkhash Lake from 1970–1987 were mainly caused by intense human activities, including impoundment of the Kapchagay Reservoir and expansion of irrigated farmland in Kazakhstan. After the Kapchagay Reservoir's completion in 1970, Ili River inflow decreased from $14.82 \times 10^9\text{ m}^3$ to $6.02 \times 10^9\text{ m}^3$ [?]. Simultaneously, with the development of irrigated agriculture in the basin, agricultural water consumption increased dramatically from $116.1 \times 10^9\text{ m}^3$ to $148.2 \times 10^9\text{ m}^3$ [?], causing continuous declines in Balkhash Lake's water level, area, and volume.

From 1987–1995, Kazakhstan terminated reservoir impoundment plans, regulated reservoir discharge, and improved channel sedimentation conditions, leading to ecological improvement [?]. After the Soviet Union's dissolution in 1991, Kazakhstan's economy suffered, state support for farms ended, land privatization was implemented, and water fees were introduced, causing irrigated area in the Balkhash Lake basin to decline sharply [?, ?]. Many irrigation districts relying on electric pumps were abandoned, and reduced agricultural water

use further contributed to slow water level recovery [?], with area and volume showing corresponding increases. From 1987–2006, basin irrigated area ranged between 2,000–3,000 km², substantially reduced compared to the 1970s (Figure 12). During this period, Balkhash Lake water level showed clear recovery trends. Therefore, intense human activities (including Kapchagay Reservoir impoundment and irrigated farmland expansion in Kazakhstan) were the main drivers of lake dynamics from 1970–1987, while human activities also played important roles in long-term trends.

Previous studies indicate [?, ?, ?, ?, ?] that Balkhash Lake dynamics are influenced by multiple factors including temperature, precipitation, evaporation, glacier meltwater, and human activities. Quantitative assessment of each factor's driving role during different periods and systematic understanding of the processes and causes of lake dynamics require further research. Multi-mission altimetry satellites provide effective technical means for lake water level monitoring. Compared with conventional methods, altimetry satellites are not limited by natural environments or manpower, can cover more lakes, and integration of different satellite altimetry data can yield long time series of lake level information, which is significant for studying lake dynamics and their driving factors.

4 Conclusion

Based on ICESat-1 and CryoSat-2 altimetry monitoring results, Balkhash Lake water level decreased rapidly from 1970–1987 at an average rate of $-0.13 \text{ m} \cdot \text{a}^{-1}$, reaching its lowest value (340.64 m) in 1987. From 1987 to present, water level has shown an overall upward trend with periodic fluctuations. Water level exhibits regular seasonal variations, with the highest multi-year average in spring and lowest in autumn. Annual water level growth mainly occurs during the lake freezing period (late February to early June), with more dramatic fluctuations in the warm season (April–October) than in the cold season (November–March). During the study period, Balkhash Lake area showed initial significant shrinkage followed by slight recovery, decreasing from 19,996 km² to 16,641.93 km² (a 16.77% reduction). Water volume loss totaled approximately 12.33 km³. The lake's dynamic changes from 1970–1987 were mainly caused by human activities such as Kapchagay Reservoir impoundment and irrigated farmland expansion in Kazakhstan. However, the overall trends of temperature and precipitation show no obvious correlation with lake dynamics. Due to environmental complexity and uncertainty, quantitative discussion of various factors' impacts requires further research. Multi-mission altimetry satellites provide powerful tools for long-term, large-scale lake level monitoring, which is of great significance for studying lake level changes and their responses to climate and environment.

References

- [1] Shi Yafeng. Glacier recession and lake shrinking indicating the climatic warming and drying trend in Central Asia[J]. Acta Geographica Sinica, 1990,

45(1): 1-13.

[2] Liu J, Wang S, Yu S, et al. Climate warming and growth of high elevation inland lakes on the Tibetan Plateau[J]. *Global and Planetary Change*, 2009, 67(3): 209-217.

[3] Zhang Xin, Wu Yanhong. Zhari namco water level change detection using multi satellite altimetric data during 1992–2012[J]. *Journal of Natural Resources*, 2015, 30(7): 1153-1162.

[4] Yu Ge. Study on lacustrine evolution and paleoclimate dynamics in China[M]. Beijing: China Meteorological Press, 2001: 17-19.

[5] Creiaux J F, Birkett C. Lake studies from satellite radar altimetry[J]. *Comptes Rendus Geoscience*, 2006, 338(14-15): 1098-1112.

[6] Song C Q, Huang B, Richards K, et al. Accelerated lake expansion on the Tibetan Plateau in the 2000s: Induced by glacial melting or other processes?[J]. *Water Resources Research*, 2014, 50(4): 3170-3186.

[7] Zhang G Q, Xie H J, Kang S H, et al. Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003–2009)[J]. *Remote Sensing of Environment*, 2011, 115(7): 1733-1742.

[8] UNEP. GEO Year Book 2004/5[DB/OL]. [2008-12-01]. <http://www.unep.org/geo/yearbook/yb2004/033.htm>

[9] Wang X W, Gong P, Zhao Y Y, et al. Water level changes in China's large lakes determined from ICESat/GLAS data[J]. *Remote Sensing of Environment*, 2013, 132: 131-144.

[10] Zhao Yun, Liao Jingjuan, Shen Guozhuang, et al. Monitoring the water level changes in Qinghai Lake with satellite altimetry data[J]. *Journal of Remote Sensing*, 2017, 21(4): 633-644.

[11] Song C Q, Ye Q H, Sheng Y W, et al. Combined ICESat and CryoSat-2 altimetry for accessing water level dynamics of Tibetan lakes over 2003–2014[J]. *Water*, 2015, 7(9): 4685-4700.

[12] Song Chunqiao, Ye Qinghua, Cheng Xiao. Shifts in waterlevel variation of Namco in the central Tibetan Plateau from ICESat and CryoSat-2 altimetry and station observations[J]. *Science Bulletin*, 2015, 60(21): 2048.

[13] Li Peng, Li Hui. Monitoring the lakes level variation in the Dongting Lake Basin over 2003–2017 using the multi mission satellite altimetry data[J]. *Earth Science Journal of China University of Geosciences*, 2020, 45(6): 956-966.

[14] He Fei, Liu Zhaofei, Yao Zhijun. Evaluation of the monitoring accuracy of lake water level by the Jason-2 altimeter satellite[J]. *Journal of Geo-information Science*, 2020, 22(3): 494-504.

[15] Gao Le. Monitoring the changes in lake level and glacier elevation in the Tibetan Plateau using satellite altimetry data[D]. Beijing: University of Chinese Academy of Sciences, 2014.

- [16] Jiang L G, Nielsen K, Andersen O B, et al. Monitoring recent lake level variations on the Tibetan Plateau using CryoSat-2 SARIn mode data[J]. *Journal of Hydrology*, 2016, 544: 109-124.
- [17] Zwally H J, Schutz R, Bentley C, et al. GLAS/ICESat L2 global land surface altimetry data V018, 15 October to 18 November 2003[R]. Colorado: National Snow and Ice Data Center, 2003.
- [18] Bouffard J. CryoSat level-2 product evolutions and quality improvements in baseline C[J/OL]. [2019-05-19]. <https://earth.esa.int/web/guest/document-library/browse-document-library/-/article/cryosat-level-2-product-evolutions-and-quality-improvements-in-baseline-c>.
- [19] Yang X W, Wang N L, Chen A A, et al. Changes in area and water volume of the Aral Sea in the arid Central Asia over the period of 1960–2018 and their causes[J]. *Catena*, 2020, 191: 104566, doi: 10.1016/j.catena.2020.104566.
- [20] Zhang Xin, Wu Yanhong. Zhari namco water level change detection using multi satellite altimetric data during 1992–2012[J]. *Journal of Natural Resources*, 2015, 30(7): 1153-1162.
- [21] Li Junli, Chen Xi, Bao Anming, et al. Spatial temporal characteristics of lake level changes in Central Asia during 2003–2009[J]. *Acta Geographica Sinica*, 2011, 66(9): 1219-1229.
- [22] Yang Chuande. Water level of Balkhash Lake and its reason for change[J]. *Arid Land Geography*, 1993, 16(1): 36-42.
- [23] Long Aihua, Deng Mingjiang, Xie Lei, et al. A study of the water balance of Lake Balkhash[J]. *Journal of Glaciology and Geocryology*, 2011, 33(6): 1341-1352.
- [24] Guo Lidan, Xia Ziqiang, Li Jie, et al. Characteristics of climatic change in the Balkhash Lake Basin[J]. *Journal of Hohai University (Natural Sciences Edition)*, 2008, 36(3): 316-321.
- [25] Propastin P A. Patterns of Lake Balkhash water level changes and their climatic correlates during 1992–2010 period[J]. *Lakes & Reservoirs Research & Management*, 2012, 17(3): 161-169.
- [26] Propastin P A. Simple model for monitoring the water level in Balkhash Lake and discharge of the Ili River: Application of remote sensing[J]. *Lakes & Reservoirs Research & Management*, 2010, 13(1): 77-81.
- [27] Zang Jingjing, Li Guozhu, Song Kaishan, et al. Changes in water area of Balkhash Lake from 1975 to 2014[J]. *Wetland Science*, 2016, 14(3): 368-375.
- [28] Chen Cheng, Fu Wenxue, Hu Shaoling, et al. Changes of major lakes in Central Asia over the past 30 years revealed by remote sensing technology[J]. *Remote Sensing for Land and Resources*, 2015, 27(1): 146-152.

- [29] Gao Yanhua, Wang Hongliang, Zhou Xu, et al. Remote sensing monitoring and analyses of the dynamic change of Balkhash Lake in the last 30 years[J]. *Environment and Sustainable Development*, 2016, 41(1): 102-106.
- [30] Krupa E, Slyvinskiy G, Barinova S. The effect of climatic factors on the long term dynamics of aquatic ecosystem of the Balkhash Lake (Kazakhstan, Central Asia)[J]. *Advanced Studies in Biology*, 2014, 6(3): 115-136.
- [31] Wei Xin, Li Fei, Zhang Shengkai, et al. CryoSat-2 satellite altimetry and its application[J]. *Chinese Journal of Polar Research*, 2015, 27(4): 446-453.
- [32] Zhao Yun. Method of monitoring water level change of main lakes in China with radar altimeter data[D]. Beijing: Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, 2017.
- [33] Deng Mingjiang, Wang Zhijie, Wang Jiaoyan. Analysis of Balkhash Lake ecological water level evolvement and its regulation strategy[J]. *Journal of Hydraulic Engineering*, 2011, 42(4): 403-413.
- [34] Xiao Tingting, Xia Ziqiang, Guo Lidan, et al. Temperature characteristics in the Balkhash Lake Basin from 1936 to 2005[J]. *Journal of Hohai University (Natural Sciences)*, 2011, 39(4): 391-396.
- [35] Kezer K, Matsuyama H. Decrease of river runoff in the Lake Balkhash Basin in Central Asia[J]. *Hydrological Processes*, 2006, 20(6): 1407-1423.
- [36] Mahpir Jappar. Affection and countermeasure of environment of Ili Balkhash Lake Basin under human activities[C]//*Water Resources and the Environment in the Central Asia under Human Activities and Assessment of Tianshan Snow Resources*. Urumqi: Xinjiang Science & Medical Publishing House, 1997: 49-62.
- [37] Wang Jinsong, Chen Fahu, Zhang Qiang, et al. Temperature variations in arid and semi arid areas in middle part of Asia during the last 100 years[J]. *Plateau Meteorology*, 2008, 27(5): 1035-1045.
- [38] Pueppke S G, Zhang Q, Nurtazin S T. Irrigation in the Ili River Basin of Central Asia: From ditches to dams and diversion[J]. *Water*, 2018, 10(11): 1650, doi: 10.3390/w10111650.
- [39] Niels T, Sabir N, Volker B, et al. Water consumption of agriculture and natural ecosystems along the Ili River in China and Kazakhstan[J]. *Water*, 2017, 9(3): 207, doi: 10.3390/w9030207.
- [40] Qiao B, Zhu L, Wang J, et al. Estimation of lake water storage and changes based on bathymetric data and altimetry data and the association with climate change in the central Tibetan Plateau[J]. *Journal of Hydrology*, 2019, 578: 124052, doi: 10.1016/j.jhydrol.2019.124052.
- [41] Ge Li, Xi Xiaohuan, Wang Cheng, et al. Research progress of ICESat-1/GLAS in lake level monitoring[J]. *Remote Sensing Technology and Application*, 2017, 32(1): 14-19.

- [42] Wu Hongbo. Studies on changes in water level and storage of Bosten[J]. Journal of Water Resources and Water Engineering, 2019, 30(3): 9-16, 23.
- [43] Li Jing, Yue Jianping, Song Yahong, et al. System error analysis of data from multigenerational altimeter satellites with the same task[J]. Hydrographic Surveying and Charting, 2015, 35(6): 21-23.
- [44] Mcfeeters S K. The use of the normalized difference water index (NDWI) in the delineation of open water features[J]. International Journal of Remote Sensing, 1996, 17(7): 1425-1432.
- [45] Fu Yingxin, Yang Shu. Commentary on the development of Kazakhstan Ili Balkhash basin during the Soviet period[J]. Journal of Lanzhou University (Social Sciences), 2009, 37(4): 16-24.
- [46] Chen Dongdong. Water balance estimates of typical lakes in arid region of Central Asia using ICESat and Landsat data[D]. Lanzhou: Northwest Normal University, 2018.
- [47] Yang Chuande, Shao Xinyuan. Recent change of lakes in Central Asia[M]. Beijing: China Meteorological Press, 1993: 26.
- [48] Chen Fahu, Huang Wei, Jin Liya, et al. Spatiotemporal precipitation variations in the arid Central Asia in the context of global warming[J]. Science China Earth Sciences, 2011, 41(11): 1647-1657.

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