

Postprint: Monitoring Water Level Changes in Hulun Lake Based on ICESat-2 Satellite Altimetry Data

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Abstract

Variations in grassland lake water levels presage changes in the grassland ecological environment and constitute an important indicator of grassland ecological change. Utilizing ATL13 global inland water body data from the ICESat-2 satellite covering the period from November 2018 to January 2022, a high-precision water level variation time series for Hulun Lake was constructed. DAHITI, Hydroweb, and G-REALM water level data were employed for result validation. Based on the relationship between lake area and water level variation, a water level-area relationship model was established to analyze seasonal variation characteristics of lake water level and the influence of external factors on lake water level. The research results indicate that from November 2018 to January 2022, the water level of Hulun Lake exhibited an overall upward trend, with an annual average water level rise rate of $0.49 \text{ m} \cdot \text{a}^{-1}$; the lake water level decreased from March to June each year, increased from July to October, and remained stable from November to February of the following year. Through comparative validation with DAHITI, Hydroweb, and G-REALM water level data, the ICESat-2 satellite-monitored water level data demonstrate stability, high precision in the water level time series with a root mean square error of 9.7 cm, and reliable results. The ICESat-2 satellite water level monitoring results, combined with the lake water level-area model, enable multi-temporal, high-precision lake water level monitoring and calculation of seasonal water level variation time series. The results show that Hulun Lake exhibits distinct seasonal water level characteristics with a basically stable interannual variation trend: water level decreases from spring to summer and increases from summer to winter. Lake water level variation is significantly influenced by external factors; increased evaporation resulting from temperature rise is the dominant factor for lake water level decline, with temperature and evaporation displaying a strong negative correlation with water level variation. Artificial water replenishment supplements lake water volume and raises lake water level, with a particularly evident upward trend during

the 2021 injection period.

Full Text

Monitoring Water Level Changes in Hulun Lake Based on ICESat-2 Satellite Altimetry Data

Abstract

Water level changes in grassland lakes indicate shifts in the grassland ecological environment and serve as a crucial indicator of ecological change. This study utilizes ICESat-2/ATLAS ATL13 global inland water data from November 2018 to January 2022 to construct a high-precision water level change time series for Hulun Lake. The results are validated using DAHITI, Hydroweb, and G-REALM water level products. Based on the relationship between lake area and water level changes, a water level-area relationship model is developed to analyze seasonal variation characteristics of lake water level and the influence of external factors. The research findings demonstrate that from November 2018 to January 2022, the water level of Hulun Lake exhibited an overall upward trend with an average annual increase rate of $0.49 \text{ m} \cdot \text{a}^{-1}$. The lake level decreases from March to June each year, rises from July to October, and stabilizes from November to February of the following year. Comparison and verification against DAHITI, Hydroweb, and G-REALM water level data confirm that ICESat-2 satellite monitoring data are stable with high precision, achieving a root mean square error of 9.7 cm, thus proving reliable. Combining ICESat-2 satellite altimetry results with the lake water level-area model enables multi-temporal, high-precision lake water level monitoring and calculation of seasonal water level change time series. The results reveal pronounced seasonal characteristics of Hulun Lake water level with basically stable interannual trends: water level decreases from spring to summer and increases from summer to winter. Lake water level changes are significantly affected by external factors, with increased evaporation caused by rising temperature being the dominant factor causing water level decline. Temperature, evaporation, and water level changes show strong negative correlations. Artificial water injection for lake replenishment has raised the lake level, with a particularly obvious rising trend during the 2021 injection period.

Keywords: ICESat-2; satellite altimetry; water level monitoring; influencing factors; Hulun Lake

Introduction

Changes in grassland lakes are closely related to grassland ecosystems and constitute an important indicator for evaluating grassland ecosystem health. Water resource loss and replenishment are closely associated with natural environmental changes and human activities. Previous research has investigated water level monitoring techniques, though these have certain limitations such as low altimetry data resolution that cannot meet the requirements for large-scale dynamic

monitoring of medium to large inland lakes. Traditional water level monitoring technology relies on constructing gauging stations to obtain lake water level changes. While this approach offers high precision and continuous observation, it is limited by natural conditions and construction costs.

In recent years, satellite altimetry technology has been widely applied in lake water level monitoring. Since the 1990s, European Space Agency's ERS-1 (European Remote Sensing Satellite 1) and subsequent Jason series satellites, as well as NASA and CNES' s joint missions, have progressively improved water level change monitoring precision. ICESat-2 (Ice, Cloud and land Elevation Satellite-2) data provide new technical approaches for monitoring reservoir water level dynamics, compensating for deficiencies such as data gaps and poor timeliness associated with traditional measurement methods. Compared with radar altimetry, laser altimetry has smaller ground footprints and lower probability of interference from lake shores and water edge waves, offering greater advantages in lake water level monitoring. Studies have demonstrated that ICESat-2 satellite data show significant potential for monitoring inland reservoirs and lakes, with monitoring results for the upper Yangtze River showing basic consistency with gauging station observations. Research indicates that ICESat-2 satellite data will become an important component of future global reservoir water level surveys.

China has numerous medium to large lakes and reservoirs. While radar altimetry satellites have been used to compensate for poor timeliness and data gaps in traditional monitoring methods, research utilizing single-photon laser altimetry data for medium to large lake water levels remains limited. Therefore, this study employs ICESat-2/ATL13 data to extract high-precision daily average water levels for Hulun Lake, validates the results using Hydroweb, DAHITI, and G-REALM products to analyze monitoring accuracy, constructs a water level-area relationship model based on the relationship between lake area and water level, improves water level monitoring temporal resolution, and analyzes seasonal variation characteristics of lake water level along with impacts from natural and anthropogenic factors. The extracted lake water level data can provide theoretical references for lake monitoring research and ecosystem maintenance in the lake region.

Study Area and Data Sources

Study Area Overview Hulun Lake (48°30' -49°20' N, 117°00' -117°41' E), also known as Dalai Lake, is located in the western part of the Hulunbuir Grassland and ranks among China' s five largest freshwater lakes. The geographical location is shown in [Figure 1: see original paper]. Water supply to Hulun Lake primarily comes from rivers, rainfall, and artificial water injection. Since the implementation of the water replenishment project, the lake has collected water from the Kherlen River and Wuerxun River, which then flows out through the Ergun River. Seasonal variation is pronounced, with higher summer temperatures causing evaporation to far exceed precipitation and resulting in significant

water level fluctuations. In winter, lower temperatures freeze the lake surface, making water levels relatively stable.

Data Sources ICESat-2 Altimetry Satellite Data. The study utilizes ICESat-2/ATLAS ATL13 water elevation dataset from the National Snow and Ice Data Center (NSIDC, <https://nsidc.org/home>). ICESat-2 was launched on September 15, 2018, from Vandenberg Air Force Base in California. The satellite's basic parameters are listed in . The ATL13 product contains water elevation information, latitude and longitude along the satellite track, which is used to extract Hulun Lake water level information. ICESat-2 employs a 500 km orbit with a 10 kHz pulse repetition frequency, 0.2–1.2 mJ laser energy, 532 nm wavelength, 0.7 m adjacent beam spacing, and 2.3 cm single-shot ranging nominal precision. The ATLAS altimeter's ground tracks enable high-precision, large-scale monitoring, allowing dynamic monitoring of water level changes in medium to large lakes.

Other Datasets. Hydroweb water level data are released by the Global Lake Level Data Center jointly established by Russia and France (<https://theia-land.fr/?lang=en>), based on Jason-1/2/3 and ENVISAT altimetry satellite data. DAHITI (Database for Hydrological Time Series of Inland Waters) was established by the Technical University of Munich in 2014, based on Jason-2/3 and Sentinel-3 altimeter data. G-REALM water level data are produced by the USDA Foreign Agricultural Service, NASA, and the University of Maryland using Jason-1/2/3 and ENVISAT altimeters, achieving 10.0 cm precision in large lake monitoring. Landsat 8 OLI imagery data from the US Geological Survey are used to calculate lake area and determine lake boundaries. Precipitation, temperature, and evaporation data are obtained from the National Meteorological Science Data Center.

Research Methods

The data processing workflow is illustrated in [Figure 2: see original paper]. Python programming is used to read and process ICESat-2 satellite altimetry data to obtain lake water level data, which is then validated against REALM, Hydroweb, and DAHITI water level products.

Attribute Data Reading The attribute data relevant to water level monitoring are read, including water surface elevation, latitude and longitude, data acquisition time, and geoid information.

Determination of Laser Footprints Within the Lake The study area is defined, and Landsat 8 optical remote sensing imagery from periods of low water level in Hulun Lake is selected for preprocessing. The Modified Normalized Difference Water Index (MNDWI) is used to calculate water bodies in the lake region, and threshold segmentation is applied to obtain lake boundary data. The MNDWI is calculated as:

$$MNDWI = \frac{Green - MIR}{Green + MIR}$$

where *Green* represents green band reflectance and *MIR* represents mid-infrared shortwave band reflectance.

Laser footprint positions within the lake area are determined by combining the read attribute data with water body boundary information through spatial position analysis to extract laser footprint data within the lake.

Water Level Elevation Data Screening Abnormal laser footprint data are screened and removed. Although laser footprints within the lake are roughly extracted based on lake boundaries, some outliers remain and must be filtered. The Isolation Forest algorithm is used to screen and remove outliers, validated by the Interquartile Range (IQR) method and Median Absolute Deviation (MAD) method, with errors maintained within -0.8 to 0.5 cm.

Isolation Forest Model. Based on the Isolation Forest algorithm, a binary tree processing method randomly selects samples and features to partition the data. Numerous binary tree models are constructed, using the number of partitions to measure whether a point is clustered (normal) or isolated (anomalous). Partition counts are selected based on the degree of isolation of anomalous data from other data, ultimately achieving outlier identification.

Interquartile Range Method. According to the first quartile (Q_1) and third quartile (Q_3), values within the $[Q_1, Q_3]$ interval are retained while others are considered outliers and removed:

$$H_{outlier} < Q_1 - 1.5 \times IQR \quad \text{or} \quad H_{outlier} > Q_3 + 1.5 \times IQR$$

where *IQR* is the interquartile range.

Median Absolute Deviation Method. This method is more robust than sample variance and standard deviation. The median absolute deviation can effectively address the sensitivity of mean and standard deviation to outliers. The calculation method is as follows:

$$MAD = \text{median}(|H_i - \text{median}(H)|)$$

Outlier criteria:

$$H_{outlier} < \text{median}(H) - 3 \times MAD \quad \text{or} \quad H_{outlier} > \text{median}(H) + 3 \times MAD$$

where *MAD* is the median absolute deviation value, *H* is the water level elevation sequence, and *median(H)* is the median of the water level data sequence.

Lake Average Water Level Extraction After removing outliers from ICESat-2/ATL13 data, the average value of laser footprints from each track within a cycle is used as the lake water level estimate for that track. The average of all track footprint values within each cycle is then calculated as the daily lake water level average:

$$H_{gtx} = \frac{1}{n} \sum_{j=1}^n H_j$$

$$H_{avg} = \frac{1}{m} \sum_{i=1}^m H_{gtx}$$

where H_{gtx} is the average elevation of each track within a cycle, H_j is the screened water level elevation sequence, n is the number of screened points per track, and m is the number of valid tracks.

Linear Regression Model Based on the relationship between water level and area, a regression function is constructed with water level as the dependent variable and area as the independent variable. The regression function model is:

$$y = f(x_1, x_2, \dots, x_n) + \varepsilon$$

where x_1, x_2, \dots, x_n are independent variables, y is the dependent variable, f is the “regression function” of y on independent variables, and ε is random error.

Results and Analysis

Characteristics of Daily Average Water Level Changes in Hulun Lake

Using ICESat-2/ATL13 data, daily water level changes were calculated to construct a high-precision daily water level variation time series, shown in [Figure 3: see original paper]. From November 2018 to January 2022, the overall water level showed an upward trend with an average annual increase rate of $0.49 \text{ m} \cdot \text{a}^{-1}$. Water level changes were primarily manifested as: rising from March to June, decreasing from July to October, and rapid increase from November to February of the following year, mainly due to implementation of artificial lake replenishment projects. The highest water level reached 544.43 m in November 2021, the lowest level was 543.45 m in July 2019, with an annual variation range of 0.77 m. In 2019, the highest level was 543.66 m in November and the lowest was 543.45 m in July, with an annual range of 0.21 m and an average level 0.48 m higher than the 2018-2022 mean. In 2020, the highest level was 543.66 m in November, the lowest was 543.26 m in July, with an annual range of 0.40 m and an average level 0.21 m higher than the overall mean.

ICESat-2 satellite altimetry data were available for the Hulun Lake region from November 2018 to January 2022, with dense laser footprints in each observation cycle. The standard deviation of each cycle ranged from 0.02 to 0.05 m, with a mean standard deviation of 0.03 m. The distribution between expected values and standard deviations was stable, indicating high data quality ([Figure 4: see original paper]).

Water Level Accuracy Verification Previous studies have shown that Hydroweb and DAHITI water level product data are of high quality and suitable for validating lake water level results. Therefore, REALM, Hydroweb, and DAHITI water level product data were selected for comparative analysis with the water level data extracted in this study. First, the mean value was subtracted from each dataset to obtain relative water level changes. Each dataset was then resampled (with interpolation for missing values) to obtain temporally aligned data. A filtering process with a window length of 30 days was applied to each pair of datasets, and differences were calculated. The results are shown in .

Comparative analysis between the lake water level sequence obtained in this study and the Hydroweb and DAHITI dataset sequences shows that the water level data extracted in this research have stable deviations and reliable precision, suitable for dynamic monitoring of Hulun Lake water level changes. The standard deviation of ICESat-2 altimetry water level observations per cycle is distributed between 0.02-0.05 m, with stable distribution between expected values and standard deviations, indicating high data quality. Compared with ICESat-2 altimetry water level data, the root mean square error with REALM, DAHITI, and Hydroweb water level data is 9.7 cm, demonstrating reliable data precision.

Seasonal Variation Characteristics of Lake Water Level Hulun Lake is located in northern China in the Northern Hemisphere, with spring beginning in March and winter ending in February of the following year. Landsat 8 OLI imagery data are used to extract water body area in the Hulun Lake basin during this period based on multiple water index methods. The improved MNDWI, which shows better water extraction performance, is selected to calculate lake area. Analysis shows that the area and water level of Hulun Lake exhibit essentially consistent trends. Data from dates corresponding to ICESat-2 altimetry satellite monitoring water level data are selected to construct a linear regression model of the relationship between lake area and water level monitored by the altimetry satellite, as shown in equation:

$$y = 0.0116x + 519.684$$

where x is lake area (km^2) and y is the corresponding water level (m). The coefficient of determination $R^2 = 0.94$, accurately describing the relationship

between lake water level and area changes. This model can effectively compensate for the impact of low temporal resolution of satellite altimetry data on lake water level extraction.

Combining altimetry data with the lake water level-area model to calculate monthly average water level further analyzes seasonal variation characteristics, with results shown in [Figure 6: see original paper]. The water level shows obvious seasonal variation characteristics: winter > spring > autumn > summer. The main reason is that the lake is frozen in winter, less affected by external factors, and maintains stable water levels. From 2018 to 2021, the interannual seasonal variation trend of lake water level was consistent: water level decreased from spring to summer and increased from summer to winter, with the lowest water level in summer. The 2021 water level change trend differed from the previous three years, primarily due to two factors: natural factors such as temperature and precipitation, and anthropogenic factors including artificial replenishment projects, environmental protection, and grazing.

Hulun Lake has a unique geographical location and climate. Water supply comes from the Kherlen River, Wuerxun River, and artificial water injection projects, causing lake level rises. Precipitation in the Hulun Lake basin is concentrated in June–August, when evaporation far exceeds rainfall, making rainfall's contribution to lake water volume extremely limited. Without human influence, the lake level would decrease. The water level showed slow growth from 2018 to 2020, with rapid increase beginning in March 2021. Combined with evaporation, temperature, and precipitation data from the Xin Barag Right Banner meteorological station and the impact of artificial water injection, comprehensive analysis shows that from March to June, temperature and evaporation in the Hulun Lake basin rise rapidly. Although precipitation also increases during this period, water loss from lake surface evaporation far exceeds replenishment from precipitation, causing water level decline. From July to October, evaporation decreases while precipitation reaches its annual maximum, and lake water level rises slowly. From November to February of the following year, the lake surface freezes, external factors have minimal impact, and water level remains stable. Due to implementation of the Hulun Lake water replenishment project beginning at the end of March 2021, water was injected into the lake, causing rapid water level rise from April to October 2021. Compared with precipitation, the artificial water injection project is the main factor causing lake level rise.

Impact Factor Analysis Lake water level change results from the combined influence of many factors, primarily divided into two categories: (1) natural factors including evaporation, river supply, temperature, and precipitation; and (2) anthropogenic factors including artificial water injection projects, environmental protection, and grazing. Statistical analysis of ICESat-2 monitoring water level with air temperature, precipitation, and evaporation is shown in [Figure 7: see original paper].

Temperature indirectly affects lake water level; increased evaporation caused by

rising temperature is a non-negligible factor for lake water level decline. From spring to autumn, evaporation changes show strong negative correlation with lake water level changes. Precipitation is concentrated in June–August, but its contribution to lake water volume is far lower than water loss caused by evaporation, resulting in weak correlation between water level and precipitation. From March to June, temperature and evaporation in the Hulun Lake basin rise rapidly while precipitation also increases, but water loss from lake surface evaporation far exceeds precipitation replenishment, causing water level decline. From July to October, evaporation decreases and precipitation reaches its maximum, causing slow water level rise. From November to February, the frozen lake surface minimizes external influences, maintaining stable water levels. Due to the artificial water injection project implemented at the end of March 2021, water level rose rapidly from April to October, with the 2021 average level reaching 544.43 m, 0.77 m higher than the 2018–2022 average.

Conclusions

Satellite altimetry technology for water level data extraction offers significant advantages over traditional water level monitoring methods, enabling dynamic lake water level monitoring without ground interference. Using ICESat-2 altimetry data, this study constructed a high-precision daily water level change time series for Hulun Lake. The ICESat-2 altimetry water level data were validated against REALM, DAHITI, and Hydroweb water level products, showing stable deviations and reliable precision with a root mean square error of 9.7 cm. The main conclusions are as follows:

- 1) From November 2018 to January 2022, the lake water level showed an obvious upward trend with an average annual increase rate of $0.49 \text{ m} \cdot \text{a}^{-1}$. The water level decreases from March to June, increases from July to October, and remains stable during the November–February freezing period. In 2019, the highest water level was 543.66 m in November, the lowest was 543.45 m in July, with an annual range of 0.21 m and an average level 0.48 m higher than the overall mean. In 2020, the highest level was 543.66 m in November, the lowest was 543.26 m in July, with an annual range of 0.40 m and an average level 0.21 m higher than the overall mean. In 2021, the highest level reached 544.43 m in November, the lowest was 543.66 m in July, with an annual variation of 0.77 m and an average level 0.77 m higher than the 2018–2022 average.
- 2) The standard deviation of ICESat-2 altimetry water level observations per cycle is distributed between 0.02–0.05 m, with stable distribution between expected values and standard deviations, indicating high data quality. The lake water level-area relationship model effectively addresses data gaps in altimetry satellites and compensates for the impact of low temporal resolution on lake water level extraction. Calculated seasonal water level change sequences show stable interannual trends and obvious seasonal characteristics: water level decreases from spring to summer and increases

from summer to winter.

- 3) Hulun Lake water level changes are closely related to basin evaporation, precipitation, and artificial water injection projects. From March to June each year, temperature and evaporation rise rapidly, with evaporation far exceeding precipitation, causing lake water level decline. From July to October, precipitation reaches its annual peak while evaporation gradually decreases, and river supply slowly raises water levels. From November to February, the frozen lake surface minimizes external influences, maintaining stable water levels. Due to artificial water injection project implementation, water level rises rapidly from April to October. Compared with precipitation, the artificial water injection project is the main factor causing lake level rise.

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