Lake Balkhash Water Balance Variations and Their Influencing Factors over the Past 60 Years: Postprint

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Abstract

Based on hydrological observation and remote sensing monitoring data, this study obtains information on the area and water level changes of Lake Balkhash over the past 60 years, reconstructs the time series of lake water volume changes, and identifies the characteristics of water volume variations in Lake Balkhash; a water balance model for Lake Balkhash is established based on lake water income (inflow runoff, precipitation) and expenditure (lake surface evaporation) to analyze the variation characteristics of water balance components and quantitatively parse the impacts of climate change and human activities on the water volume changes of Lake Balkhash. The results show that: (1) From 1961 to 2020, the water volume of Lake Balkhash first decreased sharply and then fluctuated and increased, with 1987 as the inflection point; the variation of inflow runoff is basically consistent with the process of lake water volume change, with an average annual inflow runoff of approximately 14.04 km3 · a-1; precipitation in the lake area fluctuated and increased at a rate of 0.28 mm · a-1; the average annual evaporation from the water body is approximately 17.95 km3 · a-1, with the minimum of 16.10 km3 in 1987 and the maximum of 20.30 km3 in 2008. (2) Over the past 60 years, groundwater and the lake have replenished each other, with relatively large amounts of groundwater recharging the lake in the 1970s and 1980s, with a recharge volume of approximately 1.91 km3. (3) At the lake scale, inflow discharge is significantly correlated with Lake Balkhash water volume and is the dominant factor affecting lake water volume changes; at the watershed scale, the contribution rate of climate fluctuation to the long-term variation of inflow discharge is 71.67%, while the contribution rate of human water consumption is 28.33%; during 1970–1985, the contribution rate of Kapchagay Reservoir impoundment and surrounding cropland expansion to the sharp reduction of inflow water reached 47.47%, and human activities clearly exacerbated the lake level decline during this period.

Full Text

Water Balance Changes and Influencing Factors of Lake Balkhash in the Past 60 Years

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Abstract

Based on hydrological observations and remote sensing monitoring data, this study extracted information on Lake Balkhash' s area and water level changes over the past 60 years, reconstructed the lake' s water volume time series, and identified the characteristics of water volume variations. A water balance model for Lake Balkhash was established based on water income (inflow runoff, precipitation) and expenditure (lake surface evaporation) to analyze the changing characteristics of water balance components and quantitatively parse the impacts of climate change and human activities on lake water volume changes. The results showed that: (1) From 1961 to 2020, Lake Balkhash' s water volume first decreased sharply then fluctuated and increased, with 1987 as the inflection point. The change process of inflow runoff was basically consistent with lake water volume changes, with an average annual inflow of approximately 14.04 km^3. Precipitation in the lake area fluctuated and increased at a rate of 0.28 $mm \cdot a^{-1}$. The average annual water surface evaporation was about 17.95 km^3, with minimum and maximum values of 16.10 km^3 and 20.30 km^3, respectively. (2) Groundwater and lake water supplemented each other, with relatively high groundwater recharge (about 1.91 km^3) in the 1970s and 1980s. (3) At the lake scale, inflow runoff was significantly correlated with Lake Balkhash' s water volume and represented the dominant factor affecting lake water volume changes. At the watershed scale, climate fluctuations contributed 71.67% to long-term inflow changes, while human activities contributed 28.33%. The Kapchagay Reservoir impoundment and surrounding cultivated land expansion from 1970–1985 contributed 47.47% to the sharp reduction in inflow, with human activities clearly exacerbating the lake level decline during this period.

Keywords: Lake Balkhash; water balance; factorial analysis; evaporation; water volume; inland river basin

Introduction

Central Asia is a vast region where mountain-oasis-desert-terminal lake systems represent typical water formation and utilization patterns in inland river basins. Climate change affects both water resource formation and storage in mountainous areas while intensifying water consumption processes in oases and deserts. Combined with increasingly intensive human activities, water resources in Central Asian inland river basins have shown significant changes and spatiotemporal variations, exacerbating water shortages at regional and watershed scales and inducing ecological problems in midstream and downstream areas, particularly in terminal lake zones. Lake Balkhash is a typical inland lake in the arid region of Central Asia, characterized by large water surface area and relatively shallow depth. It possesses abundant wetland and aquatic resources. Due to climate change, agricultural irrigation, and particularly the Kapchagay Reservoir impoundment, Lake Balkhash experienced a sharp water volume reduction during the 1970s–1980s, causing lake level decline and delta ecological environment degradation, which has attracted widespread attention in Kazakhstan and internationally.

Previous studies have focused on lake hydrological characteristics such as water level and area changes. Research indicates that Lake Balkhash exhibits periodic wet-dry alternation characteristics, with water levels fluctuating between 340–344 m over 48–52 year cycles. The lake experienced a wet-dry process in the early 20th century, with levels continuously declining for 15 years. In 1987, the lake reached its lowest recorded level, approximately 2.38 m lower than the 1946 level, with area shrinking by about 790 km^2, primarily in the southern Uzynaral Strait and delta regions. After the 1990s, water levels began to recover, reaching historical highs in 2010. However, lake hydrological evolution reflects external water balance changes, and current research on Lake Balkhash' s water balance remains limited. Deng et al. and Long et al. noted that due to Kapchagay Reservoir construction and irrigation water withdrawal in the left-bank irrigation district, inflow to the lake in the 1980s was 24.28% lower than the multi-year average. Nakayama extracted area changes using remote sensing data, combined with water level observations and meteorological data to analyze water balance from 2002–2011. Following the Soviet Union' s dissolution in the 1990s, large areas of cultivated land were abandoned in Kazakhstan, reducing irrigation water withdrawal and increasing inflow, allowing Lake Balkhash to enter a new water balance state. However, previous water balance research has primarily focused on pre-1985 periods, lacking analysis of recent water balance component changes and interactions, as well as quantitative assessment of climate change and human activity impacts.

Therefore, this study selected Lake Balkhash in Kazakhstan as a typical research area. Based on Landsat TM/ETM+/OLI data, we extracted lake area and water level information, calculated water volume changes using historical literature data, and utilized meteorological reanalysis datasets to calculate regional water consumption through multiple methods. We established a water balance model to analyze changes in water balance components including lake water volume, evapotranspiration, precipitation, inflow runoff, and groundwater, and parsed the interaction between water income and expenditure. From both lake and watershed scales, we quantitatively distinguished the impacts of climate change and human activities on lake water volume changes. The results provide data support for water resource management and ecological protection in the Lake Balkhash basin.

1.1 Study Area Overview

Lake Balkhash (hereinafter referred to as "the lake") is an inland lake located in southeastern Kazakhstan within the Balkhash-Alakol Basin. A peninsula—Saryesik Peninsula—extends from the southern to northern shore, dividing the lake into eastern and western parts. The lake' s multi-year average temperature is approximately 6.2°C, with multi-year average precipitation of about 194.78 mm. Lake Balkhash receives water from six rivers: the Ili, Karatal, Aksu, Lepsy, and Ayaguz rivers. The Ayaguz River ceased surface runoff input in 1970. Originating from the Tianshan Mountains, the Ili River flows westward into the western lake as the main water source, contributing 76.74% of total inflow. In contrast, the four rivers flowing into the eastern lake have much smaller runoff, and evaporation in the eastern lake far exceeds river replenishment, resulting in the lake' s characteristic east-saline, west-fresh salinity distribution. The Kapchagay Reservoir, built on the Ili River in 1970, has a normal storage level of 485 m, reservoir area of 1847 km^2, and total storage capacity of 28.14 km^3, making it the largest reservoir in the Ili-Balkhash basin.

1.2 Data Sources and Processing

Lake area and water level data acquisition was divided into two phases. The first phase (1961-2002) used data from Nakayama and Long et al., while the second phase (2002-2020) derived from USGS remote sensing data, including Landsat TM/ETM+/OLI imagery concentrated in September-October each year for area extraction. Water level information for 2002-2020 was obtained from Jason1/2/3 altimetry satellite data products.

Meteorological data were derived from the Climatic Research Unit (CRU) TS 4.05 dataset from the University of East Anglia (http://data.ceda.ac.uk/badc/cru/data/cru_{ts}/), with 0.5°$×$0.5° spatial resolution, including monthly mean temperature, precipitation, and evapotranspiration. High-resolution gridded datasets have been widely applied globally, with validated accuracy and applicability in Central Asia. Due to sparse meteorological stations and the lake' s elongated shape, single-site data cannot reflect spatial differences in meteorological elements. Zhang et al. found significant positive correlations between observed temperature and precipitation data around Lake Balkhash and CRU TS data, with correlation coefficients reaching 0.9. Therefore, this study used CRU TS grid data to extract average precipitation sequences and evaporation products for the lake area. The evaporation product was calculated using the Penman-Monteith formula.

Annual runoff data for the Ili River' s Kayirgan, Kashang, and Uzynaral stations were obtained from 1961-2015. Delta water consumption data for 1990-2015 came from Xie et al. Inflow data for the Karatal, Aksu, Lepsy, and Ayaguz rivers were obtained from the National Cryosphere Desert Data Center (http://www.ncdc.ac.cn).

1.3.1 Lake Water Volume Calculation

Based on Nakayama' s 1961-2002 Lake Balkhash water volume data sequence, water level-area-volume capacity curves were constructed. Water volume changes from 2002–2020 were estimated using remotely sensed water level and area time series data. The formula for calculating lake volume from surface elevation H and area A is:

$$V = \frac{1}{3}(H_2 - H_1)(A_1 + A_2 + \sqrt{A_{1A}2})$$

where V is lake volume from water surface elevation H_1 to H_2, and A_1 and A_2 are corresponding lake surface areas.

1.3.2 Runoff Time Series Interpolation and Extension

Analysis revealed significant correlations between annual Ili River inflow and Lake Balkhash' s annual water level change and water volume. Therefore, backward stepwise regression analysis was used to establish statistical prediction models for inflow based on lake water volume and water level, interpolating inflow from 1961-2020. To eliminate human impacts, the period 1961–1969 (before Kapchagay Reservoir impoundment) was selected as the calibration period, with 1970–1985 as the validation period for establishing stepwise regression equations. Overall model performance was good, with prediction errors within the allowable range of GB/T 22482-2008 "Hydrological Information Forecasting Standards," effectively simulating inflow variations.

Additionally, based on Ili River inflow and delta water consumption from Xie et al., Uzynaral station runoff data at the delta inlet were extended. Using precipitation-runoff correlations, Kayirgan station upstream runoff data were extended, and downstream correlations were used to obtain Kapchagay Reservoir inflow and outflow data.

1.3.3 Water Balance Model

The relationship between lake storage change and water increase/decrease during a period can be expressed by the water balance equation:

$$\Delta V = (P + Q_{\text{inflow}} + Q_{\text{groundwater in}} - E - Q_{\text{outflow}} - Q_{\text{groundwater out}}) \times \Delta t$$

where ΔV is lake storage change (km^3), Δt is calculation period (year), A is lake surface area (km^2) as a function of water level (h), P is precipitation in the study area (km^3), E is total evaporation in the study area (km^3), and Q terms represent various inflow and outflow components.

As Lake Balkhash is a terminal lake for inflow rivers with no outflow rivers, the water balance equation simplifies to:

$$\Delta V = (Q_{\text{river inflow}} + Q_{\text{groundwater in}} - Q_{\text{groundwater out}} - E + P) \times \Delta t$$

The residual term (Q_{residual}) represents the difference between calculated and observed water volume changes, expressed as:

$$Q_{\text{residual}} = \Delta V - (Q_{\text{river inflow}} - E + P)$$

When groundwater monitoring data are unavailable, the residual term can approximate groundwater change. When lake water level and groundwater level are equal during wet years with increased inflow, lake water supplements riparian groundwater (positive residual). Conversely, during dry years with reduced inflow, lake level drops below groundwater level, and riparian groundwater seeps into the lake (negative residual).

2.1 Water Storage Changes in Lake Balkhash

From 1961-2020, Lake Balkhash' s water level and area showed a trend of initial decline followed by increase (Fig. 2). Water level fluctuated and decreased at 3.6 $mm \cdot a^{-1}$ from 1961-1987, with the maximum decline rate of 13.1 $mm \cdot a^{-1}$ in 1970. In 1987, water level reached 340.6 m, near the lowest recorded level, 2.4 m below the maximum level. Subsequently, water level began fluctuating upward, rising 1.72 m after 1987 and stabilizing after 2010. Lake area decreased significantly at 38.46 $km^2 \cdot a^{-1}$ from 1961-1987, then increased at 8.61 $km^2 \cdot a^{-1}$, reaching a minimum of 16,732.18 km^2 in 1987 (5.21% below the maximum area). By 2020, area recovered to 17,258.93-17,562.67 km^2, fluctuating near 1980s levels.

Lake water volume showed a similar decline-increase pattern, divided into four stages (Fig. 2): Stage 1 (1961-1969) showed small fluctuations with overall stability; Stage 2 (1970-1987) saw sharp water volume reduction at 0.52 $km^3 \cdot a^{-1}$, with water level dropping 2.31 m; Stage 3 (1988-2000) showed rapid increase at 0.95 $km^3 \cdot a^{-1}$, with water level rising 1.72 m; Stage 4 (2001-2020) exhibited small fluctuations around 1,061.51 km^3, approximately 90% of 1960s storage.

2.2.1 Precipitation

Precipitation data show that over the past 60 years, average annual precipitation in the lake area was 194.78 mm $\cdot$ a^{-1} (3.35 km^3), with no significant trend, consistent with previous studies. Precipitation showed obvious interannual variability, with a maximum of 4.73 km^3 in 1992 (41% above average) and minimum of 2.98 km^3 in 1974 (11% below average). From 1961–1987, lake surface precipitation showed a fluctuating decreasing trend with a multi-year average of 3.19 km^3. After 1988, precipitation fluctuated significantly and increased, but remained around the multi-year average of 3.56 km^3.

2.2.2 Inflow Runoff

Inflow runoff is the main water income source for Lake Balkhash, with Ili River inflow changes following the same pattern as total inflow (Fig. 4). Annual inflow showed large interannual variability, with average annual total inflow of 14.04 km^3, of which Ili River contributed 10.84 km^3. From 1961–1969, total inflow showed high-level oscillation characteristics. Inflow dropped sharply from 1970–1985, maintaining a significant decreasing trend with a minimum of 8.90 km^3 in 1987. After 1988, inflow gradually increased, peaking in 2010, with no obvious trend after 2000.

2.2.3 Evaporation Water Consumption

Lake surface evaporation is the main water expenditure pathway for Lake Balkhash. With rising lake area temperatures, lake potential evaporation showed an increasing trend. Water body evaporation showed fluctuating increase with large interannual variation (Fig. 5). From 1961–1987, evaporation decreased at 0.12 km^3 $\cdot$ a^{-1}, reaching a minimum of 16.1 km^3 in 1987. After 1987, evaporation increased at 0.08 km^3 $\cdot$ a^{-1}, reaching a maximum of 20.3 km^3 in 2008. The increasing trend in evaporation was not significant, as evaporation is influenced by multiple factors including lake area, temperature, wind speed, humidity, radiation, and atmospheric pressure. The multi-year average water body evaporation was 17.95 km^3, similar to results from Long et al.

Lake Balkhash water balance component changes are shown in Fig. 6. Results indicate the residual term ranged from -2.7 to 1.0 km^3. The residual was positive in the 1960s and 1970s, indicating lake water recharged groundwater with maximum average recharge of 0.93 km^3 $\cdot$ a^{-1}. Other decades showed negative residuals, indicating groundwater recharged the lake, with larger average groundwater recharge in the 1980s and 1990s (0.11 km^3 $\cdot$ a^{-1} and 2.61 km^3 $\cdot$ a^{-1}, respectively). This occurred because Kapchagay Reservoir impoundment sharply reduced Ili River inflow. After 2000, groundwater recharge decreased to 0.19 km^3 $\cdot$ a^{-1}, as the lake could maintain water balance through surface runoff and precipitation. Long et al. indicated that groundwater primarily recharged Lake Balkhash from 1990–2015, with annual groundwater exchange of approximately 1.6 km^3, similar to our results.

Discussion

In the Lake Balkhash region, lake surface evaporation is the main water dissipation pathway, while inflow runoff is the primary water income source. The interaction between water income and expenditure determines the lake' s historical evolution and future trends. This study introduced correlation analysis and factorial analysis to explore the influence of various factors on lake water volume changes at different temporal scales from both lake and watershed perspectives.

At the lake scale, correlation analysis between temperature, precipitation, inflow, evaporation, and lake water volume showed that inflow runoff correlated well with lake water volume, though correlation coefficients varied across periods (Table 1). Overall, Lake Balkhash water volume showed low correlation with lake area temperature and precipitation but significant positive correlation with inflow (passing 99% confidence tests), indicating inflow is the dominant factor controlling lake water volume changes.

At the watershed scale, climate change and human activities indirectly drive lake water volume changes by affecting inflow. The Ili River, originating from the northern slopes of Khan Tengri Peak in the western Tianshan Mountains, is the main water source, contributing 76.74% of total inflow. As a transboundary river, it is affected by upstream mountain water supply, midstream agricultural water use, and downstream delta water consumption. The main runoff generation zone is in China, while consumption occurs primarily in Kazakhstan (12.4 km^3 in Kazakhstan vs. 3.96 km^3 in China, accounting for 76% and 24% of total consumption, respectively). Studies show that from 1961-2000, Tianshan Mountain temperatures increased and precipitation increased at 8.8 $mm \cdot (10a)^{-1}$. Ili River outflow from China to Kazakhstan increased significantly, with average outflow from 1990-2010 26.5% higher than from 1960-1979. These studies indicate that upstream water production increased, yet Ili River inflow to Lake Balkhash decreased, suggesting excessive consumption within Kazakhstan.

Based on CRU TS data, we extracted precipitation and temperature change sequences for the upper Ili River basin (Fig. 7). From 1961-2020, mountain precipitation increased and temperatures continued rising. Runoff at upstream hydrological stations in Kazakhstan also showed slight increasing trends.

To quantitatively distinguish climate change and human activity impacts on Ili River inflow, we analyzed runoff changes between Kashang and Uzynaral stations (Table 2). From 1970-1985, Kapchagay Reservoir impoundment caused dramatic increases in water consumption between Kashang and Uzynaral stations, with an average increase of 2.39 $km^3 \cdot a^{-1}$. Notably, this period coincided with a long-term climate fluctuation-induced dry period, with upstream inflow decreasing by approximately 0.8 km^3 compared to the 1960s. From 1986-1999, despite increased upstream inflow, water consumption between stations remained high, and inflow to the delta decreased by 0.95 km^3. After 2000, with significantly increased upstream inflow, mainstem water withdrawal increased slightly, but inflow to the delta remained higher overall.

Factorial analysis results show that Ili River inflow was affected differently by climate change and human activities across periods (Table 3). Before Kapchagay Reservoir construction (pre-1970), human impacts were minor, and inflow was primarily climate-driven. From 1970–1985, reduced upstream inflow due to climate fluctuations entered a dry period, while reservoir impoundment and cultivated land expansion caused sharp increases in Ili River water consumption, leading to severe inflow reduction. Human activities were the main cause of this reduction, contributing 47.47%. During this period, lake level decline rate reached 14 $cm \cdot a^{-1}$, far exceeding the natural decline rate of 9 $cm \cdot a \cdot^{-1}$ recorded since the 20th century, indicating that human activities significantly accelerated lake level decline.

After the Soviet Union' s dissolution in the early 1990s, cultivated land area in Kazakhstan first decreased due to abandonment, then gradually expanded after 2000 to 21,100 km^2. Kapchagay evaporation and irrigation water withdrawal maintained large volumes, but the impact of mainstem water consumption on Ili River inflow weakened after 2000, with contribution rates of about 28.33%. In summary, climate change at the watershed scale dominates long-term Ili River inflow fluctuations, while human activity impacts have intensified since 1970, particularly the 47.47% contribution from reservoir impoundment and evaporation during 1970–1985, which accelerated Lake Balkhash' s water level decline.

Conclusions

Based on 60 years of precipitation, evaporation, inflow, and lake water volume data for Lake Balkhash, this study analyzed the interaction between water income and expenditure and quantitatively assessed influencing factors from lake and watershed scales. The main conclusions are:

(1) From 1961–2020, Lake Balkhash' s water volume first decreased sharply then fluctuated and increased, changing from 1,157.18 km^3 to 1,061.51 km^3. Inflow changes were consistent with lake water volume changes, with average annual surface inflow of 14.04 km^3. Lake surface precipitation was 3.35 $km^3 \cdot a^{-1}$. Lake evaporation was closely linked to area changes, with average annual evaporation of 17.95 km^3. Groundwater replenished the lake in a "wet in, dry out" pattern, with average annual groundwater recharge of 0.52 km^3. Groundwater recharge increased to 2.61 km^3 in the 1980s due to Kapchagay Reservoir interception, while the 1960s and 1970s saw lake water recharging groundwater at 0.93 km^3 and 0.11 km^3, respectively. After the 21st century, groundwater recharge decreased to 0.19 km^3.

(2) At the lake scale, inflow runoff was significantly correlated with Lake Balkhash water volume and represented the dominant factor controlling lake water volume changes. At the watershed scale, climate change was the main factor driving long-term Ili River inflow fluctuations, contribut-

ing 71.67%. Human activities, particularly irrigation water withdrawal and reservoir impoundment since 1970, have increasingly impacted Lake Balkhash' s water volume. The Kapchagay Reservoir impoundment and evaporation from 1970–1985 contributed 47.47% to the sharp reduction in inflow at Uzynaral station, accelerating Lake Balkhash' s water level decline.

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Note: Figure translations are in progress. See original paper for figures.