Characteristics of Water Level Changes in Bosten Lake from 1960 to 2018 and Analysis of Influencing Factors: Postprint

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Abstract

Based on measured data of water level, inflow and outflow runoff, and meteorological station observations for Bosten Lake from 1960 to 2018, a detailed analysis of water level variations and their influencing factors over the past 60 years was conducted using Ensemble Empirical Mode Decomposition (EEMD), water balance, and climate elasticity methods. The results show that: (1) From 1960 to 2018, the water level of Bosten Lake exhibited an overall declining trend, specifically manifested in four stages of "decline-rise-decline-rise". (2) On the interannual scale, the water level displayed quasi-periodic oscillations of 3-4 years and 8-9 years, while on the interdecadal scale it showed periodic variations of approximately 29-30 years and 33-34 years. (3) From 1960 to 2018, the cumulative contribution rates of precipitation, temperature, and potential evapotranspiration to the runoff of the Kaidu River, Huangshui Gully, and Yanqi reached 85.1%, 42.1%, and 23.8%, respectively, while the cumulative contribution rates of underlying surface, other meteorological variables, and anthropogenic factors to runoff were approximately 14.9%, 57.9%, and 76.2%, respectively. (4) Analysis of the causes of water level changes in Bosten Lake at different stages: the main reason for the sharp decline in water level from 1960 to 1987 was related to reduced inflow runoff and large lake surface evaporation; increased temperature and precipitation leading to increased inflow was the main cause of the significant water level rise from 1988 to 2002; reduced inflow runoff and increased outflow water volume led to the significant water level decline from 2003 to 2014; the significant increase in Bosten Lake' s inflow water volume and strict control of outflow water volume were the main reasons for the marked water level rise from 2015 to 2018.

Full Text

Analysis of Water Level Variation Characteristics and Influencing Factors of Bosten Lake from 1960 to 2018

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Abstract

Using measurements of water level, inflow/outflow runoff, and meteorological station data for Bosten Lake from 1960 to 2018, this study employs ensemble empirical mode decomposition (EEMD) and water balance principles to analyze water level trends in detail. The climate elasticity method is used to explore the response of lake water level to hydroclimatic factors across different periods, and the complex response process of lake level to climate change and human activities is analyzed. The results reveal: (1) The water level of Bosten Lake showed an overall significant decreasing trend from 1960 to 2018, specifically characterized by four phases of "descending-rising-descending-rising". (2) EEMD analysis indicates that the water level exhibits quasi 3-4 a and 8-9 a periodic oscillations on interannual scales, and quasi 29-30 a and 33-34 a periodic variations on interdecadal scales. (3) From 1960 to 2018, the cumulative contribution rates of precipitation, temperature, and potential evapotranspiration to runoff in the Kaidu River, Huangshuigou, and Yanqi Basin reached approximately 85.1%, 42.1%, and 23.8%, respectively, while other factors (including underlying surface characteristics and human activities) contributed approximately 14.9%, 57.9%, and 76.2% to runoff changes. (4) Analysis of water level variation causes in different periods shows that: the sharp decline from 1960-1987 was mainly related to reduced inflow runoff and high lake surface evaporation; the significant rise from 1988-2002 resulted from increased inflow due to rising temperatures and increased precipitation; the decrease from 2003-2014 was caused by reduced inflow and increased outflow; and the obvious rise from 2015-2018 was primarily due to significantly increased inflow and strict control of outflow volume.

Keywords: Bosten Lake; water level change; ensemble empirical mode decomposition; water balance; climate elasticity; influencing factors

1. Introduction

Inland lakes in arid regions are among the most sensitive geographic units responding to global climate change and are easily affected by human activities. Both excessively low and high water levels can have adverse impacts. Water levels that are too low lead to wetland area shrinkage, vegetation degradation, biodiversity loss, and fisheries damage, while excessively high levels expand water surface area, intensify soil salinization and agricultural losses, increase food security risks, and can cause flood disasters and socioeconomic losses when exceeding certain ecological thresholds. The causes of lake water level changes are extremely complex, especially for plain lakes in arid areas, which are influenced by geographic characteristics, climate change, glacier cover, and human activities. Therefore, strengthening scientific research on lake changes in arid regions is crucial for understanding water balance and providing guidance for regulating these important water resources.

As the largest inland freshwater lake in China, Bosten Lake has been a focus of many scholars studying water level changes. Previous research using water balance and climate elasticity methods has shown that influencing factors differ significantly across periods. This paper, based on long-term measured data and water balance principles, provides a detailed analysis of water level variation trends and nonlinear processes across different periods. The climate elasticity method is employed to explore the response degree of lake water level to hydroclimatic factors at different stages, aiming to provide scientific support for sustainable water resource utilization and ecological development in the Bosten Lake basin.

1.1 Study Area Overview

Bosten Lake (41°56 N–42°14 N, 86°40 E–87°56 E) is located in southern Xinjiang and is China' s largest inland freshwater lake [Figure 1: see original paper]. The region has a typical inland climate, with a multi-year average temperature of 6.3°C, annual precipitation of only about 70 mm, and potential evaporation of 2000 mm. As a typical throughput lake in Xinjiang, Bosten Lake serves as both the terminal lake of the Kaidu River (one of the four source streams of the Tarim River) and the supply source for the downstream Kongque River. Water sources include the Kaidu River, Huangshuigou, Qingshui River, and numerous small streams from the southern Tianshan slopes, with the Kaidu River and Huangshuigou as the main tributaries, accounting for 84.6% and 9.7% of total inflow, respectively. Bosten Lake functions as a natural reservoir regulating temporal and spatial water distribution in the Kaidu-Kongque River basin and serves as an important water storage facility for the Bayingolin Mongol Autonomous Prefecture, playing vital ecological roles in regulating river runoff and purifying water quality.

1.2 Data Selection

The study utilizes four main datasets: (1) Runoff data: measured annual runoff data from the Dashankou and Baolangsumu stations (Kaidu River), Huangshuigou station, and Tashidian station (Kongque River) provided by the Xinjiang Tarim River Basin Administration. (2) Meteorological data: daily temperature, precipitation, wind speed, evaporation, sunshine hours, and vapor pressure data from 1960–2018 for Bayanbulak, Baluntai, and Yanqi stations obtained from the China Meteorological Data Service Network. (3) Lake water level data: measured annual water level data (1960-2018) and monthly water level data (2000-2018) from the Bosten Lake Administration. (4) Land use data: 1990-2015 land use data from the Resources and Environmental Sciences Data Center of the Chinese Academy of Sciences, with 30 m resolution raster data including 6 primary and 25 secondary land use types. Remote sensing interpretation primarily used Landsat TM/ETM data, updated with Landsat 8 coverage.

1.3 Research Methods

1.3.1 Ensemble Empirical Mode Decomposition (EEMD) EEMD is suitable for analyzing nonlinear and non-stationary time series, effectively extracting trend and periodic information. The method involves adding white noise sequences of given amplitude to the original signal, performing EMD decomposition to obtain intrinsic mode functions (IMFs), and then ensemble averaging multiple decompositions so that the added white noise cancels out:

$$C_j(t) = \frac{1}{N}\sum_{i=1}^{N} C_{ij}(t)$$

where $C_j(t)$ is the jth IMF component of the original signal after EEMD decomposition, N is the number of added white noise sequences, and $C_{ij}(t)$ is the jth IMF obtained from the ith decomposition with added white noise.

1.3.2 Mann-Kendall Trend and Mutation Test The Mann-Kendall test is a nonparametric method for detecting trends in time series. For a time series $x_1, x_2, ..., x_n$, the test statistic S is defined as:

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i)$$

where sgn is the sign function. The standardized test statistic UF_k is calculated as:

$$UF_k = \frac{S - E(S)}{\sqrt{\operatorname{Var}(S)}}$$

where $E(S)$ and $\operatorname{Var}(S)$ are the mean and variance of S. By analyzing runoff from the Kaidu River, Huangshuigou, and Yanqi stations for mutation points, the study divides the time series into pre-mutation baseline and post-mutation periods.

1.3.3 Climate Elasticity Method Based on the climate elasticity method, the elasticity coefficient ε_i of meteorological factors is calculated as:

$$\varepsilon_i = \frac{\Delta Q_i/Q}{\Delta X_i/X_i}$$

where ΔQ_i and X_i are the annual runoff change caused by meteorological factors and the value of different climate variables, respectively. The total runoff change is:

$$\Delta Q = \Delta Q_c + \Delta Q_v$$

$$\Delta Q_c = (\varepsilon_P \Delta P/P + \varepsilon_{ET_0} \Delta ET_0/ET_0 + \varepsilon_T \Delta T/T)Q$$

where ε_i represents the elasticity coefficient of meteorological factors (temperature T, precipitation P, and potential evapotranspiration ET_0); ΔQ, ΔP, ΔET_0, and ΔT are changes in runoff, precipitation, potential evapotranspiration, and temperature; and ΔQ_c and ΔQ_v are runoff changes caused by meteorological factors and other factors (including underlying surface characteristics and human activities).

1.3.4 Water Balance As a throughput lake, Bosten Lake' s water balance equation is:

$$\Delta V = Q_{in} + P_s - E_s - Q_{out} + \Delta V_x$$

where ΔV is the lake water volume change; Q_{in} and Q_{out} are inflow and outflow volumes; P_s is lake surface precipitation; E_s is lake surface evaporation; and ΔV_x is water volume change caused by errors and groundwater exchange.

1.3.5 Potential Evapotranspiration Calculation Potential evapotranspiration data are calculated using the Penman-Monteith formula recommended by the FAO, based on daily meteorological observations:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_0 is reference evapotranspiration; R_n is net radiation; G is soil heat flux; e_s is saturation vapor pressure; e_a is actual vapor pressure; T is air temperature at 2 m height; u_2 is wind speed at 2 m height; Δ is the slope of the saturation vapor pressure curve; and γ is the psychrometric constant.

1.3.6 Lake Surface Evaporation Calculation Annual lake surface evaporation is calculated using the evaporation pan method:

$$E_l = E_{\Phi 20} \times k \times s$$

where E_l is annual evaporation per unit area; $E_{\Phi 20}$ is evaporation measured by a $ $20 mm evaporation pan; k is the lake surface evaporation correction coefficient; and s is lake surface area.

2. Results

2.1 Water Level Changes in Bosten Lake

Mann-Kendall trend test results show that Bosten Lake' s water level exhibited a significant decreasing trend from 1960 to 2018 ($P < 0.01$, -0.08 $m \cdot a^{-1}$), with four distinct phases [Figure 2: see original paper]. From 1960–1987, the water level decreased by nearly 3.2 m at a rate of -0.11 $m \cdot a^{-1}$. From 1988-2002, it rose by nearly 1.9 m at 0.13 $m \cdot a^{-1}$. From 2003-2014, it decreased by nearly 1.2 m at -0.10 $m \cdot a^{-1}$. Since 2015, the water level has risen by nearly 0.45 m at 0.72 $m \cdot a^{-1}$. The lowest (1046.65 m) and highest (1049.36 m) water levels occurred in 1987 and 2002, respectively, differing by 2.71 m.

Intra-annual water level variation shows a bimodal pattern [Figure 2b: see original paper], with the highest levels in July (1046.45 m) and April (1046.43 m), forming high-water periods, and the lowest in January (1045.18 m) and October (1046.10 m), forming low-water periods. In spring, rising temperatures accelerate snow and glacier melt in upstream mountainous areas, increasing downstream runoff and raising lake levels, peaking in April. After April, water level scheduling and surrounding agricultural activities cause levels to decline. Increased precipitation in summer and autumn, combined with complete snow and glacier melt, increases inflow, resulting in the highest levels in July. In winter, minimal upstream inflow from the Kaidu River leaves the lake at its lowest level.

2.2 Multi-scale Variation Characteristics

EEMD decomposition of Bosten Lake' s 1960–2018 water level anomalies yields 6 IMF components and one trend component [Figure 3: see original paper], reflecting fluctuations from high to low frequencies. Period significance tests show that the 29–30 a and 33–34 a scales pass significance tests, indicating these are very significant periodic oscillations . The 3–4 a period is weak, while the 8–9 a period shows quasi-periodic oscillation.

Variance contribution rates reveal that interannual variation accounts for 85.51% of total water level variation, while interdecadal variation contributes 14.49%, indicating that interdecadal oscillations dominate long-term water level changes. Correlation analysis between IMF components and original water level anomalies shows that interdecadal variations correlate significantly with original runoff anomalies. The IMF5 component (29-30 a scale) has the largest variance contribution (83.04%), with obvious oscillations throughout the study period. The IMF3 component represents quasi 8-9 a periodic oscillation, prominent after 1990, contributing 6.88% to total variance. The IMF2 component shows quasi 3-4 a periodic oscillation, contributing 1.68% to variance. The trend component shows a nonlinear decreasing trend over 59 years.

2.3 Water Balance of Bosten Lake

Analysis shows that lake surface evaporation and outflow contributed 65% and 35% to water level decline, respectively [Figure 4: see original paper]. From 1960-1987, inflow and lake surface precipitation showed decreasing trends, while water level dropped 3.24 m and lake volume decreased by 3.10 km^3. From 1988-2002, inflow, precipitation, evaporation, and outflow all increased, with water level rising 1.93 m and volume increasing by 1.98 km^3. From 2003-2014, these factors decreased, causing water level to drop 1.20 m and volume to decrease by 1.02 km^3. From 2015-2018, increased inflow and outflow, combined with decreased precipitation, led to a 0.45 m water level rise and 0.58 km^3 volume increase .

2.4 Influencing Factors

2.4.1 Impact of Meteorological Factors on Runoff Runoff is the dominant factor affecting Bosten Lake' s water level, showing highly consistent variation with lake level changes ($P < 0.01$) [Figure 5: see original paper]. Correlation coefficients between precipitation, temperature, potential evapotranspiration and runoff (P,Q, T,Q, and ET0,Q) indicate that precipitation has the most significant correlation with runoff in both the Kaidu River and Huangshuigou, making it the most critical factor affecting runoff change.

Based on stage changes of meteorological factors and runoff from 1960-2018, climate elasticity coefficients were calculated. For the Kaidu River headwaters: P = 2.91, T = 2.10, and ET0 = -0.85, meaning that 1% increases in precipitation, temperature, and potential evapotranspiration would cause runoff changes of +2.91%, +2.10%, and -0.85%, respectively. For Huangshuigou: P = 2.45, T = 1.91, and ET0 = -0.67.

In the Yanqi Basin, with a catchment area of 4134.2 km^2 and aridity index ($\phi = ET_0/P$) > 5 (typical of arid regions), runoff climate elasticity coefficients are P = 2.31, T = 1.68, and ET0 = -0.72. When precipitation increases by 10%, annual runoff depth increases by 23.1%; when temperature rises 1°C, runoff increases by 1.68%; and when potential evapotranspiration increases by 10%, runoff increases by 7.2%.

From 1990-2002 compared to the baseline period, precipitation increased by 45.05 mm in the Kaidu River basin, 46.61 mm in Huangshuigou, and 11.72 mm in Yanqi, causing runoff depth increases of 20.56 mm, 12.30 mm, and 1.91 mm, respectively. Temperature increases of 1.10°C, 0.97°C, and 0.90°C led to runoff depth increases of 10.40 mm, 3.10 mm, and 1.20 mm. Potential evapotranspiration increases of 65.20 mm, 70.41 mm, and 10.33 mm caused runoff depth decreases of 6.20 mm, 10.33 mm, and 0.90 mm.

Combined effects of precipitation, temperature, and potential evapotranspiration increased Kaidu River runoff depth by 24.76 mm (85.1% of total increase), while other factors contributed 14.9%. In Huangshuigou, meteorological factors contributed 5.07 mm (42.1%), while other factors contributed 57.9%. In Yanqi Basin, meteorological factors directly caused 15.00 mm of runoff change (23.8% of total), while other factors contributed 76.2% [TABLE:4, TABLE:5].

2.4.2 Impact of Human Factors on Water Level Changes From 1960–1987, Baolangsumu inflow accounted for 87.33% of Dashankou runoff, while water consumption reached 12.67% of Dashankou flow, indicating significant impact on Bosten Lake' s water volume . The basin entered a wet period in 1988, with Dashankou runoff peaking at 4.49 km^3 in 2002, when lake level also reached its maximum. However, due to unrestricted water use, the lower Tarim River suffered severe ecological degradation. To restore the downstream "green corridor," an ecological water transfer project was implemented in 2000, transferring water from Bosten Lake to Daxihaizi Reservoir, with total ecological water transfer volume of 1.91 km^3 from 2000–2014, contributing to lake level decline.

Land use data show that from 1990–2015, cultivated land and urban-rural construction land in the Bosten Lake basin increased, with cultivated land growth reaching approximately 30.5% . This land use change alters underlying surface conditions, potentially affecting regional climate and runoff. Since 2015, strict control of outflow has been a major factor in the rapid water level recovery, in addition to increased inflow.

3. Discussion

Sensitivity analysis of Kaidu River runoff to meteorological factors shows that precipitation, temperature, and potential evapotranspiration have cumulative contribution rates of 85.1% to runoff change, with other factors contributing about 14.9%. This is consistent with hydrological sensitivity method results from other studies. The contribution rates differ significantly among meteorological factors, with precipitation being markedly higher than temperature and potential evapotranspiration, similar to findings in the Luanhe River basin.

Wavelet analysis further validates the EEMD decomposition, showing that the 29–30 a scale contributes most to wavelet variance, consistent with interdecadal scales from EEMD, though differing slightly from other studies likely due to different research periods. The longer time series in this study enhances result reliability.

Analysis of regional climate and teleconnections shows that Bosten Lake basin hydrological processes are significantly influenced by the Northern Hemisphere Polar Index and Tibetan High, which affect mid-latitude westerly trough and ridge systems, thereby influencing the basin' s climate.

The main causes of water level changes differ across periods: reduced inflow and high evaporation (1960-1987); climate change-induced increased inflow (1988-2002); reduced inflow and increased outflow (2003-2014); and increased inflow combined with controlled outflow (2015-2018). Runoff is the primary factor causing water level variation cycles.

Evapotranspiration loss significantly impacts water level changes. Lake surface evaporation increases with surface area, especially during warmer months. Coordinating water level and evaporation can reduce water loss and improve utilization efficiency. Since Kaidu River runoff concentrates in summer (June-August), accounting for ~65% of annual flow, water transfer scheduling should prioritize downstream water delivery during peak crop growth and evaporation periods (June-September), while maintaining higher lake levels during low-temperature, low-evaporation periods (November-March) to minimize annual evaporation losses.

4. Conclusions

From 1960-2018, Bosten Lake water level showed an overall decreasing trend, experiencing a "descending-rising-descending-rising"process. Specifically: 1960-1987 decreased at -0.08 $m \cdot a^{-1}$; 1988-2002 increased at 0.26 $m \cdot a^{-1}$; 2003-2014 decreased at -0.10 $m \cdot a^{-1}$; and 2015-2018 increased at 0.72 $m \cdot a^{-1}$, with a total decline of 3.24 m over 59 years.

EEMD analysis reveals quasi 3-4 a periodic oscillations on interannual scales and quasi 29-30 a and 33-34 a periodic variations on interdecadal scales, with particularly pronounced oscillations at the 29-30 a scale. Interdecadal variations dominate long-term water level changes, with the 29-30 a scale contributing 83.04% to total variance.

Meteorological factor sensitivity analysis shows that during 1990-2002, precipitation, temperature, and potential evapotranspiration contributed 85.1% to Kaidu River runoff, 42.1% to Huangshuigou runoff, and 23.8% to Yanqi Basin runoff changes. Other factors contributed 14.9%, 57.9%, and 76.2%, respectively.

Water balance analysis indicates that from 1960-1987, decreased inflow and high evaporation caused water level decline; from 1988-2002, climate change-induced increased inflow drove water level rise; from 2003-2014, decreased inflow and increased outflow led to water level drop; and from 2015-2018, increased inflow and controlled outflow caused water level rise.

In addition to climate change, human activities such as agricultural irrigation and water conservancy projects increasingly influence Bosten Lake water level changes, particularly in the plains below mountain passes and in the Yanqi Basin where human activity is intensive. The Bosten Lake basin water resource system is vulnerable, and while climate change exacerbates water resource uncertainty, human water use will play a key role in the lake’ s future.

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