Stable Hydrogen and Oxygen Isotopes as Indicators of Water Evaporation and Recharge Sources in Dali Lake (Postprint)

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Abstract

To investigate the applicability of the stable isotope mass balance method for water balance calculations in closed inland lakes of cold and arid regions, Dali Lake on the Inner Mongolia Plateau was selected as the study area. Based on analysis of hydrogen and oxygen stable isotope (δD, $ $18O) characteristics in watershed water samples, the indicative significance of δD and $ $18O for water evaporation and recharge sources was discussed. The results demonstrate that during summer, hydrogen and oxygen stable isotope values in Dali Lake water continuously decreased, primarily influenced by precipitation processes; during winter, the freezing process resulted in enrichment of hydrogen and oxygen isotopes in the ice. The $ 18*O*− $D relationship points for Dali Lake water plot to the lower right of the local meteoric water line, indicating the most intense evaporation in the lake area; the $ 18*O*− *Drelationshippointsforsomeriverwaterandgroundwaterplottotheupperleftofthelocalmeteoricwater*
and annual groundwater recharge of approximately 1.65$×10⁸*m*^{3}$. Under conditions accounting for kinetic fractionation and the isotopic composition of the initial water body, and utilizing the relationship between δD and the proportion of remaining water during water stable isotope fractionation, it was calculated that evaporative water loss from Dali Lake was approximately 41%-46% of the initial water body.

Full Text

Indication of Hydrogen and Oxygen Stable Isotopes on Water Evaporation and Recharge Sources in Dali Lake

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Abstract

This study investigated the applicability of the stable isotope mass balance method for calculating water balance in closed inland lakes of cold and arid regions, using Dali Lake on the Inner Mongolia Plateau as the study area. Based on the analysis of hydrogen and oxygen stable isotope (δD, $ $18O) characteristics in watershed water samples, we examined the indicative role of δD and $ $18O in water evaporation and recharge sources. The results demonstrated that the stable isotopic values of Dali Lake water continuously decreased during summer, primarily influenced by precipitation processes. During winter, the freezing process enriched hydrogen and oxygen isotopes in the ice. The δD-$ $18O relationship for lake water plotted to the lower right of the local meteoric water line, indicating the most intense evaporation in the lake area. Some river water and groundwater δD-$ 18*Orelationshippointsfellabovethelocalmeteoricwaterline*, *suggestingthatlocalatmosphericprecipitationw*
m^3 and an annual groundwater recharge of about 1.65$×10^{8}$ m^3. Under consideration of kinetic fractionation and the initial isotopic composition of water bodies, the relationship between δD and the proportion of residual water during stable isotope fractionation indicated that evaporative loss from Dali Lake amounted to approximately 41%-46% of the initial water body.

Keywords: hydrogen and oxygen stable isotopes; evaporation; recharge; Dali Lake

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1. Study Area and Methods

1.1 Study Area Overview Dali Lake (43°12 -43°24 N, 116°24 -116°45 E) is located in Hexigten Banner, central-eastern Inner Mongolia, at an elevation of 1226 m. Situated on the northern edge of the East Asian summer monsoon, the lake experiences a temperate continental monsoon climate. As a typical grassland inland lake, Dali Lake receives surface water and atmospheric precipitation inputs primarily during summer, while groundwater recharge dominates in winter. With a relatively simple hydrological cycle, it represents an ideal region for studying the applicability of stable isotope methods for estimating lake water balance in inland closed lakes. The lake is semi-saline, fed by the Gongger River, Shali River, Liangzi River, and Haolai River, with spring water inflow in the southwestern area and no outflow. The annual average temperature is approximately 1.4°C, with the number of days below -36.7°C accounting for 51.7% of the year. The lake is covered by ice and snow from mid-November to the following year, with a freezing period reaching 189 days. The annual precipitation is 253 mm, while the annual evaporation measured by a standard evaporation pan reaches 1437 mm.

1.2 Sample Collection Sampling sites were established considering Dali Lake' s area, water depth variations, and the distribution of estuary locations.

Using a GPS receiver, 12 sampling points were deployed in the lake area, designated as DL-1, DL-2, ···, DL-12. Specifically, one sampling point was placed at each lake inlet (DL-1, DL-2, DL-3, DL-4), one near the shore (DL-11, DL-12), and the remaining points were distributed in the central lake area according to depth differences. River water sampling points were established 500 m upstream from the estuary of the Gongger River, Shali River, Liangzi River, and Haolai River. Groundwater was represented by well water and spring water based on proximity to the lake area, totaling 10 sampling points.

Samples were collected during the non-freezing period (May–October 2018) for lake surface water, inflowing river water, and groundwater, as well as during the freezing period (January 2019) for lake surface water and ice samples. Summer lake water samples were collected directly at sampling points using a water sampler from a boat, with three samples collected each time for a total of 36 samples. During winter, lake water samples were collected after drilling through the ice, with one ice sample and one water sample collected per site, yielding 12 ice samples and 12 water samples. Groundwater samples totaled 30, and river water samples numbered 24. All samples were stored in 50 mL polyethylene bottles after rinsing three times with the original water, then sealed and refrigerated before isotopic analysis. Additionally, atmospheric precipitation was collected using a standard rain gauge, yielding 12 precipitation samples.

1.3 Methods

1.3.1 Water Balance Equation and Isotope Mass Balance Equation

Based on the hydrogen isotopic composition of water bodies, we applied the stable isotope mass balance equation (assuming the lake is well-mixed and maintains a constant volume over the long term) to estimate lake evaporation. The lake water balance equation and isotope mass balance equation are as follows:

$$\frac{dV}{dt} = I - Q - E \quad (1)$$

$$\frac{d(V\delta_L)}{dt} = I\delta_I - Q\delta_Q - E\delta_E \quad (2)$$

where I is the inflow to the lake, Q is the outflow, E is lake evaporation, and δ represents the stable isotopic values of inflow water, outflow water, and evaporating vapor, respectively.

The isotopic composition of evaporating water vapor δ_E was calculated using the Craig-Gordon open-water evaporation model:

$$\delta_E = \frac{\delta_L - h\delta_A - \varepsilon_k}{1 - h + \varepsilon_k/10^3} \quad (3)$$

where δ_L is the isotopic composition of lake water, h is relative humidity over the water surface, α^+ is the equilibrium fractionation factor for hydrogen isotopes, $^+$ is the equilibrium separation factor, _k is the kinetic fractionation coefficient, and δ_A is the hydrogen isotopic composition in the atmosphere.

Temperature is the primary factor controlling hydrogen and oxygen isotope fractionation during Rayleigh equilibrium fractionation. The equilibrium fractionation coefficient α^+ and separation factor $^+$ for hydrogen are temperature-dependent. Based on Horita’ s relationship between hydrogen equilibrium fractionation coefficient and temperature, we derived experimental values:

$$\ln(\alpha^+) = \exp\left(\frac{1158.8T^3}{10^9} - \frac{1620.1T^2}{10^6} + \frac{794.84T}{10^3} - 0.16104 + \frac{2999200}{T^2}\right) \quad (4)$$

$$\varepsilon^+ = (\alpha^+ - 1) \times 1000 \quad (5)$$

The kinetic fractionation coefficient _k is related to relative humidity h and boundary layer conditions through the function: _k = C_k(1 - h), where C_k is the kinetic constant (C_k = 12.5‰). Using this formula, we calculated Dali Lake’ s kinetic fractionation coefficient as 3.8‰.

The atmospheric hydrogen isotopic composition δ_A was calculated using:

$$\delta_A = -0.11 + 5.17 \times \text{Precipitation} \quad (6)$$

where precipitation is the annual precipitation amount (253 mm).

As Dali Lake is a terminal lake, outflow is negligible, and water loss occurs primarily through evaporation. Recharge sources include river water, groundwater, and atmospheric precipitation. Therefore, lake evaporation E and groundwater recharge I_g can be calculated as:

$$E = P + I_s + I_g - \Delta V \quad (7)$$

$$I_g = \frac{E\delta_E - P\delta_P - I_s\delta_s}{\delta_g - \delta_E} \quad (8)$$

where P is precipitation, I_s is surface water inflow, I_g is groundwater inflow, δ_P is the weighted average hydrogen isotopic composition of annual precipitation (‰), δ_s is the weighted average hydrogen isotopic composition of inflowing river water (‰), and δ_g is the mean hydrogen isotopic composition of groundwater around Dali Lake (‰).

1.3.2 Residual Water Fraction from Evaporation Under Rayleigh equilibrium evaporation conditions, the hydrogen and oxygen stable isotopic composition of residual water follows the Rayleigh fractionation model relative to the ratio of residual water to original water:

$$\delta = \delta_0 + (\alpha - 1) \ln f \quad (9)$$

where δ_0 is the initial isotopic composition of the water body, and f is the fraction of residual water.

Natural evaporation fractionation differs from ideal equilibrium fractionation. Studies show that water evaporation is influenced by both equilibrium and kinetic fractionation, with kinetic fractionation producing greater isotopic effects than equilibrium fractionation. Therefore, kinetic fractionation must be considered in actual water evaporation processes.

1.3.3 Isotope Mixing Model River water in the Dali Lake watershed is jointly recharged by groundwater and atmospheric precipitation. We employed a binary mixing model to distinguish contributions from different sources:

$$\delta_R = f_g \delta_g + (1 - f_g) \delta_P \quad (10)$$

where δ_R is the river water isotopic composition, δ_g is the groundwater isotopic composition, δ_P is the precipitation isotopic composition, and f_g is the proportion of groundwater source.

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2. Results

2.1 Temporal and Spatial Variation Characteristics of Hydrogen and Oxygen Isotopes in Water Bodies Affected by recharge and evaporation processes, the hydrogen and oxygen isotopic composition of water bodies varies with time due to differences in precipitation and evaporation across different periods. Comparing lake water isotope samples collected during summer 2018 revealed a continuously decreasing trend in oxygen isotope values, with relatively large differences between June and July, while August and September showed similar compositions. Hydrogen isotopes exhibited similar overall trends (Fig. 2). During summer, Dali Lake's isotopic composition showed a temporal pattern of continuous decrease, accompanied by concentrated precipitation in July and August, while groundwater recharge remained relatively constant throughout the year. This indicates that summer precipitation processes in July–August had a dilution effect on lake water, demonstrating the influence of precipitation on regional water isotopic composition.

Isotopic fractionation occurs during water freezing, enriching δD and \$ \$18O in ice. In Dali Lake ice, δD values were approximately 8.2‰ heavier than in underlying water, while $ $18O values were about 1.1‰ heavier. The differences in stable isotopes between ice and underlying water illustrate the impact of freezing on lake water. Variations in water depth and isotopic enrichment degree at different sampling sites created differences in fractionation extent. For example, the difference between ice and water at DL-12 (ice δD value minus water δD value) was 7.8‰, while at DL-1 it was 9.1‰; the ice-water difference for $ $18O at DL-12 was 1.0‰, and at DL-1 it was 1.3‰. Overall, however, the same pattern emerged: δD and $ $18O were enriched in ice compared to water.

Comparing ice and water samples from frozen and non-frozen periods, ice samples showed the most enriched hydrogen and oxygen stable isotopic composition. Meanwhile, water samples from the frozen period had isotopic compositions most similar to those from the non-frozen period, with July samples showing relatively depleted isotopic composition.

Comparing isotopic compositions of Dali Lake’ s recharge water sources across different months revealed that atmospheric precipitation in July had the most depleted values, coinciding with the maximum precipitation amount and demonstrating a clear atmospheric precipitation dilution effect. Groundwater composition was relatively complex and requires further investigation.

2.2 Relationships of Hydrogen and Oxygen Isotopic Composition in Water Bodies By fitting the δD-$ $18O relationship in atmospheric precipitation samples from the Dali Lake watershed, we established the local meteoric water line (LMWL). Analyzing the δD-$ $18O relationships in river water, groundwater, and lake water samples revealed that most groundwater and river water sample points fell below the global meteoric water line (GMWL), with some river water points falling to the lower right of the GMWL (Fig. 4), primarily due to evaporation enrichment. Lake water δD-$ $18O points all fell to the lower right of both the GMWL and the local evaporation line, indicating the strongest evaporation effects. Additionally, the δD-$ $18O values of atmospheric precipitation in the Dali Lake watershed showed relatively small variation ranges. River water δD-$ $18O values were distributed to the lower left of the GMWL, with more depleted values, indicating that lake water experienced much greater evaporative fractionation than river water. Clearly, evaporation intensity differed between frozen and non-frozen periods. Summer lake water samples showed that July samples were significantly influenced by precipitation, causing depletion of hydrogen and oxygen stable isotopes. After July, as precipitation decreased sharply and lake evaporation intensified, lake water isotopes became progressively enriched, with evaporation exerting a clear influence on isotopic deviation. When precipitation undergoes evaporation, residual water follows the evaporation line distribution. During infiltration, δD and $ $18O become enriched through evaporation and water-rock interaction. If groundwater originates from local precipitation, its δD-$ $18O relationship should fall on or below the local meteoric water line. However, most river water and groundwater points in the Dali Lake watershed fell above the local meteoric water line, and atmospheric precipitation weighted averages were significantly enriched compared to groundwater and river water, indicating that local atmospheric precipitation is not their primary recharge source.

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3. Discussion

3.1 Calculation of Evaporation and Recharge in Dali Lake Based on 2018 data showing precipitation of approximately 253 mm, river inflow of 20 mm, and pan evaporation of 1437 mm, we calculated Dali Lake’ s unit area annual evaporation as 1422 mm by substituting coefficients into equation (7). The total annual evaporation volume was 2.69$×10^{8}$ m^{3}, with a groundwater recharge of 1.65$×10^{8}$ m^{3} (accounting error of 15 mm). This demonstrates that estimating Dali Lake’ s evaporation using the hydrogen-oxygen isotope mass balance method is feasible. Groundwater recharge accounts for 872 mm, representing about 61% of total lake supply, confirming groundwater as the main recharge source.

3.2 Relationship Between Water Body Isotopic Composition and Residual Water Although Dali Lake receives recharge from groundwater, river water, and atmospheric precipitation, and its isotopic composition is affected by local precipitation, most groundwater and river water does not originate from local atmospheric precipitation (Fig. 4). Therefore, quantifying the differential contributions of various recharge sources is necessary to identify the main controlling factors of lake water balance.

Dali Lake’ s stable isotopic values show minimal interannual variability, with relatively uniform mixing and small lake area fluctuations. The lake area was approximately 189 km^{2} in 2018, with annual variation less than 5%, maintaining relatively stable water volume—conditions that satisfy the stable isotope mass balance method requirements. Using this method, we estimated lake evaporation and groundwater recharge. The initial isotopic composition of evaporating water is generally determined by the intersection of the local precipitation line and evaporation line, yielding an initial hydrogen isotopic composition δ_0 of -62‰. However, the measured minimum groundwater hydrogen isotope value was -87‰, which we assumed represents unevaporated groundwater. Different initial δD values inevitably affect estimates of lake water evaporation.

Assuming local atmospheric precipitation as the main water source, residual lake water would be 0.60-0.64 of the initial water, representing a loss of 36%-40% of the initial volume. However, most river water showed evaporation degrees less than zero, indicating that local precipitation is not their primary source. Using the minimum groundwater isotope value as the initial composition, residual lake water was 0.54-0.59 of the initial volume, representing a 41%-46% loss. Since lake isotopic composition is clearly influenced by local precipitation, this calculated loss may be overestimated. Given that groundwater is Dali Lake’ s main recharge source, the actual evaporative loss is likely about 41%-46% of the initial water body, a relatively reliable estimate. This approach—using the relationship between lake water hydrogen-oxygen stable isotopic composition and residual water proportion to calculate evaporative loss—may provide an effective method for assessing water body evaporation extent.

3.3 Analysis of Groundwater and River Water Recharge Relationships in Dali Lake Watershed Isotopic characteristics of Dali Lake' s recharge water show that river water is affected by atmospheric precipitation but has more depleted δD-$ $18O values, indicating precipitation is not its main source. Compared with groundwater, river water shows similar stable isotopic values, suggesting possible interconversion between river water and groundwater. Hydrochemical studies of the Dali Lake watershed indicate that river water and groundwater are primarily controlled by rock weathering, with atmospheric precipitation playing a very weak role, further supporting groundwater recharge to rivers.

When the isotopic values of river water, groundwater, and atmospheric precipitation are known, the isotope mixing model can determine the proportion of river water derived from groundwater. Among different rivers, the Gongger River accounts for 70-87% of total river recharge, the Liangzi River for 10-20%, and the remaining two rivers for only 3-10%. Thus, the Gongger and Liangzi Rivers are Dali Lake' s main river recharge sources. Analysis shows groundwater accounts for 68-81% of river water recharge, making it an important source. Dali Lake' s groundwater recharge is 1.65$×10^{8}$ m^3, accounting for 61% of total lake supply. Considering groundwater' s recharge role, its contribution to Dali Lake' s water balance becomes even more critical.

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4. Conclusions

1) Summer water bodies in the Dali Lake watershed were affected by precipitation processes to varying degrees, with hydrogen and oxygen stable isotopic compositions showing significant temporal and spatial variations. Lake water isotopic values continuously decreased during summer, with inflowing rivers showing similar trends, while groundwater composition changed minimally. The winter freezing process enriched hydrogen and oxygen stable isotopes in ice. Based on δD-$ $18O relationship characteristics across different water bodies, Dali Lake water experienced the strongest evaporation, and local atmospheric precipitation may not be the primary recharge source for groundwater.
2) Building on qualitative analysis of Dali Lake' s hydrological processes, we quantitatively calculated evaporation using the stable isotope mass balance method. The 2018 evaporation was approximately 1422 mm (2.69$×10^{8}$ m^3). Groundwater is the main recharge source for Dali

Lake, with recharge of about 1.65$×10^{8}$ m^{3}, accounting for approximately 61% of total supply.

3) Considering the lake' s main recharge sources, residual lake water was about 0.41–0.46 of the initial water body. This result is relatively reliable. Using the relationship between lake water hydrogen-oxygen stable isotopic composition and residual water proportion to calculate evaporative loss may be an effective method for assessing water body evaporation extent.

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