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Stable Isotope Tracing of Water Sources and Recharge Contributions to Qinghai Lake, Northeastern Qinghai–Tibet Plateau

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Abstract

To elucidate the recharge relationships and hydrological processes among different water bodies in the Qinghai Lake Basin, precipitation, river water, groundwater, and lake water samples were collected from April to November 2024. The hydrogen and oxygen stable isotope compositions (δ^2H and $\delta^{18}O$) were determined to characterize their spatiotemporal variations, and the MixSIAR model was applied to quantitatively evaluate the recharge contributions among different water bodies. The results show significant differences in stable isotope compositions among the various water bodies. Overall, lake water exhibited the most enriched isotopic signatures, whereas groundwater was the most depleted and isotopically stable, while precipitation displayed the largest variability. Precipitation isotopes exhibited pronounced seasonal effects. River water showed a depletion–enrichment–depletion pattern, reflecting the important recharge contributions from wet season precipitation and frozen-soil meltwater. Groundwater exhibited relatively weak seasonal variations and a distinct smoothing effect. In contrast, the isotopic composition of lake water was jointly controlled by evaporative fractionation and multiple recharge sources, with the highest enrichment occurring in spring and gradual depletion during wet season and dry season. Spatially, significant isotopic differences were observed among rivers. Groundwater was relatively enriched in the western part of the basin and depleted in the eastern part, whereas lake water exhibited an opposite pattern, characterized by enrichment in the east and depletion in the west. The Local Meteoric Water Line (LMWL) of the Qinghai Lake Basin was defined as $\delta^2H = 8.07\delta^{18}O + 37.48$ ($R^2 = 0.96$). Both the slope and intercept were higher than those of the Global Meteoric Water Line (GMWL), indicating that locally recycled evaporated moisture played an important role in regional precipitation formation. The river water line showed characteristics similar to those of the groundwater line, suggesting strong hydraulic connectivity between river water and groundwater. In contrast, the lake water line deviated markedly from the meteoric water line, indicating significant evaporative fractionation of lake water. The MixSIAR results indicate that the contributions of river water, groundwater, and precipitation to lake water were 37.5%, 33.9%, and 28.6%, respectively. These findings reveal the complex hydrological connections and transformation processes among multiple water bodies in the Qinghai Lake Basin and provide a scientific basis for water resource management and ecological environmental protection in inland basins of the Qinghai–Tibet Plateau.

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Keywords: Qinghai Lake Basin; hydrogen and oxygen stable isotopes; different water bodies; MixSIAR model; the Tibetan Plateau

1. Introduction

Water is an indispensable resource for the survival and development of human civilization, and the hydrological cycle and water balance represent fundamental issues in physical geography research [1]. With the intensification of global climate change and human activities, hydrological processes and water body distributions worldwide have undergone substantial alterations [2]. According to the Blue Book on Climate Change in China (2024), both the mean annual precipitation and surface air temperature in China exhibited significant increasing trends during 1961–2023, with surface air temperature increasing by 0.30 °C per decade and annual precipitation increasing by 5.2 mm per decade [3]. Under the intensified warm–humid climate trend over the Tibetan Plateau [4], atmospheric circulation patterns have also undergone significant changes [5], substantially influencing regional hydrological processes. As a climatically sensitive region on the Tibetan Plateau, the Qinghai Lake Basin has experienced pronounced hydrological responses to enhanced plateau monsoon activity, weakened westerly circulation, and regional warming and humidification. In addition, vegetation recovery, permafrost degradation, and increased runoff within the basin have further altered the regional water cycle. Consequently, the water level of Qinghai Lake exhibited a transition from a declining trend to a rising trend around 2004 [6]. In recent years, precipitation, evaporation, and runoff within the Qinghai Lake Basin have all increased, accompanied by a continuous rise in lake water level. The persistent expansion of Qinghai Lake has attracted considerable attention regarding its water sources and the underlying driving mechanisms. Therefore, systematic investigations of stable hydrogen and oxygen isotopes in different water bodies across the basin, together with quantitative assessment of the relative contributions of different recharge sources to lake water, are of great significance for improving the understanding of regional hydrological cycling processes.

Stable isotopes have become ideal tracers for investigating hydrological cycling processes and provide valuable insights into key issues such as water sources, flow pathways, and transformation processes [7,8]. Stable water isotopes in natural waters, including $^{1}H_{2}{}^{18}O$ and $^{1}HD^{16}O$, although occurring in relatively low abundances, are highly sensitive to environmental changes [9]. During hydrological cycling and water transformation processes, isotopic fractionation occurs, resulting in differences in isotopic compositions among various water bodies. Mixing models based on stable isotope data and isotope mass balance principles have been widely applied in hydrological studies and source apportionment analyses, providing an effective approach for quantitatively identifying the interactions and transformation relationships among different water bodies [10]. However, traditional isotope mixing models exhibit limitations in accounting for isotopic fractionation effects, end-member uncertainty, and spatiotemporal variability, making it difficult to effectively quantify uncertainties in source contributions. The Bayesian mixing model MixSIAR incorporates a probabilistic framework that simultaneously considers multiple sources of uncertainty, including isotopic fractionation, end-member variability, and observational errors, while integrating prior information to generate robust estimates of source contributions. This approach substantially improves the reliability and interpretability of the results [11] and provides methodological support for quantitatively resolving water transformation processes in complex hydrological systems [12]. In recent years, studies based on Bayesian mixing models have increasingly focused on the interactions and con-

version proportions among different water bodies, including precipitation, surface water, groundwater, and cryospheric meltwater. For example, Pei et al. [13] systematically investigated the isotopic characteristics of precipitation, surface water, and groundwater in the Inner Mongolia region of the Yellow River Basin and clarified the transformation mechanisms and hydraulic connections among different water bodies. Hao et al. [14] quantified the contributions of different water sources to lake water based on δ^2H and $\delta^{18}O$ data, demonstrating that lake water was primarily controlled by atmospheric precipitation recharge, while significant hydraulic connectivity existed between groundwater and river water. Liu et al. [15] quantified the potential water sources of river runoff under different permafrost conditions over multiple years, further revealing the regulatory effects of underlying surface conditions on runoff generation processes.

Current studies in the Qinghai Lake Basin have primarily focused on individual subbasins, with research topics involving stable isotopes of different water bodies [16–18], hydrological recharge relationships [19], and atmospheric moisture recycling processes [20]. The investigated water bodies include precipitation [16], river water [19], soil water [17], and groundwater [20,21]. However, existing studies have largely concentrated on individual water bodies, with limited efforts devoted to systematically quantifying the integrated relationships among precipitation, surface water, groundwater, and lake water. Against the background of regional warming and humidification, the dynamic variations in source contributions from different water bodies and their driving mechanisms remain poorly understood. Accordingly, this study systematically collected precipitation, river water, groundwater, and lake water samples across the Qinghai Lake Basin and analyzed their hydrogen and oxygen stable isotopes in combination with meteorological data. The study aimed to characterize the isotopic compositions and spatiotemporal variations in different water bodies and to quantitatively investigate the transformation relationships among multiple water bodies within the basin using a Bayesian mixing model. In particular, the relative contributions of different water sources to Qinghai Lake recharge were quantitatively identified. This study seeks to fill the current research gap in quantitative multi-water-body analysis in the Qinghai Lake Basin and provide new scientific insights into hydrological cycling processes and regional water resource changes in alpine inland basins.

2. Materials and Methods

2.1. Study Area

The Qinghai Lake Basin is located in the northeastern Tibetan Plateau, extending from 36°15′ to 38°20′ N and from 97°50′ to 101°20′ E, with a total drainage area of approximately 29,661 km^2. The basin is characterized by a topography that is higher in the northwest and lower in the southeast, with surrounding mountain ranges generally exceeding 4000 m in elevation. Natural geographical elements within the basin, including landforms, climate, and soils, exhibit an approximately concentric zonal distribution from the lake basin toward the surrounding mountainous regions. Annual precipitation in the basin ranges from 291 to 579 mm, with pronounced seasonal variability. Most precipitation occurs between May and September, resulting in distinct wet and dry seasons. Located within the semi-arid region of the Tibetan Plateau, the Qinghai Lake Basin belongs to an inland drainage system. Most rivers originate from the surrounding high mountains and ultimately discharge into Qinghai Lake. There are 33 rivers with drainage areas exceeding 50 km^2 within the basin, among which the major tributaries include the Buha River, Shaliu River, Hargai River, Quanji River, Heima River, Daotang River, and Ganzi River. The river network distribution is markedly asymmetric across the basin. The western and northern regions are relatively extensive, with dense river networks and high runoff volumes, whereas the southeastern region is comparatively narrow, characterized by sparse river networks, lower runoff, and

predominantly seasonal rivers. Qinghai Lake is the largest inland saline lake in China. Compared with the surrounding rivers, the initial freezing and complete freeze-up dates of Qinghai Lake occur relatively later, and the ice-cover duration is comparatively shorter, with a multi-year average ice-cover period of approximately 112 days. The lake water level reached its lowest recorded elevation of 3192.86 m in 2004, after which it continuously increased, reaching 3197.3 m by 2025.

2.2. Sample Collection

The distribution of sampling sites in this study is shown in Figure 1. Sampling was conducted during the ice-free period of Qinghai Lake from April to November 2024. Precipitation samples were collected at the Qinghai Lake National Wetland Ecosystem Observation and Research Station (37.0368° N, 99.7391° E). Precipitation sampling followed the meteorological definition of a precipitation event, whereby all precipitation occurring from 20:00 on one day to 20:00 on the following day was considered a single event and collected as one sample. Precipitation samples were collected using a self-designed precipitation collector consisting of a funnel and a conical flask. After each precipitation event, water samples were transferred into 60 mL HDPE amber reagent bottles. River water, groundwater, and lake water samples were collected at 10-day intervals, resulting in a total of 21 sampling campaigns. River water samples were collected from the major first-order tributaries discharging into Qinghai Lake, including the Buha River, Heima River, Daotang River, Ganzi River, Hargai River, Shaliu River, and Quanji River. River water was sampled at river mouths using a telescopic water sampler at a depth of 5–10 cm below the water surface under relatively stable flow conditions. Groundwater and lake water sampling sites were uniformly distributed around Qinghai Lake. A total of eight groundwater sampling sites (G1–G8) and seven lake water sampling sites (L1–L7) were established. All water samples were stored in 60 mL HDPE amber reagent bottles, sealed with Parafilm to prevent evaporation, and refrigerated at −4 °C prior to laboratory analysis. During the frozen period of Qinghai Lake (December to March of the following year), effective sampling could not be conducted because both the rivers and the lake were frozen. Therefore, this study focused only on the stable isotope characteristics and hydrological recharge relationships during Normal-flow season (April–May 2024), wet season (June–August 2024), and dry season (September–October 2024).

2.3. Sample Processing and Analysis

All samples were sealed immediately after collection and transported to the laboratory for low-temperature storage. Due to the relatively high salinity of lake water samples, water extraction was performed prior to isotope analysis using an automated vacuum condensation extraction system (LI-2100, LICA Inc., Beijing, China) to avoid isotopic fractionation during pretreatment. The extracted water samples were transferred into 2 mL sample vials and sealed with Parafilm prior to analysis. Before measurement, all samples were filtered through 0.22 μm membrane filters and analyzed using a liquid water isotope analyzer (TLWIA-912, LGR Inc., Mountain View, CA, USA). During the analytical process, three standard samples were used for calibration, and measurements were conducted in a sequence of three unknown samples following each standard. Each analytical cycle consisted of 12 injections (3 standards and 9 samples), totaling 72 injections. At the end of each cycle, calibration curves were generated based on the standard samples to correct the measured values. Each sample was injected six times, with the first two injections discarded to eliminate potential memory effects. The average of the remaining four injections was used as the final isotopic value.

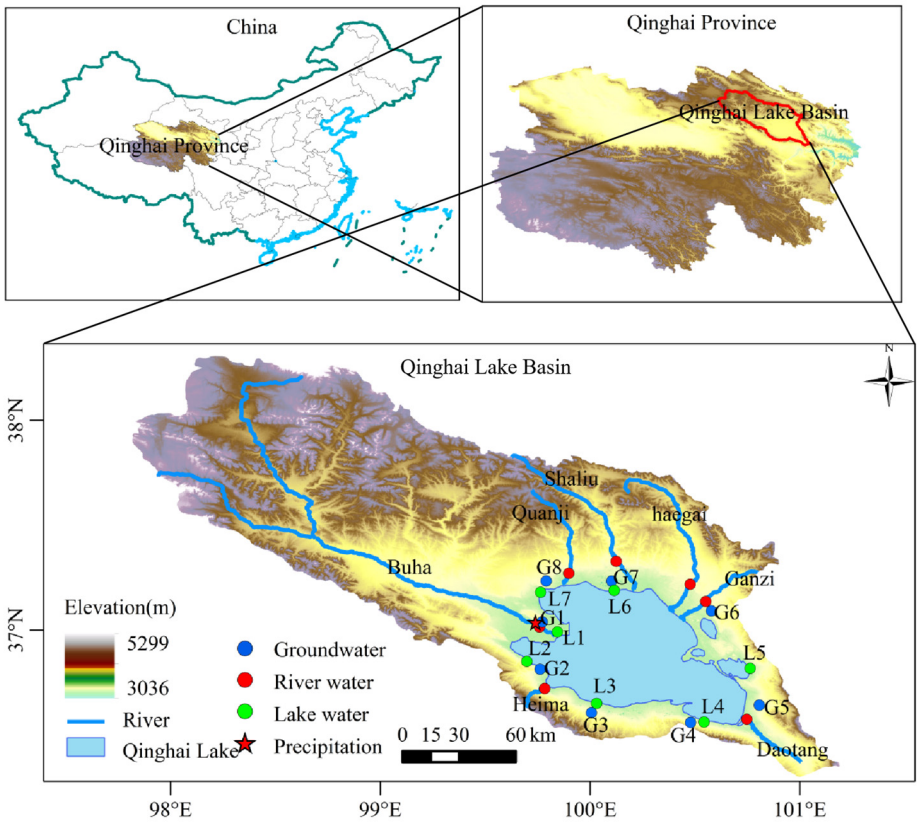

Figure 1. Qinghai Lake Basin and the distribution of sampling points.

The isotopic compositions of all water samples were expressed in per mil (‰) relative to the Vienna Standard Mean Ocean Water (V-SMOW) standard [22]. The analytical precision values for $\delta^{18}O$ and $\delta^{2}H$ measurements were ±0.025‰ and ±0.1‰, respectively. The isotopic composition was calculated using the following equation:

$$\delta_{sample} = \frac{R_{sample} - R_{V\text{-}SMOW}}{R_{V\text{-}SMOW}} \times 1000‰ \quad (1)$$

where R_{sample} and $R_{V\text{-}SMOW}$ represent the hydrogen or oxygen isotope ratios in the water sample and the standard solution, respectively.

2.4. D-Excess

D-excess is an important parameter characterizing the isotopic composition of $\delta^{2}H$ and $\delta^{18}O$ in water bodies and is closely related to evaporative fractionation processes. Lower d-excess values generally indicate stronger evaporative enrichment effects [23]. The d-excess value is calculated as follows:

$$\text{d-excess} = \delta^{2}H - 8\delta^{18}O \quad (2)$$

2.5. MixSIAR Model

To quantitatively estimate the contributions of different water sources to mixed water bodies, the Bayesian isotope mixing model MixSIAR was employed in this study. MixSIAR is a stable isotope-based source apportionment model that assumes the water composition of a mixed water body is derived from multiple source end-members. By comparing the hydrogen and oxygen stable isotopic compositions of mixed water bodies with those of

potential source waters, the model quantitatively estimates the proportional contributions of different water sources to the mixed system. The model can be expressed as follows:

$$X_{ij} = \sum_{k=1}^{k} P_k \left(S_{jk} + C_{jk} \right) + \varepsilon_{ij} \quad (3)$$

$$S_{jk} \quad N\left(\mu_{ij}, \omega_{jk}^2 \right) \quad (4)$$

$$C_{jk} \quad N\left(\lambda_{jk}, \tau_{jk}^2 \right) \quad (5)$$

$$\varepsilon_{ij} \quad N\left(\sigma_j^2 \right) \quad (6)$$

where X_{ij} represents the stable isotope value j of the mixed water body i (i = 1, 2, 3, . . ., N: j = 1, 2, 3, . . ., J), Pk denotes the proportional contribution of source k to the mixed water body; and S_{jk} is the isotopic ratio of isotope j in source k, where μ represents the mean value and ω is the standard deviation. C_{jk} is the isotopic fractionation factor of isotope j for source k, where λ and τ denote its mean and standard deviation, respectively; ε denotes the residual error term. which is generally assumed to have a mean and standard deviation of 0 [24].

The MixSIAR model can estimate the posterior probability distributions of source contributions while accounting for uncertainty in source end-members and variability in the mixing process, thereby overcoming the limitation of traditional linear mixing models that provide only a single deterministic solution. Based on the hydrological processes in the study area, precipitation, river water, and groundwater were defined as three potential end-members. The δ^2H and $\delta^{18}O$ data for each end-member were derived from the observed samples, and their statistical distributions were characterized using the mean and standard deviation. To evaluate the discriminability of the end-members, the degree of overlap among the isotope distributions of different water types was examined, together with their distributions in the δ^2H–$\delta^{18}O$ bivariate space. When some degree of overlap existed among the end-members, MixSIAR accounted for this overlap by incorporating uncertainty in the source distributions, thereby avoiding systematic biases associated with forcing complete separation among end-members. Therefore, the end-member classification in this study was considered statistically acceptable. In the model, lake water was defined as the mixture, while precipitation, river water, and groundwater were specified as source end-members, based on the following mass-balance relationships: isotope compositions were assumed to follow linear mixing, and the contributions of all sources were constrained to sum to one. Thus, the model simulations primarily represented the "apparent mixing relationships" during the observation period. In addition, no informative prior information was specified in the model; instead, uniform priors were adopted so that the results were primarily driven by the observed data, thereby minimizing the influence of subjective assumptions. For uncertainty assessment, the MixSIAR model was implemented within a Bayesian framework, with the posterior probability distributions of all model parameters constituting the core outputs. In this study, the posterior means, standard deviations, and 95% credible intervals were used to comprehensively characterize the uncertainty of the model results. Furthermore, sensitivity analyses, including perturbation of end-member data and removal of outliers, were conducted to further evaluate the response of model outputs to changes in input conditions, thereby assessing the robustness and reliability of the results [24].

3. Results

3.1. Characteristics of Stable Isotopes in Different Water Bodies

The ranges of δ^2H, $\delta^{18}O$, and d-excess values for different water bodies in the Qinghai Lake Basin are presented in Figure 2. During the study period, a total of 66 precipitation events were recorded in the basin, with precipitation occurring predominantly during the wet season. The δ^2H values of precipitation ranged from −108.65‰ to 14.34‰, with a mean value of −38.31‰, whereas $\delta^{18}O$ values ranged from −17.53‰ to −2.01‰, with a mean value of −9.39‰. The large isotopic variability indicates that precipitation isotopes are highly sensitive to changes in climatic conditions and moisture sources. The Qinghai Lake Basin is located in a cold semi-arid climatic region, where annual evaporation substantially exceeds precipitation [25]. Consequently, precipitation is prone to pronounced evaporative fractionation during both its formation and descent processes. The d-excess values of precipitation ranged from 15.67‰ to 50.66‰, with a mean value of 36.82‰. Deuterium excess in precipitation is closely related to the temperature and humidity conditions of moisture source regions and is also influenced by secondary evaporation during raindrop descent [23]. The d-excess values observed in the study area were consistently higher than the global average of 10‰, indicating a substantial contribution of recycled moisture to regional precipitation formation [26]. Under the cold and arid environmental conditions of the basin, large amounts of recycled water vapor generated through surface evaporation are re-incorporated into regional precipitation, resulting in elevated d-excess values. This finding further suggests that evaporated moisture derived from lake water and soil water exerts a strong influence on precipitation formation and reflects the important role of moisture recycling in the hydrological cycle of the Qinghai Lake Basin.

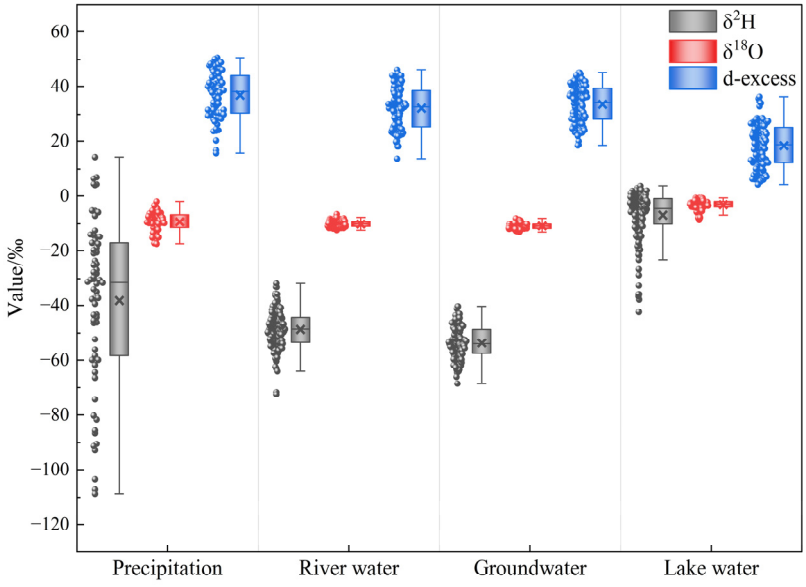

Figure 2. Box-and-whisker plots of δ^2H, $\delta^{18}O$, and d-excess for water bodies in the Qinghai Lake basin.

The δ^2H values of river water in the Qinghai Lake Basin ranged from −72.51‰ to −31.81‰, with a mean value of −48.66‰, whereas $\delta^{18}O$ values ranged from −12.55‰ to −6.57‰, with a mean value of −10.11‰. The overall depleted isotopic composition of river water indicates substantial contributions from high-altitude precipitation, snow and ice meltwater, and groundwater recharge. In general, rivers originating from high-elevation mountainous regions or receiving glacier and snowmelt inputs tend to exhibit relatively depleted stable isotope signatures [23]. The d-excess values of river water ranged from 13.72‰ to 46.08‰, with a mean value of 32.22‰. Elevated d-excess values are commonly

associated with enhanced evaporation processes, which can result in positive shifts in deuterium excess [27]. However, the mean d-excess value of river water was lower than that of precipitation, indicating that river water is recharged not only by precipitation but also by groundwater and frozen-soil meltwater. Compared with precipitation, river water exhibited a narrower range of isotopic variation, suggesting that the river system exerts a buffering effect on precipitation isotope signals. On the one hand, substantial inputs of isotopically depleted snow and ice meltwater and groundwater contribute to the overall depletion of river water isotopes. On the other hand, evaporation within river channels promotes the enrichment of heavy isotopes in the remaining water. The combined effects of these processes suppress extreme fluctuations in river-water isotopic compositions [28]. Previous studies have shown that the isotopic variability of precipitation exceeds that of river water in the Naqu River Basin on the Qinghai–Tibet Plateau [29]. This pattern is mainly attributed to the influence of soil-water retention and groundwater regulation on river runoff. In addition, river isotopic variation is closely related to catchment area. Following the convergence of runoff generated from multiple precipitation events, stable isotopes are continuously mixed within the river system, resulting in reduced isotopic variability in river water [30].

The δ^2H values of groundwater in the Qinghai Lake Basin ranged from −68.50‰ to −40.31‰, with a mean value of −53.55‰, whereas δ^{18}O values ranged from −13.18‰ to −8.04‰, with a mean value of −10.89‰. Compared with river water and precipitation, groundwater exhibited more depleted isotopic compositions and a relatively narrower range of variation. This pattern suggests that groundwater has undergone long-term water–rock interactions and subsurface flow mixing processes, during which hydrogen and oxygen isotope fractionation occurred, resulting in relatively stable isotopic signatures. The isotopic composition of groundwater was most similar to that of river water, indicating a strong hydraulic connection between these two water bodies. Compared with other water sources, groundwater is likely an important contributor to sustaining river baseflow in the basin. The d-excess values of groundwater ranged from 18.51‰ to 45.05‰, with a mean value of 33.61‰. More depleted δ^2H and δ^{18}O values were generally associated with higher d-excess values, indicating that groundwater was less affected by evaporation processes [31]. The relatively high d-excess values observed in groundwater further suggest that groundwater recharge was mainly derived from precipitation infiltration and isotopically depleted water sources from high-altitude regions. In addition, evaporative losses during infiltration were limited. Furthermore, owing to the relatively long residence time of groundwater within aquifers, its isotopic composition exhibits a pronounced "time-averaging effect", which weakens the direct influence of short-term climatic fluctuations on groundwater stable isotopes [32].

The δ^2H values of lake water in the Qinghai Lake Basin ranged from −42.38‰ to 3.71‰, with a mean value of −6.89‰, whereas δ^{18}O values ranged from −8.63‰ to −0.63‰, with a mean value of −3.15‰. Compared with precipitation, river water, and groundwater, lake water exhibited markedly higher stable isotope values, indicating pronounced isotopic enrichment. As the largest inland lake in China, Qinghai Lake has a relatively long water residence time and lacks substantial surface-water outflow. Under prolonged evaporation, lighter isotopes preferentially escape from the lake water, resulting in the continuous enrichment of heavy isotopes in the remaining water body [33,34]. In addition, strong solar radiation and the cold semi-arid climate further enhance evaporative fractionation, leading to persistent enrichment of stable isotopes in lake water. The d-excess values of lake water ranged from 4.24‰ to 36.34‰, with a mean value of 18.35‰. Compared with precipitation, river water, and groundwater, lake water exhibited the highest mean δ^2H and δ^{18}O values. This pattern can be attributed to the combined influence

of multiple recharge sources and intense evaporation driven by strong solar radiation, which enhances isotopic fractionation. These results are consistent with the climatic characteristics of the Qinghai Lake Basin, where evaporation exceeds precipitation under arid and semi-arid conditions [35]. A comparison of stable isotopes between lake water and groundwater within the same region shows that lake water exhibits substantially higher δ^2H and $\delta^{18}O$ values than groundwater, further confirming the long-term influence of strong evaporation on lake water [35]. In general, stable isotope values in lake water tend to become progressively enriched during prolonged periods without precipitation recharge. In contrast, following precipitation events, particularly heavy rainfall events, large inputs of isotopically depleted precipitation and river water dilute the lake water, resulting in a noticeable depletion of lake-water isotopes [36]. The isotopic variability of lake water was considerably smaller than that of precipitation, indicating that the lake system exerts a strong buffering effect on precipitation isotope signals. As lake water represents the long-term integration of precipitation, river water, and shallow groundwater inputs, the combined effects of multiple recharge sources and internal water mixing reduce the direct influence of short-term precipitation events on the stable isotope composition of lake water.

3.2. Temporal Variation Characteristics of Stable Isotopes in Different Water Bodies

Stable isotope compositions of different water types exhibited distinct temporal variations (Figure 3). The δ^2H, $\delta^{18}O$, and d-excess values of precipitation, river water, groundwater, and lake water all showed significant temporal variability. However, the responses of different water types to climatic factors, moisture sources, and evaporation processes varied considerably, reflecting the complex water transformation processes and isotope fractionation mechanisms within the hydrological cycle of the study area. Among all water types, precipitation exhibited the most pronounced temporal variations in stable isotopes. The mean δ^2H values of precipitation decreased in the following order: wet season (−24.49‰), dry season (−47.61‰), and normal-flow season (−68.78‰). The mean $\delta^{18}O$ values followed the order of wet season (−7.91‰), dry season (−10.03‰), and normal-flow season (−12.85‰), while the mean d-excess values decreased in the order of wet season (38.81‰), normal-flow season (37.03‰), and dry season (32.71‰). Precipitation stable isotopes were most enriched during the wet season, whereas pronounced isotopic depletion occurred during the normal-flow season, indicating that precipitation isotope compositions were strongly regulated by seasonal moisture sources and precipitation processes. During the wet season, higher temperatures and enhanced evaporation increased the contribution of locally recycled moisture, while intensified sub-cloud evaporation during rainfall events promoted the enrichment of heavy isotopes in precipitation [37]. In contrast, with decreasing temperature and enhanced long-range moisture transport during the normal-flow season, heavy isotopes were preferentially removed through continuous condensation processes, resulting in progressive depletion of precipitation δ^2H and $\delta^{18}O$ values [38]. Furthermore, the higher d-excess values during the wet season suggested a potentially stronger contribution of terrestrially recycled moisture to precipitation in the study area [39], highlighting the complexity of regional moisture sources.

River water stable isotopes also exhibited pronounced temporal variations. The mean δ^2H values of river water decreased in the following order: wet season (−43.68‰), dry season (−51.54‰), and normal-flow season (−53.45‰). The mean $\delta^{18}O$ values followed the order of wet season (−9.86‰), dry season (−9.78‰), and normal-flow season (−10.72‰), while the mean d-excess values decreased in the order of wet season (35.21‰), normal-flow season (32.45‰), and dry season (26.82‰). River water stable isotopes exhibited a temporal pattern characterized by "depletion–enrichment–re-depletion". The relatively depleted isotopic compositions during the dry season may be associated with the input of isotopically

depleted water derived from winter snowmelt and pre-freezing processes under low-temperature conditions. River water stable isotope values reached their maximum in July, indicating a significant shift in river recharge sources during the wet season. Enriched wet-season precipitation and seasonal permafrost meltwater became the dominant contributors to river recharge. Meanwhile, higher temperatures and stronger solar radiation during the wet season enhanced evaporative fractionation in river channels, further enriching river water stable isotopes [40]. In contrast, river water stable isotopes were most depleted during the normal-flow season. Runoff during this period was mainly controlled by precipitation inputs, baseflow, and groundwater recharge, while weakened evaporation effects resulted in an overall depleted isotopic composition of river water. The higher d-excess values of river water during the wet season indicated strong hydrological connectivity between river water and wet-season precipitation, as well as a relatively rapid water renewal rate.

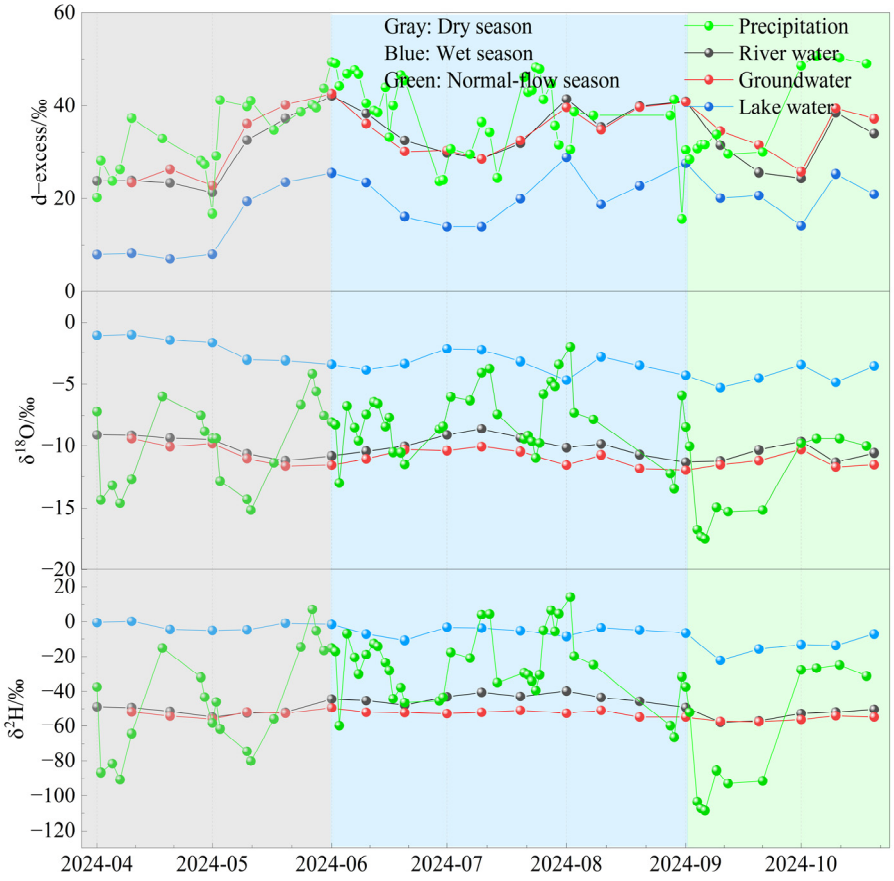

Figure 3. Temporal variation characteristics of δ^2H and $\delta^{18}O$ in precipitation, river water, groundwater, and lake water.

Groundwater stable isotopes showed relatively weaker temporal fluctuations. The mean δ^2H values of groundwater decreased in the following order: wet season (−52.08‰), dry season (−53.37‰), and normal-flow season (−55.91‰). The mean $\delta^{18}O$ values followed the order of dry season (−10.38‰), wet season (−10.87‰), and normal-flow season (−11.34‰), whereas the mean d-excess values decreased in the order of wet season (34.91‰), normal-flow season (32.87‰), and dry season (29.73‰). Overall, groundwater stable isotopes exhibited a gradual depletion trend over time, but the temporal variations were considerably smaller than those observed in precipitation and river water, indicating that groundwater isotopic compositions were relatively stable. This stability is mainly attributed to the processes occurring during precipitation infiltration, including mixing with soil water, evaporative losses, and groundwater aquifer storage, which weaken the

direct influence of precipitation isotope signals and result in a pronounced "time-averaging effect" in groundwater [32,41]. Under alpine cold-region conditions, permafrost and the seasonal active layer play important roles in regulating groundwater circulation. The frozen layer restricts deep water migration, whereas enhanced permeability of the active layer during thawing periods facilitates the recharge of shallow groundwater by precipitation and soil water. Groundwater subsequently provides continuous recharge to rivers through subsurface flow processes. Moreover, the relatively stable isotopic composition of groundwater suggests that groundwater circulation in the study area has a relatively long residence time and that groundwater recharge exhibits a certain degree of lag effect.

Lake water exhibited the highest degree of stable isotope enrichment and pronounced seasonal variations. The mean δ^2H values of lake water decreased in the following order: dry season (−2.72‰), wet season (−5.39‰), and normal-flow season (−13.11‰), while the mean $\delta^{18}O$ values followed the order of dry season (−1.87‰), wet season (−3.02‰), and normal-flow season (−4.31‰). The mean d-excess values decreased in the order of normal-flow season (21.42‰), wet season (20.51‰), and dry season (12.31‰). Overall, lake water stable isotopes exhibited a gradual depletion trend, while remaining substantially more enriched than those of the other water types, indicating that the lake has been strongly affected by long-term evaporation. During the dry season, precipitation and river inflow to the lake were relatively limited, and the lake relied mainly on groundwater recharge. Meanwhile, higher wind speeds and lower air humidity enhanced lake-surface evaporation, resulting in pronounced enrichment of lake water δ^2H and $\delta^{18}O$ and a marked decrease in d-excess. During the subsequent wet season, continuous inputs of substantial precipitation and river runoff enhanced water exchange within the lake, while the evaporative enrichment effect was diluted, leading to a gradual depletion of lake water stable isotopes. During the normal-flow season, lake water isotope values decreased further, indicating that continued inputs of precipitation and river water during the wet and normal-flow seasons exerted a pronounced dilution effect on lake water. The relatively low d-excess values of lake water further reflected strong evaporative fractionation, which is an important isotopic characteristic of closed or semi-closed lake systems [42].

The generally consistent temporal variations in stable isotope compositions among different water types indicate strong hydrological connectivity and recharge relationships within the regional hydrological system. Temporal variations in precipitation isotope compositions can be rapidly transmitted to river water and subsequently influence the isotopic characteristics of groundwater and lake water to some extent [43,44]. Among different water types, river water exhibited the most sensitive response to precipitation variations, whereas groundwater showed stronger buffering and smoothing effects. In contrast, lake water isotope compositions were mainly controlled by the combined effects of precipitation inputs, river recharge, groundwater exchange, and lake evaporation [45]. Therefore, variations in regional precipitation not only directly regulate the stable isotope compositions of different water bodies but also exert profound influences on watershed-scale hydrological processes by altering water exchange mechanisms and hydrological pathways within the basin [46].

3.3. Spatial Variation Characteristics of Stable Isotopes in Different Water Bodies

Owing to differences in temperature conditions, moisture sources, recharge pathways, and underlying surface characteristics, the stable isotope compositions of different natural water bodies exhibit pronounced spatial variability. The mean δ^2H and $\delta^{18}O$ values of river-water sampling sites are shown in Figure 4. The mean δ^2H values of different tributaries decreased in the following order: Quanji River (−43.54‰) > Shaliu River (−45.77‰) > Hargai River (−48.03‰) > Daotang River (−50.47‰) > Heima River (−50.63‰) > Buha

River (−50.87‰) > Ganzi River (−51.31‰). Similarly, the mean $\delta^{18}O$ values decreased in the following order: Quanji River (−9.54‰) > Daotang River (−9.62‰) > Shaliu River (−9.97‰) > Hargai River (−10.19‰) > Heima River (−10.39‰) > Buha River (−10.47‰) > Ganzi River (−10.57‰) (Figure 4a). Among the tributaries, the Quanji River exhibited the highest mean $\delta^{2}H$ and $\delta^{18}O$ values and therefore the most enriched isotopic composition, whereas the Ganzi River exhibited the lowest mean $\delta^{2}H$ and $\delta^{18}O$ values and the most depleted isotopic composition (Figure 4b,c). The spatial variability of river-water stable isotopes is mainly controlled by precipitation recharge characteristics, catchment-scale evaporation intensity, and runoff generation processes [44]. The Quanji River watershed is characterized by a relatively low elevation and a short flow path. In addition, local precipitation and evaporation exert strong influences during the wet season, resulting in relative enrichment of heavy isotopes in river water. In contrast, the Buha River has a larger catchment area and receives a greater proportion of recharge from high-altitude precipitation, snow and ice meltwater, and groundwater, leading to an overall depleted isotopic composition. Furthermore, differences in vegetation cover, permafrost development, and water residence time among river catchments may further influence evaporative fractionation processes, thereby contributing to the spatial heterogeneity of river-water stable isotopes. Overall, the spatial patterns of river-water isotopes reflect differences in hydrological processes among distinct hydrogeomorphic units across the Qinghai Lake Basin from southeast to northwest [47].

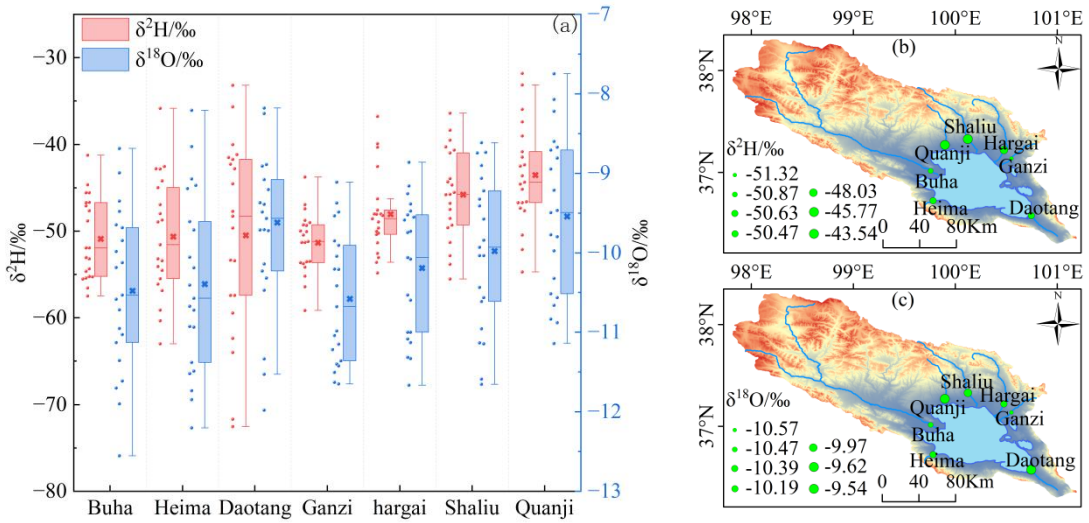

Figure 4. Spatial distribution characteristics of $\delta^{2}H$ and $\delta^{18}O$ in river water. Note: (**a**) Comparison of $\delta^{2}H$ and $\delta^{18}O$ values at different sampling sites; (**b**) spatial distribution of $\delta^{2}H$; (**c**) spatial distribution of $\delta^{18}O$.

The mean $\delta^{2}H$ and $\delta^{18}O$ values of groundwater sampling sites are shown in Figure 5. Overall, stable isotopes were relatively enriched in the western part of the Qinghai Lake Basin and relatively depleted in the eastern part (Figure 5a). Previous studies have demonstrated that the spatial variability of groundwater stable isotopes is closely related to groundwater depth [17]. Groundwater in the eastern and southern parts of the basin is generally characterized by shallow water tables and frequent exchange with the surface environment, making it more susceptible to evaporative influences. In contrast, groundwater in the northern and western regions of the lake occurs at greater depths, where groundwater circulation is relatively isolated and evaporation effects are weaker. As a result, distinct regional differences in stable isotope compositions are observed. Overall, the spatial variability of stable isotopes among most groundwater sampling sites was relatively small, indicating strong mixing and storage effects within the groundwater system and sug-

gesting that groundwater isotopic compositions remained comparatively stable. Among all sampling sites, G5 and G6 exhibited anomalously depleted isotopic signatures (Figure 5b,c), with δ^2H and $\delta^{18}O$ values markedly lower than those of other groundwater samples. This pattern suggests that groundwater in this area may be predominantly recharged by deeper groundwater sources. In addition, the groundwater may be characterized by longer flow paths and weaker evaporative effects, thereby preserving relatively depleted stable isotope signatures [48]. With the exception of G6, isotopic differences among the remaining groundwater sampling sites were relatively small, and no pronounced spatial pattern was observed. This finding further indicates that the groundwater system is less affected by environmental factors and maintains a relatively stable isotopic composition.

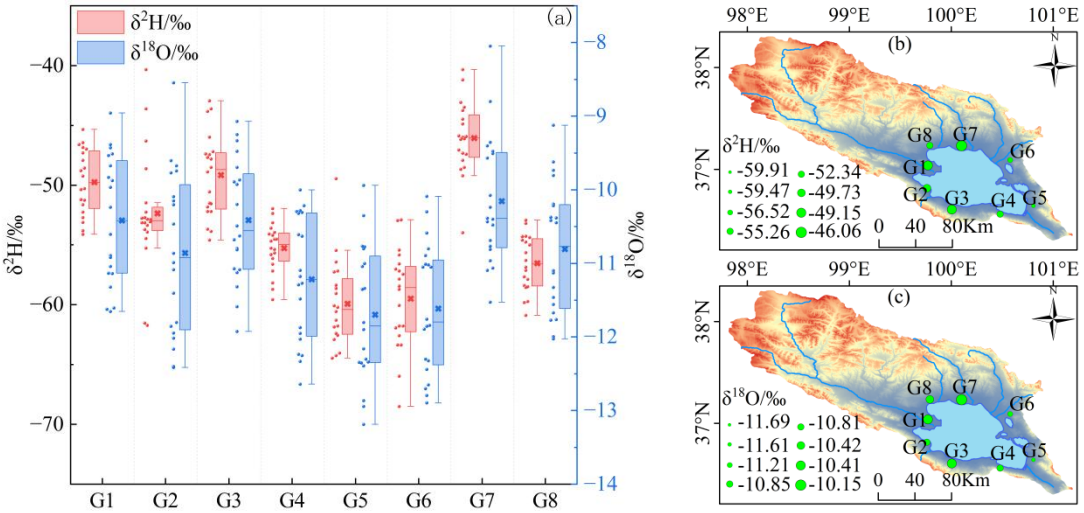

Figure 5. Spatial distribution characteristics of δ^2H and $\delta^{18}O$ in groundwater. Note: (**a**) Comparison of δ^2H and $\delta^{18}O$ values at different sampling sites; (**b**) spatial distribution of δ^2H; (**c**) spatial distribution of $\delta^{18}O$.

The mean δ^2H and $\delta^{18}O$ values of lake-water sampling sites are shown in Figure 6. The stable isotope composition of lake water exhibited pronounced spatial heterogeneity. Owing to the large surface area of Qinghai Lake, different regions of the lake vary in terms of recharge sources, water exchange rates, and evaporation intensity, resulting in substantial spatial differences in the enrichment of heavy isotopes. Overall, stable isotopes were relatively enriched in the eastern part of the lake and relatively depleted in the western part (Figure 6a). However, the L7 sampling site exhibited anomalously enriched isotopic signatures, with mean δ^2H and $\delta^{18}O$ values reaching −2.73‰ and −2.51‰, respectively (Figure 6b,c), indicating that lake water in this area has been subjected to strong evaporative effects over a prolonged period. Enhanced evaporation preferentially removes lighter isotopes, leading to the continuous enrichment of heavy isotopes in the remaining lake water. In contrast, the L1 and L3 sampling sites were located near the mouths of inflowing rivers and exhibited the most depleted isotopic compositions, indicating that river recharge exerted a significant dilution effect on the isotopic composition of lake water. The river network within the Qinghai Lake Basin is characterized by a markedly uneven spatial distribution. River systems are more developed in the western and northern parts of the basin, where large rivers such as the Buha River and Shaliu River continuously deliver substantial amounts of isotopically depleted water to the lake. Consequently, the isotopic composition of lake water along the western shoreline is strongly influenced by river recharge and remains relatively depleted. By contrast, river networks in the southeastern part of the lake are relatively sparse, and inflow volumes are comparatively low. As a result, the rate of lake-water renewal is slower, allowing heavy isotopes to accumulate

continuously under persistent evaporation, which leads to elevated δ^2H and $\delta^{18}O$ values in lake water. These findings indicate that the spatial isotopic patterns of Qinghai Lake are jointly controlled by river recharge intensity and lake evaporation. Differences in water exchange capacity among different regions of the lake are a key factor driving the spatial heterogeneity of lake-water stable isotopes.

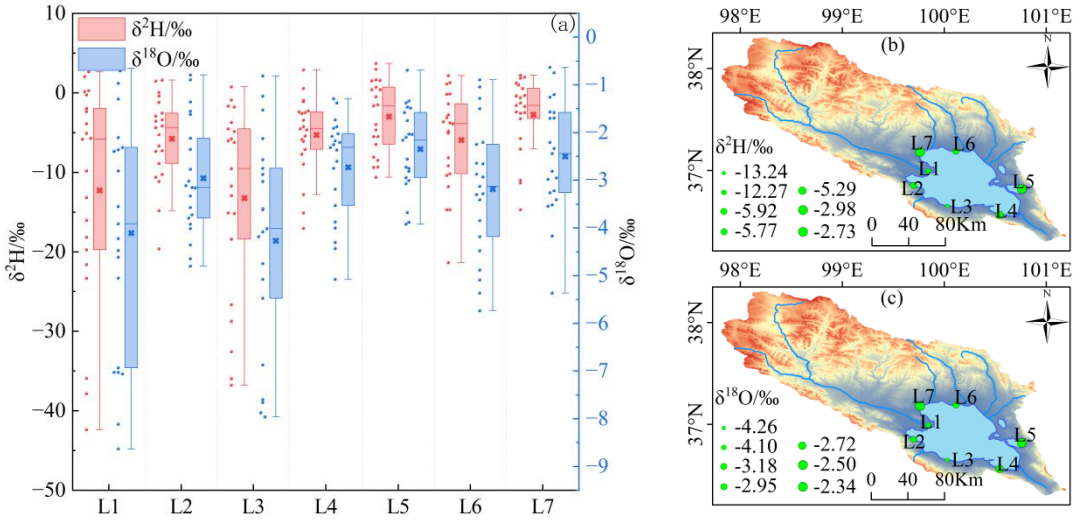

Figure 6. Spatial distribution characteristics of δ^2H and $\delta^{18}O$ in lake water. Note: (**a**) Comparison of δ^2H and $\delta^{18}O$ values at different sampling sites; (**b**) spatial distribution of δ^2H; (**c**) spatial distribution of $\delta^{18}O$.

4. Discussion

4.1. Relationship Between δ^2H and $\delta^{18}O$ in Different Water Bodies

Craig proposed the Global Meteoric Water Line (GMWL), which describes the linear relationship between δ^2H and $\delta^{18}O$ in precipitation as $\delta^2H = 8\delta^{18}O + 10$ [22]. Based on the δ^2H and $\delta^{18}O$ values of precipitation, river water, groundwater, and lake water, linear regression models were used to establish the characteristic isotope lines for different water bodies in the Qinghai Lake Basin (Figure 7). The Local Meteoric Water Line (LMWL) of the Qinghai Lake Basin was defined as $\delta^2H = 8.07\delta^{18}O + 37.48$ ($R^2 = 0.96$). The River Water Line (RWL) was expressed as $\delta^2H = 3.64\delta^{18}O - 11.79$ ($R^2 = 0.55$), the Groundwater Line (GWL) as $\delta^2H = 3.33\delta^{18}O - 17.19$ ($R^2 = 0.59$), and the Lake Water Line (LWL) as $\delta^2H = 4.44\delta^{18}O + 7.13$ ($R^2 = 0.86$). Marked differences in the slopes and intercepts of these water lines were observed, reflecting variations in recharge sources, hydrological cycling processes, and the degree of evaporative fractionation among different water bodies in the study area. Previous studies have shown that the slopes and intercepts of meteoric water lines vary considerably among regions owing to differences in geographical setting, climatic conditions, moisture transport pathways, and local evaporation environments [46]. The slope and intercept of the Qinghai Lake Basin LMWL were both higher than those of the Global Meteoric Water Line (GMWL) and the China Meteoric Water Line, indicating that precipitation in the study area is influenced not only by moisture transported by the westerlies but also by substantial contributions from locally recycled evaporative moisture [49]. The relatively high intercept further suggests complex moisture sources and strong moisture recycling under the cold and arid environmental conditions of the basin.

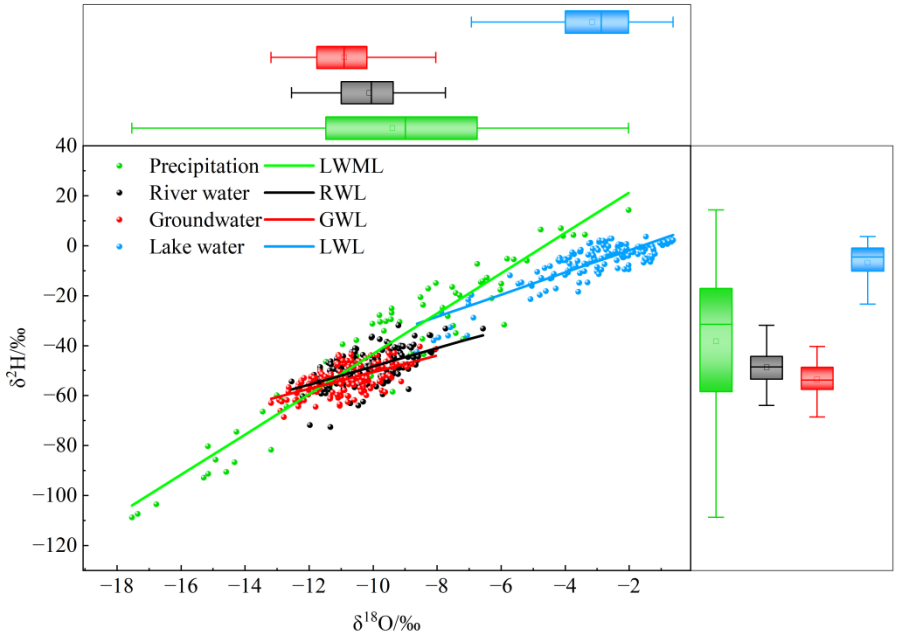

Figure 7. Relationship between δ^2H and $\delta^{18}O$ regarding precipitation, river water, groundwater, and lake water in the Qinghai Lake Basin.

The slope and intercept of the River Water Line (RWL) were both markedly lower than those of the Local Meteoric Water Line (LMWL), indicating that river water experienced substantial evaporative fractionation during surface runoff generation and transport processes, which resulted in a reduced slope of the RWL [50]. Most river-water δ^2H and $\delta^{18}O$ values were distributed close to the meteoric water line, primarily below and around its central portion, suggesting that precipitation is one of the major recharge sources of river water. At the same time, the isotopic composition of river water was continuously influenced by evaporation during flow processes. The relatively low coefficient of determination (R^2) of the RWL further indicates that river-water recharge sources are complex and may be jointly controlled by multiple water sources, including precipitation, groundwater, snow and ice meltwater, and seasonal frozen-soil meltwater [51].

The slope and intercept of the Groundwater Line (GWL) were both lower than those of the Local Meteoric Water Line (LMWL), and groundwater isotope values were generally distributed on both sides of the meteoric water line. This pattern indicates that groundwater is primarily recharged by precipitation infiltration, while it experiences a certain degree of evaporative fractionation during infiltration processes. Compared with precipitation, groundwater exhibited a more depleted isotopic composition overall, suggesting that, in addition to modern precipitation recharge, groundwater may also receive contributions from high-altitude precipitation, snow and ice meltwater, and groundwater formed during earlier hydrological periods [52]. Owing to the effects of mixing within the vadose zone and storage and regulation within aquifers during groundwater infiltration and transport, groundwater isotopic compositions exhibit a pronounced temporal integration effect [48]. Consequently, the variability of groundwater stable isotopes is relatively limited. The relatively low slope of the GWL further indicates that groundwater is subject to some evaporative influence during recharge processes; however, the degree of evaporation is substantially weaker than that observed for lake water.

The Lake Water Line (LWL) deviated markedly from the Local Meteoric Water Line (LMWL) and was characterized by a lower slope and intercept. Such isotopic characteristics are commonly observed in arid and semi-arid regions as well as in closed or semi-closed lake systems [50]. As evaporation intensifies, the slope of a water-line relationship generally

decreases, indicating that the isotopic composition of lake water is increasingly controlled by evaporative processes. During lake-water evaporation, lighter isotopes (1H and 16O) preferentially enter the atmosphere, whereas heavier isotopes (2H and 18O) become progressively enriched in the residual water body. Consequently, lake-water δ^2H and $\delta^{18}O$ values increase, causing the LWL to shift toward the lower-right side of the meteoric water line. As shown in Figure 6, most lake-water samples were distributed below the LMWL, further indicating that, although lake water has undergone substantial evaporative enrichment, its primary recharge sources remain precipitation, river inflow, and groundwater inputs. The differences among the stable isotope lines of various water bodies in the Qinghai Lake Basin reflect the complex recharge relationships and evaporative fractionation processes occurring within the regional hydrological cycle. Precipitation serves as an important recharge source for river water, groundwater, and lake water, whereas evaporation is a key factor controlling the evolution of stable isotope compositions in lake water and, to a lesser extent, in river water. The similarities and differences in stable isotope compositions among different water bodies further reveal the complexity of hydrological processes and water-body interactions within the Qinghai Lake Basin under cold and arid environmental conditions. These isotopic characteristics provide important insights into regional water transformation processes and the functioning of the basin-scale hydrological cycle.

4.2. Relationship Between δ^2H and $\delta^{18}O$ in Different Water Bodies

The stable isotope composition of lake water in the Qinghai Lake Basin was generally more enriched than that of river water and groundwater, indicating that lake water has undergone substantial evaporative enrichment during its evolution. Previous studies have shown that when isotopically depleted water recharges an isotopically enriched water body, the isotopic enrichment characteristics of the receiving water body may be further enhanced [53]. From the perspective of the δ^2H–$\delta^{18}O$ relationship, lake-water isotope values were distributed above those of river water and groundwater. The slope of the Lake Water Line (LWL) was lower than those of the Local Meteoric Water Line (LMWL) and the Groundwater Line (GWL), but higher than that of the River Water Line (RWL). In addition, the intercept of the LWL was lower than that of the LMWL but higher than those of the RWL and GWL. These characteristics indicate that the isotopic composition of lake water is jointly influenced by multiple recharge sources and evaporative processes. In theory, if precipitation is the dominant source of lake recharge, the relationship between $\delta^{18}O$ and δ^2H in lake water should follow the meteoric water line. However, in this study, lake-water isotope values were primarily distributed in the upper-right region relative to the LMWL, and the LWL deviated markedly from the meteoric water line. This pattern may be attributed to the mixing of newly recharged water and older stored water within the lake, together with significant evaporative fractionation during water recharge and residence. Based on stable isotope relationships, the recharge pathways among different water bodies within the basin can be preliminarily identified. On the one hand, precipitation directly recharges the lake through rainfall onto the lake surface. On the other hand, precipitation indirectly enters the lake through surface runoff and groundwater flow. During these processes, both surface water and groundwater may experience varying degrees of evaporation before entering the lake, thereby altering their isotopic compositions. At the seasonal scale, river-water recharge to the lake exhibited pronounced temporal variability. During the rainy season, increased precipitation and substantially enhanced river inflow resulted in a continuous rise in lake level, reaching its maximum in mid-to-late August. Correspondingly, lake-water stable isotopes exhibited a gradual depletion trend. In contrast, groundwater recharge to the lake appeared to be relatively stable throughout the study period. The spatial pattern of groundwater flow was characterized

by mountainous areas acting as recharge zones, alluvial fans and piedmont plains serving as runoff zones, and the lakeshore belt functioning as the principal discharge zone. The temporal variations in stable isotopes of lake water and groundwater showed similar patterns, both exhibiting progressive depletion over time, further supporting the persistent contribution of groundwater recharge to the lake. Furthermore, the significant linear relationships between $\delta^{18}O$ in lake water and $\delta^{18}O$ in both river water and groundwater provide additional evidence that Qinghai Lake receives recharge from both riverine and groundwater sources [19].

To complement the qualitative analysis and further quantify the contributions of different water sources to lake water, a Bayesian mixing models (MixSIAR) was applied based on the mass conservation principle of stable hydrogen and oxygen isotopes. Precipitation, river water, and groundwater were selected as source end-members. The isotopic input parameters were defined using the observed means and standard deviations of each water body, and the overlap among end-member distributions was evaluated to ensure adequate source discrimination. Considering that all water types were affected by evaporative fractionation, isotopic fractionation during hydrological processes was not incorporated into the model [54]. Given the spatial and temporal variations in isotope compositions among different water types, the mean and standard deviation of isotope values for each water source end-member were used to characterize end-member uncertainty in the model. To fully characterize model uncertainty, a Bayesian framework was adopted to obtain the posterior probability distributions of contributions from different water sources. As shown in Figure 8, the estimated contributions of precipitation, river water, and groundwater to lake water over the entire study period were 28.6%, 37.5%, and 33.9%, respectively. Previous studies have demonstrated that variations in the water balance of Qinghai Lake are primarily controlled by precipitation and river inflow, with reported contribution rates of 32.4% and 32.5%, respectively. These estimates are generally consistent with the results obtained in the present study. At the seasonal scale, the contributions of precipitation, river water, and groundwater to lake water were estimated to be 30.0%, 36.4%, and 33.6%, respectively, during normal-flow season; 29.4%, 35.8%, and 34.8%, respectively, during wet season; and 29.3%, 36.5%, and 34.3%, respectively, during dry season. All source contributions were associated with a certain degree of uncertainty, indicating dynamic substitution among different water sources, which collectively maintain the water balance of the lake.

During the study period, river water contributed the largest proportion of recharge to Qinghai Lake, whereas the contribution of precipitation was comparatively lower, and groundwater provided a relatively stable contribution. Although wet season precipitation directly recharged the lake surface, the contribution of river water increased as precipitation decreased during dry season. The transformation processes among different water types in the Qinghai Lake watershed are complex. Due to the partial overlap of isotopic signatures among end-members and the fact that evaporative fractionation effects were not explicitly considered in the model, the quantitative estimates obtained above still contain certain uncertainties. In future studies, the Craig–Gordon evaporation model and water balance model could be integrated to quantitatively correct for evaporative fractionation effects, thereby improving the reliability of lake water source contribution estimations [34]. Therefore, this study primarily focused on analyzing the relative magnitude and variation in the contributions of different water sources during the study period based on the available stable isotope data, rather than estimating their absolute proportions. The findings provide a scientific basis and valuable data support for understanding hydrological cycling processes and for the conservation and sustainable management of water resources in the Qinghai Lake Basin.

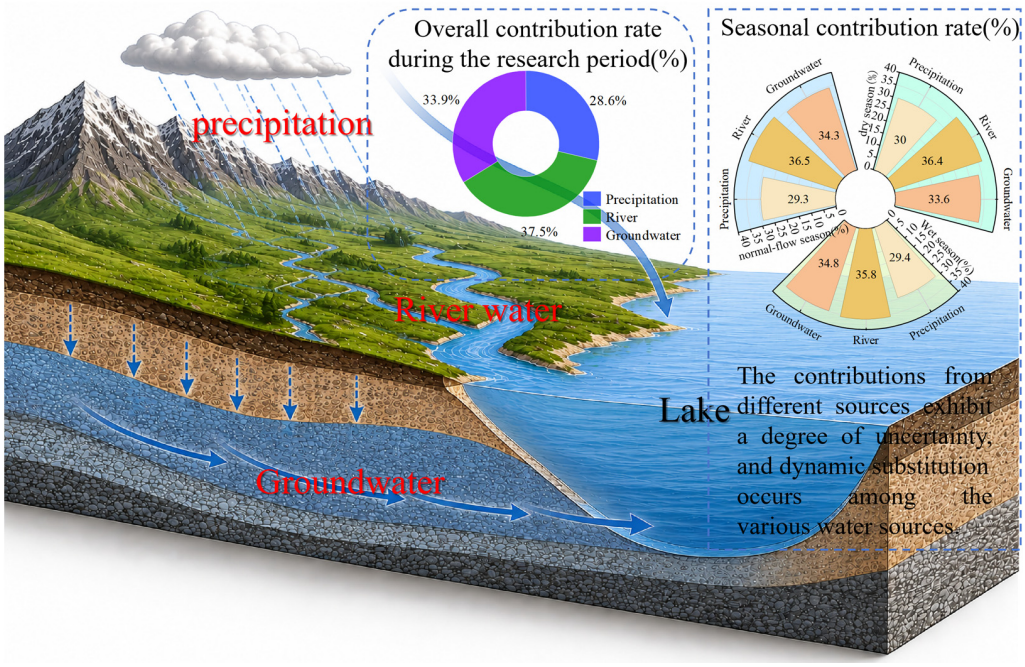

Figure 8. Contributions of precipitation, river water, and groundwater to lake water. Note: This figure was prepared by the authors based on the data and analyses of this study, with AI tools used for graphical design assistance.

5. Conclusions

(1) Stable isotope compositions of different water types in the Qinghai Lake watershed exhibited significant differences. Precipitation showed the largest fluctuations and pronounced temporal variations. River water displayed a temporal pattern characterized by "depletion–enrichment–re-depletion", which was mainly controlled by the combined effects of precipitation inputs, recharge sources, evaporation intensity, and runoff generation processes. Groundwater exhibited the most depleted isotopic compositions and relatively weak temporal variations, reflecting its pronounced buffering and smoothing effects. Lake water showed the highest isotopic enrichment, with its isotope compositions being primarily controlled by evaporation and groundwater recharge during the dry season, while being influenced by the dilution effects of precipitation and river inputs during the wet season. Spatially, river water stable isotopes exhibited significant spatial heterogeneity among different rivers, with the Quanji River showing the most enriched isotopic compositions and the Gan River exhibiting the most depleted values. Groundwater stable isotopes generally displayed a pattern of relatively enriched compositions in the western region and depleted compositions in the eastern region, which was mainly regulated by groundwater depth and the intensity of groundwater–surface water interactions. Lake water also showed clear spatial variations, with relatively enriched isotopic compositions in the eastern region due to stronger evaporative effects and relatively depleted isotopic compositions in the western region influenced by river recharge.

(2) The local meteoric water line (LMWL) of the Qinghai Lake watershed was expressed as $\delta^2H = 8.07\delta^{18}O + 37.48$ ($R^2 = 0.96$). Both the slope and intercept were higher than those of the global meteoric water line, indicating that locally recycled evaporated moisture played an important role in regional precipitation formation. The slope and intercept of the river water line were lower than those of the meteoric water line, suggesting that river water experienced significant evaporative fractionation during runoff generation and transport processes. The groundwater line showed

similar slopes and intercepts to the river water line, indicating strong hydrological connectivity between groundwater and river water. The lake water line deviated markedly from the meteoric water line, demonstrating that lake water underwent substantial evaporative fractionation while its recharge sources remained primarily associated with precipitation, river water, and groundwater.

(3) Precipitation served as an important recharge source for river water, groundwater, and lake water. River water exhibited the most sensitive response to precipitation variations, groundwater showed a pronounced buffering effect, and lake water integrated the combined influences of precipitation inputs, river and groundwater recharge, and evaporative fractionation processes. During the study period, the relative contributions of precipitation, river water, and groundwater to lake water were 28.6%, 37.5%, and 33.9%, respectively. As lake water undergoes evaporative fractionation processes, these results represent the apparent mixing relationships based on observed isotopic characteristics rather than absolute water volume contributions after fully correcting for evaporation effects. Future studies should improve the accuracy of water source contribution assessments in alpine lakes by conducting synchronized, high-frequency sampling of precipitation, river water, groundwater, and lake water, combined with evaporation correction models, multi-isotope tracing, and water balance models.

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