

August 31th, 2026

To: Prof. Margaret Zimmer, Editor of *HESS*

Subject: **Submission of EGUSPHERE-2026-3213 after revision**

Dear Prof. Zimmer,

Upon your request, we have carefully revised our manuscript EGUSPHERE-2026-3213 entitled “Effects of freeze–thaw processes on the sources and pathways of shallow groundwater recharge in the Qinghai Lake Basin”. The comments are very insightful and have helped us further improve the quality of the manuscript. The following is the point-to-point response to all the comments. The line numbers in the following response refer to the revised manuscript with changes marked.

Thank you very much for your consideration.

Best regards

Xiaoyan Li, on behalf of all co-authors

### **Response to Editor comments:**

#### **General comments:**

Thank you for your submission to HESS. This is an interesting and timely study, based on an extensive isotope-based dataset to quantitatively track shallow groundwater recharge sources and dynamics during freeze-thaw periods in an alpine system in the Qinghai–Tibet Plateau. We have received two thorough reviews and I have read through the manuscript, the reviews, and your planned revisions. Based on this, I invite you to submit a revised manuscript.

Reply: We appreciate your detailed annotations in the manuscript. The comments from the editor and reviewers are very helpful to improve the quality of our manuscript (see the replies to the following comments).

## 1. Comment:

In addition to the planned revisions as identified through the reviewer comments, I also encourage you to provide more context information to your figures. For example, please provide an inset map in Figure 1 that places the site in a larger geographic extent. In Figure 6, please explain in the caption what the x-axis labels are.

**Reply:** Thanks for your suggestion, we have added an inset map to Fig. 1 to indicate the location of the Qinghai Lake basin within the Qinghai–Tibet Plateau, providing a broader geographical context. In addition, we have added an explanation of the x-axis label in the legend of Fig. 6 and included sampling-point information at the bottom of Fig. 6. Meanwhile, we have added explanations of the error bars in the figure captions for Figures 3, 5, 6, and 7. The detailed explanation is as follows (see Lines 150, 305, 354 and 375):

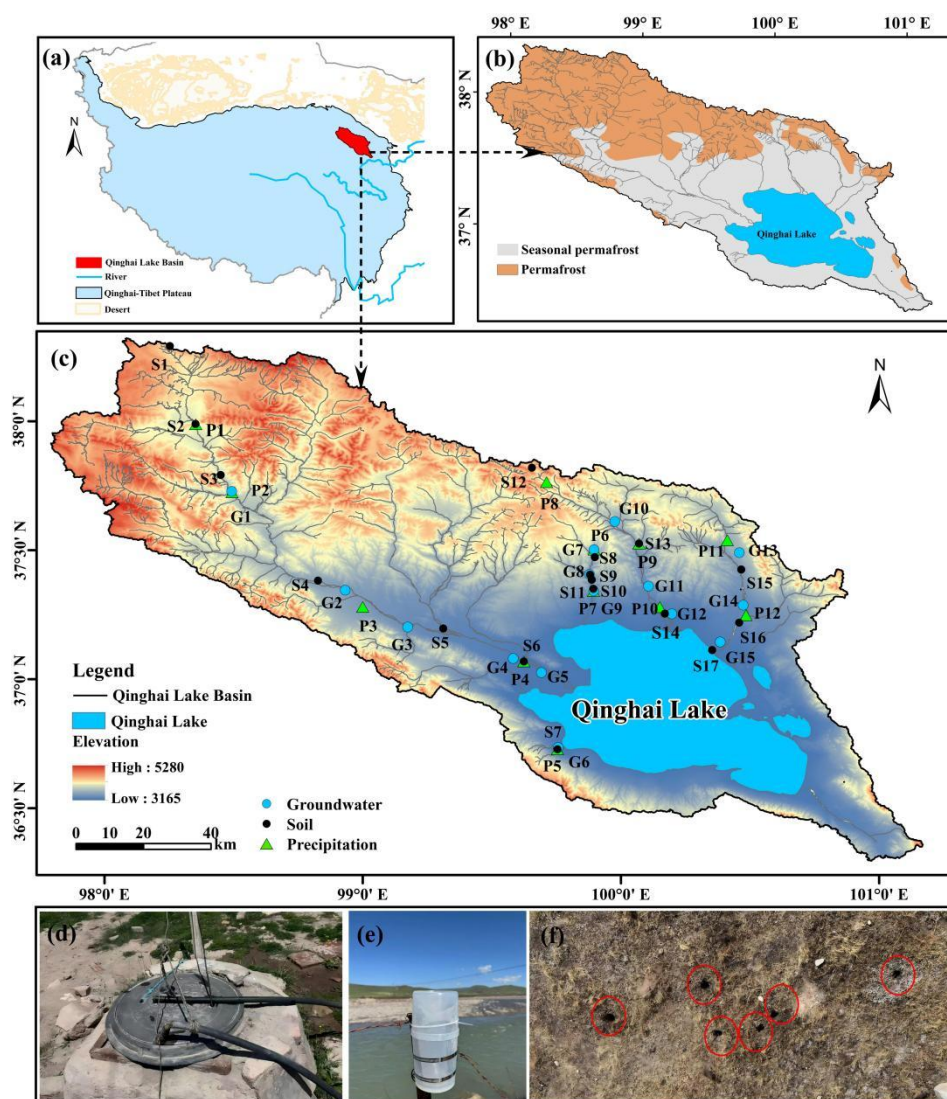


**Fig. 1.** (a) Location of the QLB on the QTP. (b) Spatiotemporal distribution of permafrost in the QLB, where gray and orange represent seasonal permafrost and permafrost, respectively. (c) Location of the QLB and distribution of sampling points. (d) Groundwater sampling. (e) Precipitation sampling. (f) Soil samples are collected monthly at adjacent locations.

**Fig. 3.** Variations in  $\delta^2\text{H}$  (a),  $\delta^{18}\text{O}$  (b), and lc-excess (c) of precipitation, groundwater, and soil water at different depths during FT periods. The error bar represents the variance of the calculated results across all data points.

**Fig. 5.** Variations in SWC among different depths during the FT periods (a: middle and upper reaches; b: downstream). The error bar represents the variance of the calculated results across all data points.

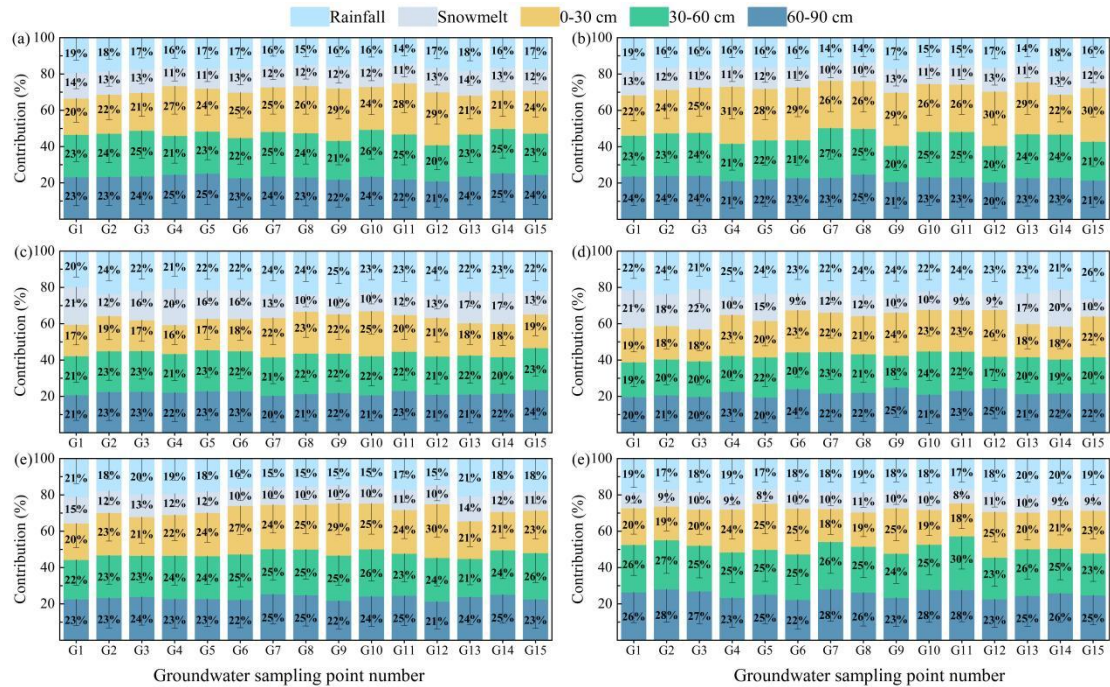


**Fig. 6.** Contribution of rainfall, snowmelt, and soil water from different depths to groundwater in the QLB during the FT periods. The error bar represents the variance of the calculated results across all data points. The x-axis labels denote sampling point numbers.

## 2. Comment:

Please provide more clarify regarding the linkage between "FT periods" and the

months listed on Figures. Is FT sporadic across all the months displayed in the figures, does FT frequency increase during certain periods? Does it happen gradually over the entire period? This was not clearly stated and it made it hard to understand or put any context on the changes in source percentages. Please explain the characteristics of FT during the study period and how each month may vary (or be similar).

**Reply:** According to your suggestion, we have revised Section 2.4.1 of the methodology to further clarify the relationship between the “FT period” and each month. During the study period, freeze-thaw cycles occurred in May. The June marked the onset of a relatively stable thawing period, no freeze-thaw cycles were observed from July through September. In October, as atmospheric and soil temperatures dropped below 0°C, the region gradually entered the freezing period. Therefore, FT does not occur continuously or sporadically throughout all months, but is primarily concentrated in May. The detailed explanation is as follows (see Lines 215-236):

#### *2.4.1 Division of FT periods*

The soil FT periods in the QLB were delineated based on air temperature ( $T_{air}$ ) and soil temperature ( $T_{soil}$ ) data (Table 2). The month containing the first day on which both daily maximum air temperature ( $T_{max, air}$ ) and daily maximum soil temperature ( $T_{max, soil}$ ) remain continuously above 0°C for 7 consecutive days is defined as the thawing period (Fig. S1). The month containing the first day on which both the daily minimum air temperature ( $T_{min, air}$ ) and the daily minimum soil temperature ( $T_{min, soil}$ ) remain continuously above 0°C for 7 consecutive days is defined as the thawed period. The freezing period is defined as the month containing the first day on which both the daily minimum air temperature ( $T_{min, air}$ ) and the daily minimum soil temperature ( $T_{min, soil}$ ) remain continuously below 0°C for 7 consecutive days. The FT process exhibited a distinct seasonal progression throughout the study period rather than occurring randomly across different sampling months.

In early May, the soil entered the initial thawing stage, and FT cycles emerged. As nighttime air temperatures continued to rise, freeze-thaw cycles disappeared in late May, and the soil subsequently entered a stable thawing period. From July to

September, the soil remained completely thawed, and no FT cycles were observed. In mid to late October, as nighttime soil temperature and air temperature dropped below 0 °C, the soil re-entered the freezing period. Accordingly, based on the seasonal variations in air temperature and soil temperature, May to June, July to September, and October were defined as the thawing period, the thawed period, and the freezing period, respectively. For details on the classification, refer to previously published literature on this study area (Zhang et al., 2024; Hu et al., 2025).

### 3. Comment:

Finally, the authors note that piston flow and preferential flow both occur. This suggests that water travels through the different soil layers (0-30, 30-60, 60-90 cm) in the matrix. Therefore, it seems like the isotopic signature of 0-30, for example, would influence the 30-60 cm signature. If that is the case, how you could quantify so cleanly the source water from specific soil layer ranges (e.g., Figure 6), while we know that these layers are vertically stacked and so water from different sources are mixing continuously? Are there errors in your modelled sourcing that would account for that? If so please address this and provide more information on error or uncertainty.

**Reply:** We fully agree with your comment. The MixSIAR model does account for isotopic measurement error and end-member uncertainty. However, soil layers are vertically stacked, and during soil sampling, water from different sources may continue to mix. Therefore, treating each soil layer as a completely independent “closed end-member” is indeed biased. According to your suggestion, we have added the error ranges for each source calculated using MixSIAR modeling in Fig. 6. At the same time, we have also added an explanation of the uncertainty in the newly added Discussion 4.4. The detailed explanation is as follows (see Lines 375 and 561-564):

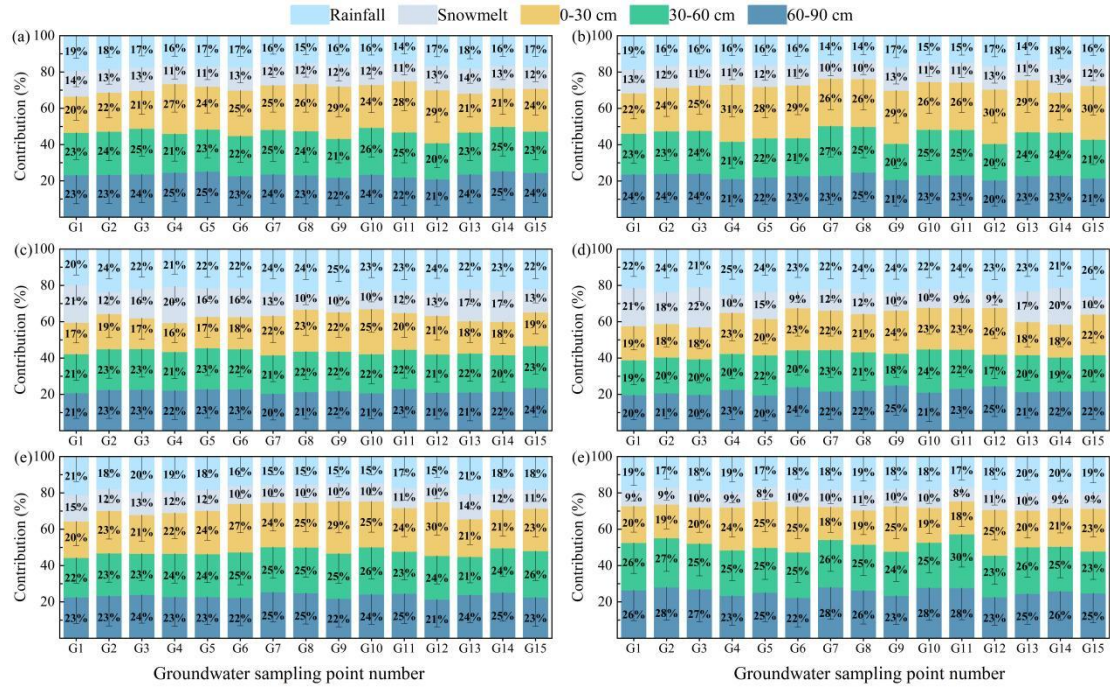


**Fig. 6.** Contribution of rainfall, snowmelt, and soil water from different depths to groundwater in the QLB during the FT periods. The error bar represents the variance of the calculated results across all data points. The x-axis labels denote sampling point numbers.

#### 4.4 Significance and Limitations

Finally, because piston flow and preferential flow coexist, water may migrate between different soil layers. Given the vertical stacking of soil layers and the continuous mixing of water from different sources, isotopic characteristics from the surface layer may be transported downward and influence the isotopic composition of deeper layers, thereby affecting the accuracy of groundwater recharge source identification.

### **Response to Anonymous Referee #1:**

This study focuses on the Qinghai Lake basin in northeastern Tibet, employing comprehensive data from stable water isotopes ( $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$ , lc-excess), soil moisture content (SWC), and the MixSIAR mixing model to systematically characterize the dynamic changes in recharge sources and pathways of shallow groundwater during different stages of the freeze-thaw cycle (melting phase, post-melting period, and freezing phase). The research aligns closely with current cutting-edge topics in hydrology and permafrost degradation under climate warming in high-altitude regions, featuring well-defined scientific questions, rigorous experimental design, ample data, and appropriate methodological applications. These findings hold significant scientific value for understanding groundwater formation mechanisms and water resource management in high-altitude regions under climate change. However, while fully acknowledging its scientific contributions, I identify certain shortcomings in the manuscript regarding the rigor of its argumentation logic, the depth of interpretation for certain data, and the completeness of methodological descriptions. To further enhance the paper's quality, I recommend a comprehensive revision. Below are the key issues and specific recommendations for improvement, for the author's consideration.

**Reply:** We sincerely thank the reviewer for the positive and encouraging comments. According to your suggestion, we have made significant revisions to the manuscript, focusing on improving the accuracy of the wording, refining the description of the methods, and adding a description of the associated limitations (see the replies to the following comments).

### **Major Comments:**

#### **1. Comment:**

The conclusion that soil water serves as a "transitional reservoir" lacks sufficient support. The author repeatedly emphasizes in the abstract and conclusions that "soil water is a key transitional reservoir linking precipitation/snowmelt water with groundwater recharge" (Lines 38–40, 511–513). However, the MixSIAR model only

provides contribution ratios for each element and cannot directly demonstrate that soil water fulfills a transitional role of receiving, storing, and releasing water over time. To substantiate this argument, it is recommended to supplement the analysis with data on the lagged variation of soil water  $\delta^{18}\text{O}$  over time (e.g., the lag time in soil water isotopic responses following precipitation events). If such evidence is unavailable, the author should downplay this aspect in the manuscript. The current discussion (Section 4.1) focuses more on changes in contribution rates than on direct dynamic evidence supporting its "transitional" nature.

**Reply:** We fully agree with your view that water isotopes can only quantify the relative contributions of end-members and cannot directly indicate the lagged variation in soil water on short timescales. According to your suggestion, we have revised the statements in the manuscript, particularly in the abstract and conclusion, regarding soil water as a key transitional reservoir. The detailed explanation is as follows (see Lines 30-52 and 570-597):

Abstract: Groundwater plays a crucial role in maintaining baseflow in rivers and ensuring water supply, particularly in alpine regions where the freeze–thaw (FT) cycle exerts a strong influence on hydrological processes. However, a systematic understanding is still lacking regarding how FT processes affect the composition of groundwater recharge sources and the transitions among recharge pathways. This study takes the Qinghai Lake basin (QLB) as a case study and combines water isotope and hydrometeorological data to quantify the dynamic characteristics of groundwater recharge sources and pathways during the FT periods. The study found that soil water (57.0%–76.3%) was the dominant source of groundwater recharge during the FT periods, followed by rainfall (13.8%–26.1%) and snowmelt (7.9%–22.0%). The thawing process enhances the vertical connectivity of the soil profile, facilitating the recharge of groundwater from snowmelt and the 60–90 cm soil layer. Furthermore, the  $\text{Ic}$ –excess value of groundwater gradually shifts from values closer to soil water to those closer to precipitation, indicating that piston flow gradually weakens during the process of groundwater recharge by soil water, while preferential flow intensifies, resulting in a pattern where piston flow and preferential flow coexist. Spatially, in the

middle and upper regions dominated by permafrost, groundwater is primarily recharged by water from the 0–60 cm soil layer traveling along longer hydrological pathways, whereas in the downstream regions of the basin dominated by seasonal frozen ground, groundwater is primarily recharged by rapid infiltration from the 30–90 cm soil layer. Our research demonstrates that in alpine permafrost regions, freeze-thaw processes regulate water storage and transport, thereby further influencing the recharge sources and pathways of shallow groundwater.

### *Conclusions*

In the context of climate warming, FT processes profoundly influence the groundwater recharge patterns in alpine regions. Using water isotope data and a MixSIAR model, this study systematically reveals the characteristics of groundwater recharge during the FT periods from the integrated perspective of recharge sources, transport pathways, and soil profile hydrological connectivity. The study found that during the FT periods, groundwater was recharged primarily by rainfall and soil water, while the contribution from snowmelt was relatively small. As the thawing process progresses, vertical hydrological connectivity within the soil profile continues to increase. Groundwater recharge from snowmelt, rainfall, and soil water in the 30–90 cm layer gradually intensifies. Meanwhile, the contribution from soil water in the 0–30 cm layer decreases significantly, indicating a gradual shift in groundwater recharge from shallow soil moisture to deeper soil moisture. The  $\delta^{18}O$ -excess value of groundwater gradually shifts from being close to that of precipitation to being close to that of soil water, reflecting the coexistence of preferential flow recharge and piston flow recharge. Spatially, in the middle and upper regions dominated by permafrost, groundwater is primarily recharged by water from the 0–60 cm soil layer traveling along longer hydrological pathways, whereas in the downstream regions of the basin dominated by seasonally frozen ground, groundwater is primarily recharged by rapid infiltration from the 30–90 cm soil layer. Overall, FT processes profoundly regulate the structure of groundwater recharge sources and transport pathways in alpine regions by controlling the connectivity among rainfall, snowmelt, soil moisture, and

groundwater. Given that permafrost degradation is expected to continue to intensify in the coming years, we propose that differences among groundwater recharge sources will likely decrease, while differences among recharge pathways may increase. The results of this study provide an important research foundation for understanding groundwater hydrological processes in alpine regions amid permafrost degradation, and contribute to deepening the understanding of the water cycle in alpine regions.

## 2. Comment:

The accuracy of the MixSIAR model is highly dependent on the representativeness of element values. In this study, precipitation elements are derived from monthly mixing samples, whereas soil water and groundwater values are based on monthly averages. However, during the melting season (May–June), diurnal freeze-thaw cycles occur, causing precipitation to manifest as rain, snow, or wet snow with distinct isotopic signatures. Additionally, snow cover may be influenced by sublimation of pre-melt snow, meltwater runoff over frozen or partially frozen surfaces, and soil surface evaporation following snowmelt. It is recommended that authors explicitly describe how such mixed precipitation samples are processed in the Methods section (2.4.3) and include a discussion (Section 4.4: Limitations) acknowledging the uncertainties introduced by this simplification, along with an analysis of its potential impact on conclusions regarding the contribution of meltwater (7.9–22.0%).

**Reply:** According to your suggestion, we have clarified in Section 2.2 how precipitation samples containing rain, snow, or wet snow were collected, composited, and processed before isotopic analysis. In Section 4.4, we have discussed the uncertainties associated with temporal averaging and processes such as snow sublimation, meltwater runoff over frozen ground, and post-melt evaporation, and have explained how these uncertainties may affect the estimated meltwater contribution of 7.9–22.0%. The detailed explanation is as follows (see Lines 193-199 and 551-556):

### *2.2 Sample collection*

Snow samples were collected from the snowpack using clean, sealed plastic bags.

When sampling, first remove the surface layer of snow, then collect a sample immediately adjacent to the soil interface, and allow it to melt naturally at room temperature on the day of sampling. All water samples, including snowwater, rainfall, and groundwater, were filtered through a 0.45  $\mu\text{m}$  membrane filter before being transferred to 100 ml polyethylene sample bottles.

#### *4.4 Significance and Limitations*

First, the snowmelt samples were collected from the snowpack, and processes such as sublimation before snowmelt and evaporation from the soil surface after snowmelt may alter the isotopic composition of snowmelt, thereby leading to an overestimation or underestimation of its contribution to groundwater recharge (Hyman-Rabeler and Loheide, 2023; Gottlieb and Mankin, 2025).

#### 3. Comment:

The text interprets a "lc-excess value closer to the precipitation end-point" as indicative of enhanced preferential flow, while a "lower LC-excess value" suggests dominance of piston flow (a soil water evaporation indicator) (Lines 43–44, 226–228). However, in Figure 3c, the variation in groundwater lc-excess across the three periods is minimal (approximately between  $-5\%$  and  $-2\%$ ). Moreover, the term "close to" is overly vague. It is recommended that the authors: a) include the difference between groundwater lc-excess and precipitation-end-point lc-excess ( $\Delta\text{lc-excess}$ ), or provide monthly data on precipitation, soil water content at different depths, and groundwater levels; and use seasonal variations of this metric to support the claim of "gradual enhancement of preferential flow," thereby enhancing the objectivity of the argument.

**Reply:** According to your suggestion, we have revised the description of the methods in Section 2.4.2 of the revised manuscript by comparing differences in  $\Delta\text{lc-excess}$  values during the freeze–thaw period to demonstrate that the isotopic evidence clearly indicates preferential flow during thawing. Meanwhile,  $\Delta\text{lc-excess}$  values for precipitation and soil water have been added to Section 4.3, providing more comprehensive evidence for the preferential flow observed during the freeze–thaw period. The detailed explanation is as follows (see Lines 237–248 and 515–517):

#### *2.4.2 Identifying the pattern of groundwater recharge from soil water*

To determine how soil water recharges groundwater in the QLB, we employed the line-conditioned excess (lc-excess) method (Landwehr and Coplen, 2006). This index quantifies the degree of deviation of a water body by calculating the vertical distance of a sample relative to the local meteoric water line (LMWL). During the recharge of groundwater by precipitation and soil water, piston flow and preferential flow typically exhibit different stable isotope signatures. Lower lc-excess values indicate that the water body has undergone evaporation, corresponding to piston flow of soil water. In contrast, the smaller the difference between the soil water lc-excess value and the precipitation lc-excess value ( $\Delta$ lc-excess), the more it indicates that preferential flow has occurred along the fast path. This method has been extensively used in permafrost watersheds on the QTP (Li et al., 2025; Li et al., 2025a).

#### *4.3 Preferential flow and piston flow coexist in the QLB*

Notably, during the thawed period, the lc-excess indices of soil water and precipitation are closest ( $\Delta$ lc-excess from 13.43 to 9.51), indicating that the role of preferential flow is gradually increasing.

#### **Minor Comments:**

##### **1. Comment:**

This manuscript uses hydrogen and oxygen isotope methods to investigate the effects of freeze-thaw processes on the sources and pathways of groundwater recharge. It is recommended that the method used be explicitly stated in the title to make the manuscript's theme clearer and more specific. For example: Freeze-thaw processes influence shallow groundwater recharge sources and pathways in the Qinghai Lake Basin: insights from water isotopes.

**Reply:** According to your suggestion, we have revised the title in the revised manuscript to “Freeze-thaw processes influence shallow groundwater recharge sources and pathways in the Qinghai Lake Basin: insights from water isotopes” to further highlight the main theme of the manuscript. The detailed explanation is as follows (see Lines 1-3):

Freeze-thaw processes influence shallow groundwater recharge sources and pathways in the Qinghai Lake Basin: insights from water isotopes.

2. Comment:

Line 31: “exerts a strong influence” It is recommended to change to “exerts a strong influence on hydrological processes” make the expression more complete.

**Reply:** According to your suggestion, we have revised the manuscript's “exerts a strong influence” to “exerts a strong influence on hydrological processes.” The detailed explanation is as follows (see Lines 30-32):

Groundwater plays a crucial role in maintaining baseflow in rivers and ensuring water supply, particularly in alpine regions where the freeze–thaw (FT) cycle exerts a strong influence on hydrological processes.

3. Comment:

Line 34: “takes the Qinghai Lake basin (QLB) as a case example”. It is recommended to change to “takes the Qinghai Lake Basin (QLB) as a case study” more in line with academic conventions.

**Reply:** According to your suggestion, we have revised the manuscript's “takes the Qinghai Lake basin (QLB) as a case example” to “takes the Qinghai Lake Basin (QLB) as a case study.” The detailed explanation is as follows (see Lines 34-37):

This study takes the Qinghai Lake basin (QLB) as a case study and combines water isotope and hydrometeorological data to quantify the dynamic characteristics of groundwater recharge sources and pathways during the FT periods.

4. Comment:

Line 37: The abbreviation "FT periods" appears for the first time; it is recommended to define it as "freeze-thaw (FT) periods" in the abstract when it first occurs (it has been defined in the main text but not in the abstract; consistency should be maintained).

**Reply:** According to your suggestion, we have defined “freeze-thaw” as “freeze-thaw

(FT) periods” when it first appears in the abstract of the revised draft and have maintained consistency throughout the manuscript. The detailed explanation is as follows (see Lines 30-32):

Groundwater plays a crucial role in maintaining baseflow in rivers and ensuring water supply, particularly in alpine regions where the **freeze–thaw (FT) cycle exerts a strong influence on hydrological processes.**

5. Comment:

Line 70: Are the references "Zhang et al., 2026" and "Biskaborn et al., 2025" unpublished or preprints? Please confirm whether they have been formally published; if in review, please indicate this.

**Reply:** According to your suggestion, we have verified the relevant references cited in the manuscript, clearly indicated their publication status in the revised version, and standardized the reference format in accordance with HESS requirements. As these revisions involve the entire reference, they are not presented here one by one.

6. Comment:

Line 83: “midwestern united states”, “United States” first letter should be capitalized.

**Reply:** According to your suggestion, we have corrected “united states” to “United States” in the revised manuscript and have simultaneously checked the full text for similar capitalization issues. The detailed explanation is as follows (see Lines 80-84):

For example, in the midwestern **United States**, **when snowmelts and then refreezes in mid-winter**, it impedes infiltration and increases runoff, resulting in a significant reduction in groundwater recharge from winter and spring snowmelt (Hyman et al., 2023).

7. Comment:

Line 134: For data such as "2.97×10<sup>4</sup> km<sup>2</sup>" and "1.23×10<sup>4</sup> km<sup>2</sup>," standardize the index format (use superscripts) and ensure no spaces are added between numbers and units throughout the text (e.g., "2.97 × 10<sup>4</sup> km<sup>2</sup>").

**Reply:** According to your suggestion, we have consistently used superscript formatting in the revised manuscript and have checked the entire text to ensure that no spaces are inserted between numbers and units, maintaining consistent formatting throughout. The detailed explanation is as follows (see Lines 134-139):

The QLB lies in the northeastern sector of the QTP, encompassing a total area of  $2.97 \times 10^4 \text{ km}^2$  (Fig. 1). Among these, permafrost primarily occurs in the upstream and high-altitude areas, covering approximately  $1.23 \times 10^4 \text{ km}^2$ , which represents 41.52% of the basin's entire area. Seasonally frozen soil is mainly distributed in the midstream, downstream, and areas surrounding the lake, covering  $1.74 \times 10^4 \text{ km}^2$ , accounting for 58.48% of the total basin area.

#### 8. Comment:

Figure 1: The subgraphs (a)–(e) in the figure caption lack sufficient detail; it is recommended to specify the exact content displayed by each subgraph in the legend (e.g., the relationship between sampling point distribution and permafrost/seasonal frozen soil boundaries).

**Reply:** According to your suggestion, we have added specific descriptions for subfigures (a)–(g) of Figure 1 in the revised manuscript and have clearly specified the content corresponding to each subfigure. The detailed explanation is as follows (see Lines 151-155):

**Fig. 1.** (a) Location of the QLB in China. (b) Location of the QLB on the QTP. (c) Spatiotemporal distribution of permafrost in the QLB, where gray and orange represent seasonal permafrost and permafrost, respectively. (d) Location of the QLB and distribution of sampling points. (e) Groundwater sampling. (f) Precipitation sampling. (g) Soil samples are collected monthly at adjacent locations.

#### 9. Comment:

Table 1: The numbering conventions ("P1, P2..." under the "Precipitation" category and "G1, G2..." under "Groundwater") should be specified in the table header or

footnote (whether based on elevation or watershed location).

**Reply:** According to your suggestion, we have added a note to Table 1 explaining the numbering convention, specifying that sampling points are numbered sequentially from upstream to downstream within each watershed. The detailed explanation is as follows (see Lines 175-177):

Note: Sampling sites within the QLB are numbered sequentially, starting from the western part of the watershed to the northwestern part, and from upstream to downstream.

#### 10. Comment:

Line 186: "Filtered through 0.45  $\mu\text{m}$  membrane filters": Are all water samples (including meltwater) filtered? Is groundwater filtered? Please provide consistent clarification.

**Reply:** According to your suggestion, we have clarified in Section 2.2 that all water samples, including rainfall, snowwater, soil water, and groundwater, were filtered through 0.45  $\mu\text{m}$  membrane filters before isotopic analysis. The detailed explanation is as follows (see Lines 197-199):

All water samples, including snowwater, rainfall, and groundwater, were filtered through a 0.45  $\mu\text{m}$  membrane filter before being transferred to 100 ml polyethylene sample bottles.

#### 11. Comment:

Line 196: In the analysis accuracy, the expressions " $\delta^2\text{H} \pm 0.5\text{‰}$ " and " $\delta^{18}\text{O} \pm 0.1\text{‰}$ " should have the symbol "‰" the numerical value; it is recommended to revise them to formats such as " $\delta^2\text{H}: \pm 0.5\text{‰}$ ".

**Reply:** According to your suggestion, we have uniformly revised this statement in Section 2.3 of the revised manuscript to " $\delta^2\text{H}: \pm 0.5\text{‰}$  and  $\delta^{18}\text{O}: \pm 0.1\text{‰}$ ". The detailed explanation is as follows (see Lines 205-206):

The instrument's analytical precision was  $\delta^2\text{H}: \pm 0.5\text{‰}$  and  $\delta^{18}\text{O}: \pm 0.1\text{‰}$ .

## 12. Comment:

Line 261: "In the 0–30 cm soil layer... lowest LC excess." Please supplement with statistical differences (and their significance) between the 30–60 cm and 60–90 cm layers; it is recommended to specify the significance test method used in the methods section to enhance the rigor of the analysis.

**Reply:** According to your suggestion, we have specified the statistical test used to compare lc-excess among the 0–30, 30–60, and 60–90 cm soil layers in Section 2.4.4. We have also reported the corresponding test statistics and p-values, and clarified which differences are statistically significant. The detailed explanation is as follows (see Lines 273-278, 291-294, 343-345 and 349-351):

### *2.4.4 Statistical analysis*

One-way analysis of variance (ANOVA) was used to compare soil water indicators ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ , lc-excess, and SWC) among different soil layers. Multiple comparisons were performed using the least significant difference (LSD) test, with the significance level set at  $p < 0.05$ . All statistical analyses were performed using SPSS version 22.0.

The  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values of soil water in all soil layers increased. Among these, the 0–30 cm soil water had the highest  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values, and its lc-excess remained significantly lower than that of the 30–90 cm soil water and groundwater ( $p < 0.05$ ). In the downstream basin, SWC in the 0–30 cm layer during the thawing period was only 15.69%, significantly lower than the 23.80% and 23.49% observed in the 30–60 cm and 60–90 cm layers, respectively ( $p < 0.05$ , Fig. 5b).

which was significantly higher than the 22.26% and 22.75% in the 0–30 cm and 30–60 cm layers, respectively ( $p < 0.05$ ).

## 13. Comment:

Line 263-264: “precipitation shifted overall from depleted to enriched”, It is recommended to specify the exact change in the average  $\delta^{18}\text{O}$  value (e.g., from -8‰ to -5‰) to enhance persuasiveness.14. Figure 3: The color differentiation in subplots (a), (b), and (c) of the figure is insufficient; it is recommended to use a color-blind-friendly palette.

**Reply:** According to your suggestion, we have included the specific changes in the average  $\delta^{18}\text{O}$  values of precipitation in the revised manuscript and optimized the color scheme in Figure 3 to make the subfigures clearer and easier to read. The detailed explanation is as follows (see Lines 289-191 and 304):

During the thawed period, the  $\delta^{18}\text{O}$  values of precipitation shifted overall from depleted to enriched ( $\delta^{18}\text{O}$ : from  $-11.57\text{‰}$  to  $-8.93\text{‰}$ ).

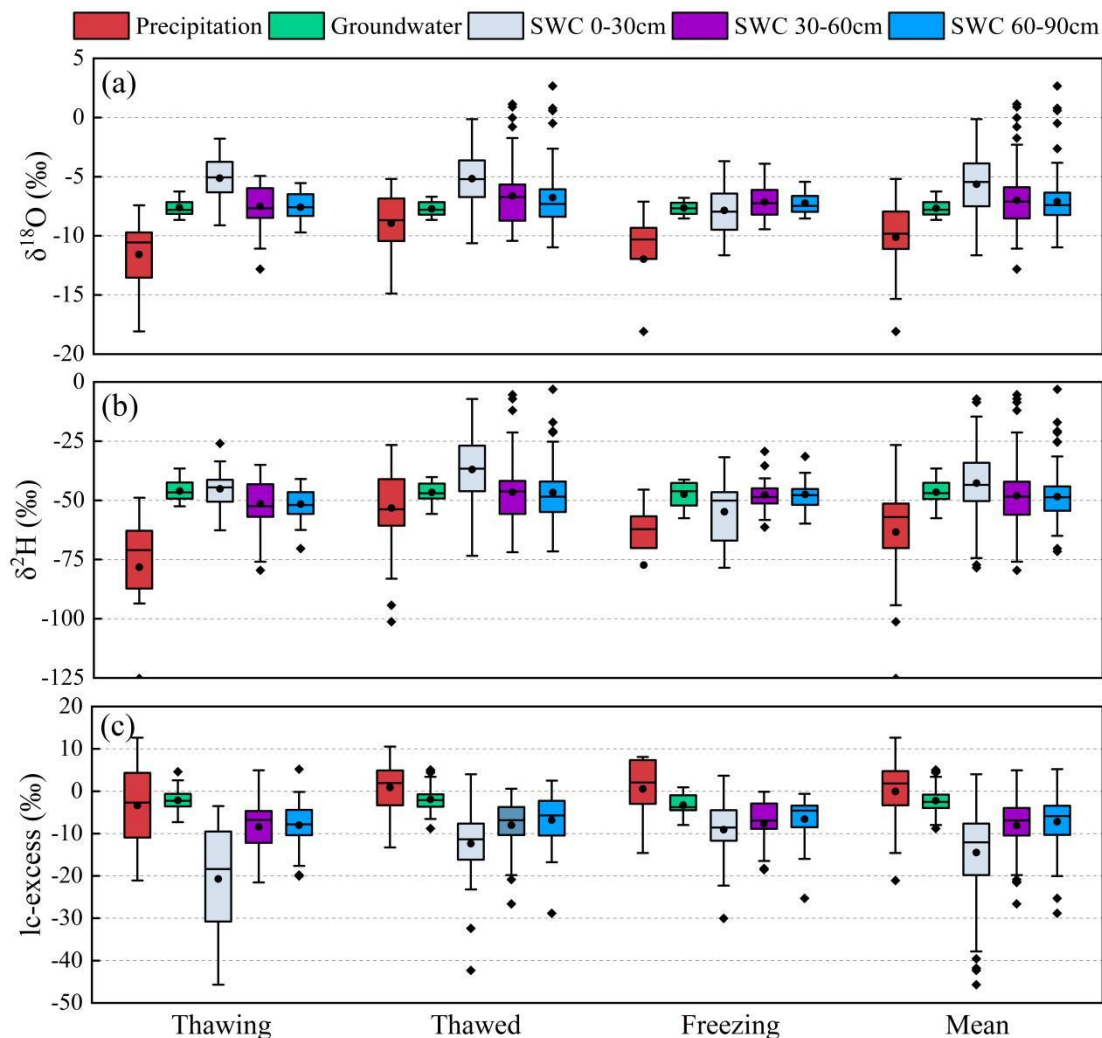


**Fig. 3.** Variations in  $\delta^2\text{H}$  (a),  $\delta^{18}\text{O}$  (b), and lc-excess (c) of precipitation, groundwater, and soil water at different depths during FT periods. The error bar represents the variance of the calculated results across all data points.

#### 14. Comment:

Line 295: “GWL was closest to the 60-90 cm SWL” , Provide  $R^2$  or the slope difference to quantify the degree of "proximity."

**Reply:** According to your suggestion, we have included the difference in slopes in the revised draft to more clearly quantify how close they are. The detailed explanation is as follows (see Lines 322-324):

The slope of the groundwater was 5.81, and the slope for 60–90 cm SWL was 5.90. These two values were the closest to each other (Fig. 4d).

15. Comment:

Line 361-362: The author mentions that "the contribution of meltwater is significantly lower than that of rainfall," yet Figure 6 shows that during the melting period, meltwater still accounts for 11.88–16.17%. It is recommended to emphasize in the discussion section that "although low, it cannot be overlooked" to avoid inconsistency in tone throughout the text.

**Reply:** According to your suggestion, we have explicitly stated in Section 4.1 of the revised draft that, although the contribution from snowmelt is relatively small, it cannot be ignored. The detailed explanation is as follows (see Lines 392-393):

Although the contribution from snowmelt is relatively small, it cannot be ignored.

16. Comment:

Line 459-461: The bidirectional freezing process causes soil water to transition from liquid to solid state. Please elaborate on the potential impact of this process on  $\delta^{18}O$ -excess (whether it may lead to isotopic fractionation), as this aspect has not been addressed in the current discussion.

**Reply:** According to your suggestion, we have further discussed the potential effects of soil-water phase transitions during bidirectional freezing on  $\delta^{18}O$ -excess and possible isotopic fractionation in Section 4.4 of the revised draft. The detailed explanation is as follows (see Lines 556-560):

*4.4 Significance and Limitations*

Second, during freezing, soil water transitions from the liquid phase to the solid phase. As the freezing front advances, light isotopes may be preferentially retained in the unfrozen liquid water, whereas heavy isotopes become preferentially enriched in the

ice phase, resulting in isotopic fractionation and altering  $\delta^{18}O$ -excess, thereby complicating the identification of recharge pathways (Zhang et al., 2025).

17. Comment:

References: The literature formats are inconsistent: some entries include volume and issue numbers, while others lack issue numbers (e.g., Alley et al., 2002; Kooi, 2016). It is recommended to strictly adhere to the author guidelines of the journal Hydrology and Earth System Sciences and maintain uniform formatting. Additionally, there are several instances of inconsistent "et al." formatting (some in italics, others not); please review these cases.

**Reply:** According to your suggestion, we have uniformly reviewed and adjusted the formatting of references and the use of "et al." throughout the revised manuscript to ensure compliance with the HESS Author Guidelines. As these revisions involve the entire reference, they are not presented here one by one.

## **Response to Anonymous Referee #2:**

This manuscript investigates the effects of freeze–thaw (FT) processes on shallow groundwater recharge sources and transport pathways in the Qinghai Lake Basin, combining stable water isotopes, hydrometeorological data, and the MixSIAR model, given ongoing permafrost degradation across alpine regions. The study provides useful insights: soil water acts as both a dominant recharge source and a transitional reservoir linking precipitation and snowmelt to groundwater, and thawing progressively enhances vertical soil-profile connectivity. Overall, the experimental design is reasonable, the data are abundant, and the analytical methods are appropriate, making this a well-structured manuscript. However, further improvements are needed in the following aspects: (1) specialized terminology should be further standardized and used consistently throughout the text; (2) figures and tables need refinement; (3) the conclusions and innovative points need further refinement and sharpening.

**Reply:** We sincerely thank the reviewers for their constructive and encouraging feedback. According to your suggestion, we have made substantial revisions to the manuscript, focusing on improving the accuracy of the wording, refining the figures and tables, and further clarifying the conclusions and points of innovation (see the replies to the following comments).

### **1. Comment:**

Use consistent terminology throughout the manuscript, including “freeze–thaw processes,” “freeze–thaw periods,” “soil water,” “shallow groundwater,” “recharge source,” and “recharge pathway.”

**Reply:** According to your suggestion, we have carefully reviewed the manuscript to ensure consistent use of “freeze–thaw processes,” “freeze–thaw periods,” “soil water,” “soil water content (SWC),” “shallow groundwater,” “recharge sources,” and “recharge pathways.” As these revisions involve the entire manuscript, they are not presented here one by one.

### **2. Comment:**

Refine the novelty and practical implications. The manuscript should more explicitly identify what is new relative to previous isotope-based studies of groundwater recharge in the Qinghai–Tibet Plateau. The practical implications for groundwater-resource management, ecohydrological protection, or river-baseflow maintenance in the Qinghai Lake Basin should also be stated more specifically.

**Reply:** According to your suggestion, we have further synthesized the deficiencies in previous research. We have also introduced a new Section 4.4 to explicitly discuss the practical implications for groundwater-resource management, ecohydrological conservation, and sustaining river baseflow in alpine regions, including the Qinghai Lake Basin. The detailed explanation is as follows (see Lines 93-100 and 538-549):

### *1. Introduction*

Currently, research on groundwater hydrological processes in alpine regions still has the following knowledge gaps: (1) most studies focus on qualitative analysis, and a detailed quantification of groundwater recharge sources remains lacking; (2) there is a lack of studies that investigate groundwater recharge processes from the perspective of the freeze-thaw period; (3) the responses of permafrost and seasonally frozen ground to climate warming, and their implications for groundwater recharge and availability, remain poorly understood.

### *4.4 Significance and Limitations*

From an integrated perspective encompassing recharge sources, transport pathways and hydrological connectivity across the soil profile, this study systematically elucidates how FT processes regulate shallow groundwater recharge in the QLB. These findings highlight the critical role of soil water in sustaining shallow groundwater recharge in alpine regions. Against the backdrop of permafrost degradation and changing precipitation patterns, the spatiotemporal dynamics of groundwater recharge may be reorganized. Meanwhile, permafrost and seasonally frozen ground exhibit distinct responses to climate warming, resulting in differing effects on groundwater recharge. Moreover, focusing solely on rainfall sources may lead to an underestimation of the contributions of snowmelt and soil water to

groundwater recharge.

3. Comment:

Line 83: “united states” should be capitalized: “United States.”

**Reply:** According to your suggestion, we have corrected “united states” to “United States” in the revised manuscript and carefully checked capitalization throughout the manuscript. The detailed explanation is as follows (see Lines 81-82):

For example, in the midwestern United States, when snowmelts and then refreezes in mid-winter.

4. Comment:

Lines 83-84: Grammatical error. “snowmelts” is not a verb form. Please revise to “when snow melts and then refreezes in mid-winter.”

**Reply:** According to your suggestion, we have revised the sentence to “when snow melts and then refreezes in mid-winter” and carefully checked the manuscript for similar grammatical errors. The detailed explanation is as follows (see Lines 81-84):

For example, in the midwestern United States, when snowmelts and then refreezes in mid-winter, it impedes infiltration and increases runoff, resulting in a significant reduction in groundwater recharge from winter and spring snowmelt (Hyman et al., 2023).

5. Comment:

Line 106: This phrasing is informal. Consider replacing with “In the Three-Rivers Headwaters Region, for example,” for a more formal academic register.

**Reply:** According to your suggestion, we have revised “Taking the Three-Rivers Headwaters Region as an example” to “In the Three-Rivers Headwaters Region, for example,” to better suit a formal academic style. The detailed explanation is as follows (see Lines 105-108):

In the Three-Rivers Headwaters Region, for example, groundwater above the permafrost layer is younger (shorter water transit time) during the thawing period, and

topographical variations affect groundwater flow pathways (Du et al., 2024).

6. Comment:

Line 107: “Younger” refers to mean residence time or isotopic age, but this is not explained. Please briefly clarify what “younger” means in this context (e.g., shorter mean transit time).

**Reply:** According to your suggestion, we have explicitly stated in the revised manuscript that “younger” denotes a shorter mean residence time in this context, corresponding to a shorter water transit time, and added this clarification where appropriate. The detailed explanation is as follows (see Lines 105-108):

In the Three-Rivers Headwaters Region, for example, groundwater above the permafrost layer is younger (shorter water transit time) during the thawing period, and topographical variations affect groundwater flow pathways (Du et al., 2024).

7. Comment:

Lines 121-122: Please revise to past tense: “we established a comprehensive ecohydrological monitoring network within the QLB.”

**Reply:** According to your suggestion, we have revised the sentence to “We established a comprehensive ecohydrological monitoring network within the QLB” and checked the manuscript to ensure that descriptions of completed work are consistently written in the past tense. The detailed explanation is as follows (see Lines 122-123):

To this end, we established a comprehensive ecohydrological monitoring network within the QLB.

8. Comment:

Line 165: Missing comma after “2015” and after “2023”. Please standardize to “Peng et al., 2015; Li et al., 2022; Peng et al., 2023.”

**Reply:** According to your suggestion, we have revised all citations in the revised manuscript to conform to the format “Peng et al., 2015; Li et al., 2022; Peng et al.,

2023” and carefully reviewed the punctuation throughout the entire manuscript. The detailed explanation is as follows (see Lines 170-171):

**Fig. 2.** Hydrogeologic profile of the QLB (based on Peng et al., 2015; Li et al., 2022; Peng et al., 2023).

#### 9. Comment:

Lines 187-190: This sentence appears at the end of the sampling section but describes a spatial classification that affects the entire study. It would be better placed earlier in Section 2.1 when the study area is introduced.

**Reply:** According to your suggestion, in the revised manuscript, we have moved the sentence “Considering the influences of elevation, topography, and groundwater burial depth, the spatiotemporal variations in this study are classified into the downstream basin and middle and upper reaches of the basin” to Section 2.1, “Study area.” The detailed explanation is as follows (see Lines 146-149):

#### *2.1 Study area*

Considering the influences of elevation, topography, and groundwater burial depth, the spatiotemporal variations in this study are classified into the downstream basin and middle and upper reaches of the basin.

#### 10. Comment:

Line 290: “its  $R^2$  decreased” — decreased relative to what baseline or period? Please specify the comparison explicitly.

**Reply:** According to your suggestion, we have explicitly stated in the revised manuscript that this  $R^2$  value is compared with that of the thawing period. The detailed explanation is as follows (see Lines 316-318):

However, compared to the thawing period, the slope of the GWL remained lower than those of all SWLs, and its  $R^2$  decreased (Fig. 4b).

#### 11. Comment:

Line 296: Spaces are missing in the legend entries, e.g., “SW 0–30cm” should be

written as “SW 0–30 cm”.

**Reply:** According to your suggestion, we have revised “SW 0–30cm” in the figure legend to “SW 0–30 cm” and carefully examined the full manuscript for other instances of missing spaces. The detailed explanation is as follows (see Lines 325-327):

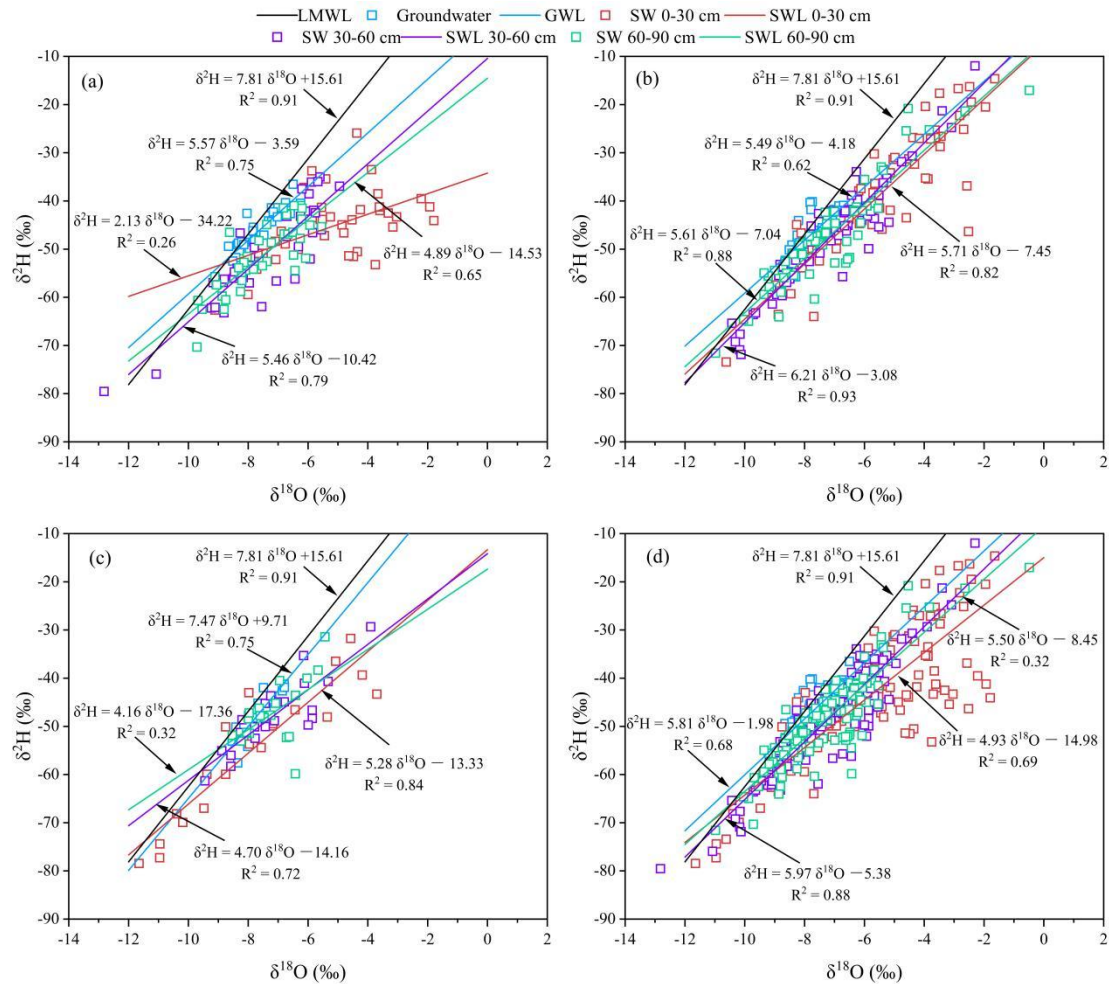


**Fig. 4.** Changes in the  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  correlation across various water types during (a) thawing, (b) thawed, (c) freezing, and (d) the entire FT periods.

## 12. Comment:

Lines 300-323: The SWC values are reported to two decimal places (e.g., 26.90%, 28.41%), implying a precision that may not be justified given the spatial heterogeneity of field measurements. Please report values to one decimal place.

**Reply:** According to your suggestion, we have ensured that all SWC values are reported to a consistent number of decimal places throughout the revised manuscript.

The detailed explanation is as follows (see Lines 169 and 295):

The SWC in the QLB exhibited pronounced spatiotemporal variation characteristics (Fig. 5). In the middle and upper reaches, SWC in the 0–30 cm, 30–60 cm, and 60–90 cm layers was 26.9%, 28.4%, and 31.1%, respectively, showing an increasing trend with depth during the thawing period (Fig. 5a). During the thawed period, the SWC in the 0–30 cm layer of the middle and upper reaches of the basin was the highest (27.8%), while that in the 30–60 cm and 60–90 cm layers decreased to 26.2% and 24.5%, respectively. During the freezing period, the differences among the layers diminished, with values of 26.9%, 25.5%, and 25.9%, respectively. Throughout the QLB, SWC was lowest in the 0–30 cm layer during the thawing period, while it was relatively higher in the 30–90 cm layer. During the thawed period, the differences among the layers decreased. The SWC in the 0–30 cm and 30–60 cm layers rose to 26.9% and 26.3%, respectively, while that in the 60–90 cm layer dropped to 24.7%. During the freezing period, SWC generally increased across all soil layers, with the 60–90 cm layer showing the most significant increase, rising to 26.7%. In the downstream basin, SWC in the 0–30 cm layer during the thawing period was only 15.7%, significantly lower than the 23.8% and 23.5% observed in the 30–60 cm and 60–90 cm layers, respectively ( $p < 0.05$ , Fig. 5b). During the thawed period, the SWC in all layers decreased to approximately 16.0%, and the differences among the soil layers became significantly smaller. During the freezing period, SWC in all layers increased overall, with the most pronounced increase observed in the 60–90 cm layer (28.3%), which was significantly higher than the 22.3% and 22.8% in the 0–30 cm and 30–60 cm layers, respectively ( $p < 0.05$ ). Overall, SWC in the middle and upper reaches of the basin was generally higher than in the downstream basin.

### 13. Comment:

Line 378: The unit “‰” is incorrect here; SWC is expressed as a percentage (%). Please correct to “26.90%–31.05%.”

**Reply:** According to your suggestion, we have revised the units of all SWC

measurements in the revised manuscript from “‰” to “%”. The detailed explanation is as follows (see Lines 409-411):

This may be related to the fact that during the thawed period, SWC in each layer of the middle and upper reaches of the basin remained at 26.90%–31.05%, significantly higher than that in the downstream basin.

14. Comment:

Line 388: Throughout the manuscript, contribution values are reported to two decimal places (e.g., 13.01%, 9.33%). This value should be given as “10.60%” for consistency.

**Reply:** According to your suggestion, we have revised “10.6” to “10.60%” in the revised manuscript and reviewed the number of decimal places reported for all contribution values throughout the manuscript to ensure a consistent format. The detailed explanation is as follows (see Lines 419-421):

In addition, with the widespread melting of snow cover in summer, the contribution rate of snowmelt to groundwater dropped to 10.60%.

15. Comment:

Lines 423-426: “This is consistent with results from modeling analyses indicating that spring hydrological processes in the alpine regions of the QTP are mainly governed by a combination of active layer temperature, thaw depth, and SWC” — no citation is provided for this modeling result. Please add the appropriate reference

**Reply:** According to your suggestion, we have added the appropriate references supporting this modeling result and reviewed the manuscript to ensure that all statements based on previous studies are adequately cited. The detailed explanation is as follows (see Lines 457-460):

This is consistent with results from modeling analyses indicating that spring hydrological processes in the alpine regions of the QTP are mainly governed by a combination of active layer temperature, thaw depth, and SWC (Wang et al., 2023b).

16. Comment:

Line 469: Decimal places should be kept consistent throughout Figure 8.

**Reply:** According to your suggestion, we have verified and harmonized the decimal places of all numerical values in Figure 8 in the revised manuscript to ensure consistency. The detailed explanation is as follows (see Line 504):

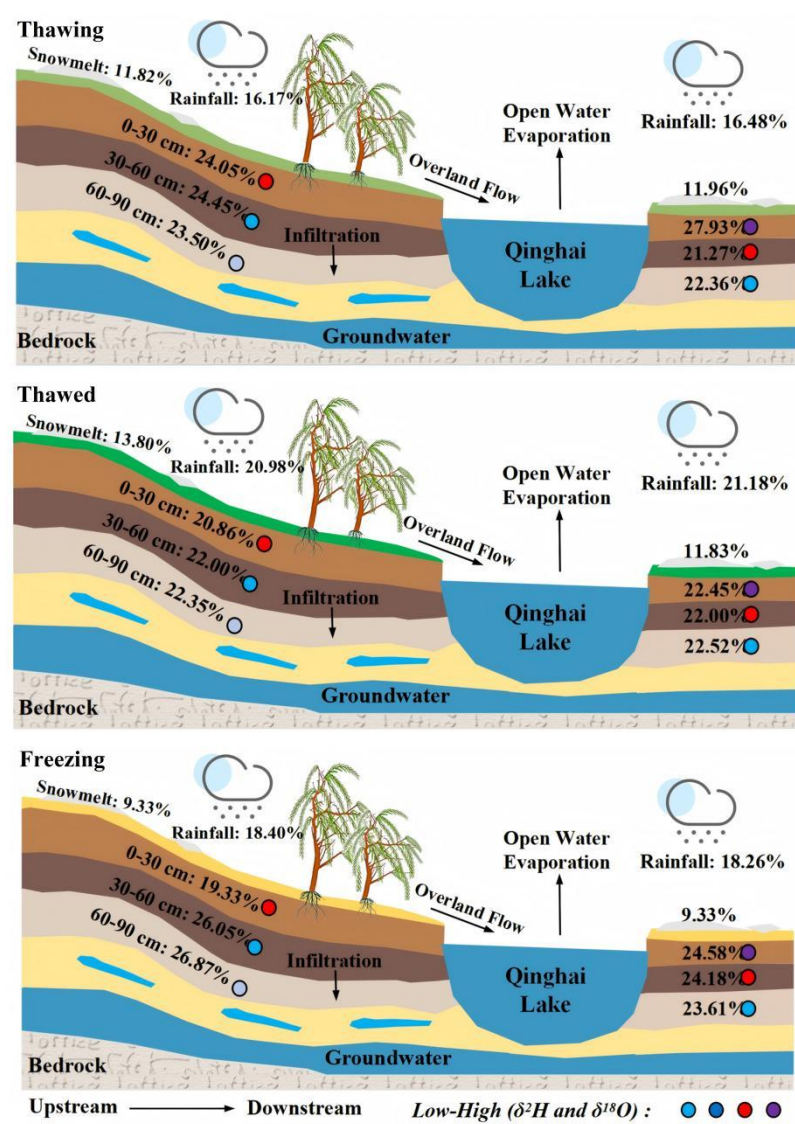


**Fig. 8.** Graphical summary of the contributions of rainfall, snowmelt, and soil water from different depths to groundwater recharge during the FT periods.

# 17. Comment:

Line 474: “RWL” has not been previously defined in the manuscript. Please define this abbreviation on first use.

**Reply:** According to your suggestion, we have corrected the abbreviation “RWL” to

“SWL” and defined “soil water level (SWL)” at its first occurrence. The detailed explanation is as follows (see Lines 309-311):

In the QLB, the  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values for precipitation, soil water, and groundwater all cluster around the LMWL, but the **soil water line (SWL)** and **groundwater line (GWL)** were generally below the LMWL (Fig. 4).

18. Comment:

Lines 492-495: Consider restructuring as: “Observations in an alpine meadow further confirm that by regulating active layer thickness, FT processes significantly alter the proportions of piston flow and preferential flow (Musa et al., 2016; Li et al., 2026b).”

**Reply:** According to your suggestion, we have revised the sentence to read: “Observations in an alpine meadow further confirm that FT processes significantly alter the proportions of piston flow and preferential flow by regulating active-layer thickness (Musa et al., 2016; Li et al., 2026b).” The detailed explanation is as follows (see Lines 528-530):

Observations in an alpine meadow further confirm that by regulating active layer thickness, FT processes significantly alter the proportions of piston flow and preferential flow (Musa et al., 2016; Li et al., 2026b).