Isotopic variations in surface waters and groundwaters of an extremely arid basin and their responses to climate change ~~Spatial–Seasonal Isotopic Variations in a Surface–Groundwater System in an Extremely Arid Basin and the Associated Hydrogeological Indications~~

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Abstract

Climate change~~warming~~ accelerates the global water cycle. However, the relationships between climate change~~warming~~ and hydrological processes in the alpine arid regions remain elusive~~unclear~~. ~~Herein,~~ We sampled surface water and groundwater at high spatial and temporal ~~spatiotemporal~~ resolution ~~sampling of surface water and groundwater was performed at~~ to investigate these relationships in the Qaidam Basin, an extremely arid area in the northeastern Tibetan Plateau. Stable H-O isotopes and radioactive ^{3}H isotope~~s~~ were combined with atmospheric simulations to examine hydrological processes and their response mechanisms to climate change~~climate change and hydrogeological characteristics~~. Contemporary climate processes~~rules~~ and change dominate the spatial and temporal variations ~~distribution pattern~~ of surface water isotopes, specifically, the westerlies moisture transport~~ation intensity~~~~westerly water vapor transport intensity~~ and the local temperature and precipitation regimes. ~~The surface water heavy isotopes enrich during the wet season and deplete during the dry season.~~ The spatial H-O isotopic compositions in the Eastern Kunlun Mountains showed a gradually depleted eastward pattern; while a reverse pattern occurred in the Qilian Mountains water system. ~~The~~ Precipitation ~~contribution~~ contributed significantly more to ~~of precipitation to~~ river discharge ~~was considerably higher~~ in the eastern ~~region of the~~ basin (approximately 45%) than in the ~~central~~ middle and western basin~~regions~~ (10%–15%). ~~The H-O isotopic compositions showed a gradually negative spatial pattern from the west to the east in the Eastern Kunlun Mountains water system; a reverse pattern occurred in the Qilian Mountains water system.This distribution pattern was jointly regulated by the westerly water vapor transport intensity and local hydrothermal condition.~~

Moreover, ~~Increased~~ increasing precipitation and shrinking cryosphere ~~cryosphere shrinkage~~ caused by current climate ~~warming~~ change have ~~mainly~~ accelerated basin groundwater circulation~~cycle~~. In the eastern and southwestern Qaidam Basin, precipitation and ~~ice/snow~~ meltwater infiltrate along preferential flow paths~~structural channels that favor water flow~~, such as ~~fractures~~faults, volcanic channels, and fissures, permitting~~facilitating~~ rapid seasonal groundwater recharge and enhanced~~increased~~ terrestrial water storage. However, compensating for water loss due to long-term ice and snow melt will be a challenge under projected~~future~~ ~~increases in~~increasing precipitation in the southwestern Qaidam Basin, ~~compensating for water loss from long-term melting of ice and snow will be challenging,~~ and the total water storage~~resources~~ may show ~~an~~ a trend of ~~initially~~ increasing ~~and then~~before decreasing ~~trend~~. Great uncertainty about water is a potential climate change risk facing the arid Qaidam Basin.

~~**Keywords:** Qaidam Basin; isotope hydrology; water cycle; spatiotemporal pattern; climate~~

1. Introduction

In the face of ongoing environmental changes~~Amidst the impending climate change process~~, a thorough understanding~~an in-depth study~~ of the hydrological cycle ~~processes~~ is a prerequisite for accurate trend forecasting, and helps to design efficient water resource management strategies~~implementing water resource management and trend forecasting~~. Over the past half ~~-~~century, ~~continuous~~ climate change~~warming~~ and more intense~~intensified~~ human activities have led to global water cycle acceleration and water resource redistribution at different scales (Huntington et al., 2006; Durack et al., 2012; Masson-Delmotte et al., 2021). For example, rapid warming has sharply expanded~~driven the~~ lakes~~rapid expansion of~~ ~~lakes~~ in the Tibetan Plateau and ~~the~~ shrunk them~~shrinking~~ ~~of lakes~~ in the Mongolian Plateau (Zhang et al., 2017), and ~~it~~ has also exacerbated~~amplified~~ the severe ~~shortage of~~ irrigation water shortage in parts of South Asia and East Asia (Haddeland et al., 2014). Moreover, ~~it~~ warming is expected to ~~also~~ reduce groundwater storage in the western ~~region of the~~ United States (Condon et al., 2020). Currently~~At present~~, the climate in arid regions of northwestern China is changing ~~are undergoing a change in climate~~ from warm–dry to warm–~~humid~~ wet (Zhang et al., 2021). The resulting uncertainties in water resources in arid alpine ~~arid~~ basins ~~water resources in this region present~~ pose new challenges ~~in~~ to understand~~ing~~ the hydrological cycle and water resources~~present state of water resources~~. These key scientific issues can be addressed~~resolved~~ by investigating the ~~spatiotemporal~~spatial and temporal distribution and controldriving mechanisms of surface water and groundwater resources in within the basin under accelerating climate changeclimate warming.

The Tibetan Plateau, also known as the “Third Pole”, has complex cryosphericcryosphere-hydrologichydrology-geodynamic processes and is especially susceptiblevulnerable to global warming (Zhang et al., 2017; Yao et al., 2022). The Qaidam Basin in the northeastern Tibetan Plateau is the area that has warmed the most in the entire Tibetan PlateauThe Qaidam Basin is situated in the northeastern Tibetan Plateau and presents the largest extent of warming in the entire Tibetan Plateau and a substantial steep rise in temperature globally (Li et al., 2015; Kuang and Jiao, 2016; Yao et al., 2022). Since 1961, the average temperature of the basin has increasedbeen rising at an alarming rate of 0.53°C per decade/10 a caused byas a result of climate warming (Wang et al., 2014), resulting in an increased in precipitation and cryospheric retreat of the cryosphere in the region (Song et al., 2014; Xiang et al., 2016; Zou et al., 2022; Wang et al., 2023). These changes have led to drasticrapid spatial changes in surface water and groundwater storage in the Qaidam Basin, increased increasing runoff or rising groundwater table over wide areas in most parts of the region (Jiao et al., 2015; Wei et al., 2021), and hydrological changes, such as the expansion of lakes, in the central and northern regions of the basin, such as the lakes expansion (Ke et al., 2022; Zhang et al., 2022). However, several questions remain to be resolvedanswered: How are hydrological changes in the basin driven by climate changes? What are the potential influences of these changes on the water resources of the basin? The dynamics of surface water and groundwater, which link precipitation and meltwater from high elevations with the low-lying lake basins, provide evidence of the effects of climate change on water cycle processes. These issues require an in-depth investigation. Rivers and groundwater carry precipitation and meltwater from high-altitude areas to the lakes in low-lying areas; information on climate-hydrology dynamics of the runoff process can provide key evidence for the entire water cycle process. Hence, tThe Qaidam Basin is therefore an excellent site for to reveal the mechanisms of global warming-induced responses to the hydrological cycle on the Tibetan Plateauinvestigating the response mechanism of the hydrological cycle in the Tibetan Plateau caused by global warming.

The isotopes of hydrogen and oxygen are useful Water isotopes (H and O) represent important components of water molecules and are useful natural environmental tracers of for the water cycle and climate reconstruction, and . they They can help elucidate the processes that control water cycle changes, thus providing scientific evidence for human adaptations and effects on future global changes (Craig, 1961; Dansgaard, 1964; Yao et al., 2013; Bowen et al., 2019; Kong et al., 2019; Zhu et al., 2023). ~~Stable w~~Water isotope records provide key information on water flow~~migration processes~~, and they can compensate for the paucity of hydrometeorological, geological, and borehole data in hydrological research. Stable H-O isotopes and radioactive ^{3}H isotope~~s~~ have been widely applied to quantify surface water or groundwater recharge sources, interactions, budgets, and ages (Befus et al., 2017; Stewart et al., 2017; Moran et al., 2019; Bam et al., 2020; Rodriguez et al.,2021; Shi et al., 2021; Ahmed et al., 2022; Benettin et al., 2022). Previous researchers have also performed a substantial amount of work on ~~the use of~~ using isotopes to delineate~~trace~~ the water cycle in the Qaidam Basin (Xu et al., 2017; Xiao et al., 2017, 2018; Zhao et al., 2018; Tan et al., 2021; Yang and Wang, 2020; Yang et al., 2021). These studies have enhanced our understanding of aquifer properties in local regions and ~~their~~ recharge mechanisms. However, past assessments of the water cycle in the Qaidam Basin have been constrained by the challenges of the harsh natural conditions and scarce ~~of~~hydrogeological data~~under the constraints of the harsh climate environment and hydrogeological survey accessibility in the Qaidam Basin, the water cycle processes in the basin in previous reports are mainly understood based on the watershed or confined regional unit scale.~~ It is a great challenge~~The use of regional research~~ to achieve a comprehensive elucidation of the basin-scale water cycle mechanism~~ is a challenge~~. Furthermore, ~~the surface water and groundwater~~ seasonal recharge ~~information~~ of the whole basin has not been systematically explored. Various hydrological, climatic, and hydrogeological conditions of the basin are caused by ~~Continuous~~ continuous changes in the topographical and tectonic spatial patterns~~ of the basin are caused by various hydrological, climatic, and hydrogeological conditions~~; moreover, the hydrological effects exerted by anthropogenic climate change~~ and regional aquifer properties~~ differ seasonally (Jasechko et al., 2014). Therefore, it is urgent~~particularly essential~~ to develop a comprehensive understanding ~~study the entire process~~ of the basin water cycle and its seasonal changes. While carrying out a comprehensive assessment of differences in isotopic composition~~isotope~~s of various potential recharge sources, it is fundamental to use the same technical methods for the systematic sampling and isotopic characterization of the basin.

In this study, we constrain the hydrological cycle of the Qaidam Basin and surrounding mountains using stable H-O and radioactive ^{3}H isotope data collected during the wet and dry seasons from eight study sites in ~~the eight~~ major watersheds in the basin~~ of the Qaidam Basin were~~

~~selected as the study sites, and constraints were placed on the hydrological cycle patterns and processes of the Qaidam Basin based on stable H-O isotope and radioactive ^{3}H isotope data from the wet-dry season~~. The study aims are:~~were to~~ 1) to ~~elucidate~~ elucidate the ~~spatial-seasonal~~ distribution pattern of surface water and groundwater isotopes ~~of surface-groundwater isotopes at different watershed scales~~ in this alpine arid basin at various spatial and seasonal scales; ~~2) analyze the composition changes of the Qaidam Basin water sources at different spatial-seasonal scales;~~ ~~3~~2) to identify and quantify the main components of the regional water cycle, their timing and spatial heterogeneity~~trace the entire water cycle process around the mountain-basin watersheds of the Qaidam Basin~~; and ~~4~~3) to reveal isotopic hydrological responses to climate change and to predict the trend ~~in~~ of the changes of Qaidam Basin water resources~~under the influence of a large extent of climate warming~~. ~~The scientific contributions of this study include clarifying the isotope hydrology responses to climate change in the Tibetan Plateau arid basin, which is one of the ecosystems most affected by climate warming worldwide, from a microscopic scale; predicting the changing trend of water resources under the condition of multiple water sources recharge; and elucidating the entire water cycle process in extremely arid basins under the influence of rapid climate change.~~

2. Study area

2.1. General features

The Qaidam Basin is a closed~~ and huge~~ fault-depression ~~basin situated in~~basin in the northeastern Tibetan Plateau surrounded by the Kunlun, Qilian and Altun Mountains (Figures 1a and 1b). The basin is one of the four main basins in China ~~With~~ with an area of approximately 250,000 km^2~~, the basin is one of the four main basins in China, and it is surrounded by the Kunlun Mountains, Qilian Mountains and Altun Mountains~~. ~~The Qaidam Basin~~It has a plateau continental climate ~~and represents~~ with a typical alpine arid inland basin ~~that is~~ characterized by drought. There are significant temperature variations ~~substantial variations~~ across~~in~~ the basin~~ temperature~~, and the ~~average~~ mean annual temperature is ~~below~~ less than 5 °C. ~~The a~~Annual precipitation ~~declines~~ varies from 200 mm in the southeastern region to 15 mm in the northwestern region. ~~The average~~ Mean annual relative humidity is 30%–40%, with a minimum of less than~~lower than~~ 5%. Modern glaciers have formed in the mountains on the western, southern and northeastern~~northern~~ sides of the basin~~,~~. The basin ~~which~~ is surrounded by more than 100 rivers~~.~~, ~~Approximately~~ about

10 rivers of which are perennial~~permanent~~, with most of the local rivers~~ representing~~ being intermittent river systems. The rivers are mainly distributed on the eastern side of the basin but ~~scant ~~are scarce on the western side. The water in the basin's lakes ~~has become~~is predominantly saline, with a total of ~~comprising ~~31 salt lakes~~ in total~~.

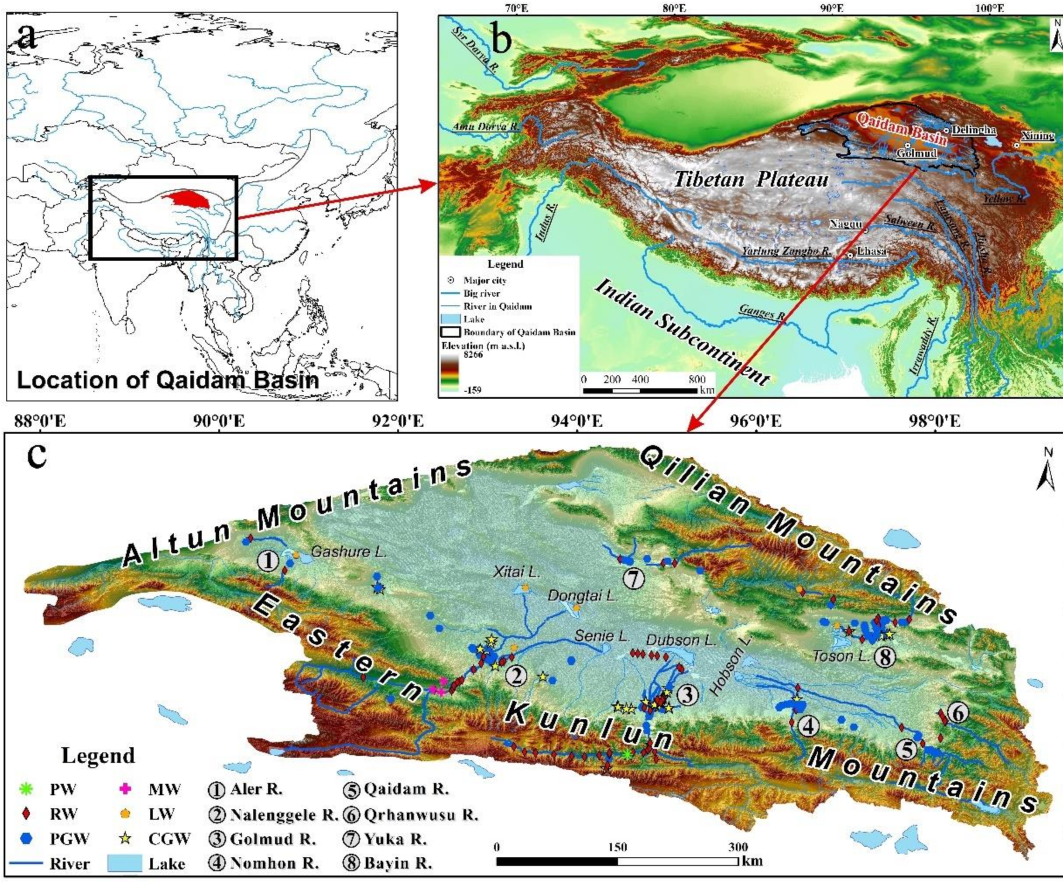


Figure 1. Location of Qaidam Basin (a, b) and the sampling sites (c).

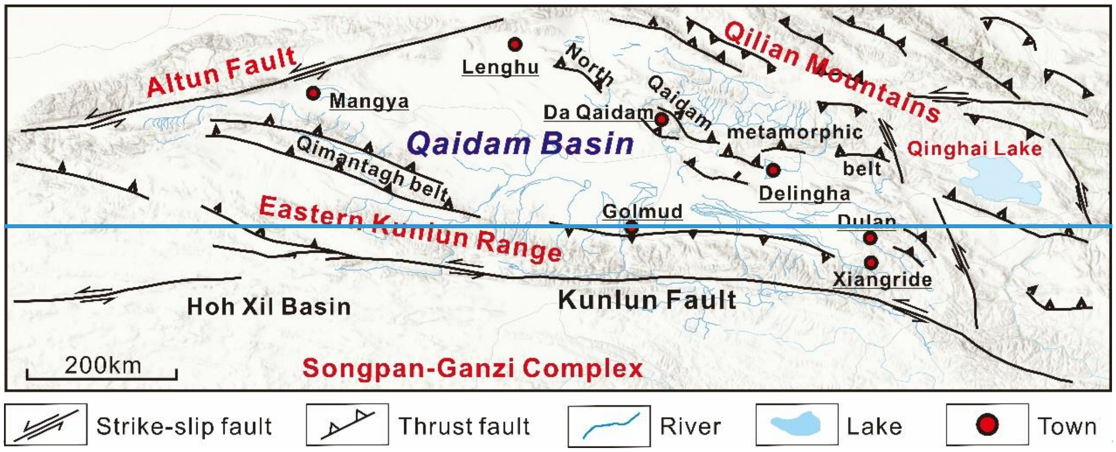
2.2 Basic hydrogeological setting~~Hydrogeology and structure~~

The basin basement consists of Precambrian crystalline metamorphic rock series, and the caprock is of Paleogene-Neogene and Quaternary strata. The mountainous area surrounding the basin is dominated by a Paleogene system, and the basin area and basin boundary zone are characterized by a wide distribution of the Paleogene-Neogene system. The Quaternary system is mainly distributed in the central basin region and the intermountain valley region. The basin terrain is slightly tilted from the northwest to southeast, and the height gradually reduces from 3000 m to approximately 2600 m. The distribution of the basin landforms ~~presents ~~shows a concentric ring shape. From the ~~edge~~ rim to the ~~center~~centre, the distribution of diluvial gravel fan~~-shaped land~~ (Gobi), alluvial–diluvial silt plain, lacustrine–alluvial silt clay plain, and lacustrine silt–salt plains follow a regular pattern. Salt lakes are extensively distributed in the lowlands~~low-lying terrains~~. The inner edge of the Gobi belt in the northwestern basin region is clustered with hills that are less than 100 m in height. The southeastern region of the basin has pronounced~~marked~~ subsidence, and the alluvial and lacustrine plains are extensive~~expansive~~. In the northeastern basin~~ region~~, a secondary small intermountain basin has been formed between the basin and the Qilian Mountains by the uplifting of a series of low mountain fault blocks of metamorphic rock series.

The Qaidam Basin is located~~situated~~ in the Qin-Qi-Kun tectonic system, where there is strong neotectonic movement, and a series of syncline-anticline tectonic belts and regional deep faults have formed around it. The fault structures in the Qaidam Basin are very well developed and include the north-easterly Altun~~Alun~~ fault in the north; north-westerly Saishenteng–Aimunik northern margin deep fault in the northeast; westerly Qaidam northern margin deep fault in the northwest; Qimantag Mountains and Burhan Budai Mountains–Aimunik northern margin deep fault in the south; and north-westerly Sanhu major fault and north-easterly Qigaisu–Dongku Fault in the central basin region.

The distribution of surface water in the basin ~~basin water system distribution~~ is constrained by~~subject to the constraints of the~~ topography and neotectonic movements~~,~~ and ~~it~~ appears to ~~present~~ have a general~~an overall~~ centripetal radial pattern (Figure 1c). There is widespread~~frequent~~ surface water~~–~~ and groundwater exchange~~,~~. The mountainous areas are rich in precipitation and ice/snow meltwater, and are the main runoff producing areas.~~which is generally manifested as an abundance of precipitation and ice/snow meltwater in the mountainous areas, which are the main runoff areas. The r~~Runoff from the mountains flows through the Gobi belt~~ in front of the mountain~~, ~~with~~ where most of it ~~infiltrating~~ infiltrates into the groundwater system~~,—~~. ~~subsequently~~ Groundwater discharges to~~flows over~~ the surface from springs in ~~in the form of~~ confined ~~artesian water~~aquifers or ~~a~~ springs at the front edge of the alluvial fan~~,~~. ~~and~~ This water finally flows into ~~the~~ terminal lakes.

Groundwater can be roughly ~~divided~~ classified as: i) ~~into~~ fractured-bedrock water~~bedrock fissure water,~~; ii) leached pore water and local confined groundwater; iii) ~~,~~ phreatic groundwater and confined artesian water~~, as well as~~; iv) saline~~salty~~ phreatic groundwater; v) ~~,~~ brine, and saline~~salty~~ confined artesian water. Surface water and groundwater salinity and solutes are gradually enriched along the flow path~~this process~~ (Figure 2; Wang et al., 2008).



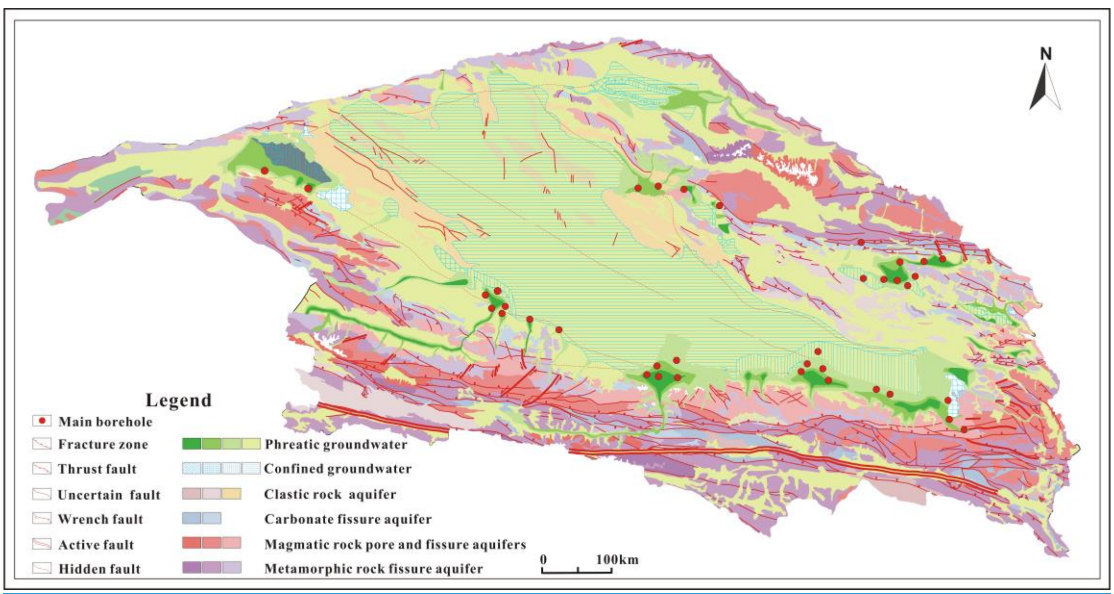


Figure 2. Hydrogeologic map~~Map~~ of the Qaidam Basin (Modified from Xi'an Center, China Geological Survey, http://www.xian.cgs.gov.cn/). The color of different patches of the same aquifer, from dark to light, denotes high to low in water yield property.~~tectonic distribution (modified after Jian et al., 2020)~~

3. Sampling and methods

3.1 Sampling and analysis

We collected ~~To elucidate the water cycle mechanisms in the Qaidam Basin, field investigations and~~ sampl~~ing~~es ~~were carried out on the~~from 8 major river–groundwater systems in the region from 2019 to 2021. We collected samples from ~~The sampling frequency of~~ 6 ~~watersheds~~ of the systems once~~essentially~~ ~~extends over~~ a hydrological year, ~~and is~~ consisting of~~represented by~~ the wet season (July–August) and the dry season (March–April). Precipitation and snow meltwater were collected from the Eastern Kunlun Mountains. Snow meltwater was collected in the dry season whereas precipitation was collected at several times during a hydrological year. In total, 239 sampling points were established: phreatic~~phrenic~~ groundwater (n = 100), confined groundwater (n = 43), spring water (n = 6), river water (n = 81), lake water (n = 5), snow meltwater (n = 3), and precipitation (n= 1). A total of 422 sets of samples were collected. No sampling point was established in the northwestern basin because the southern slope and front edge of the Altun Mountains consisted of ~~tertiary~~ Tertiary system halite sedimentation and Quaternary system ~~large~~ thick salt flats, and no freshwater body ~~is~~ was developed~~present~~. Therefore, the sample collection covers the entire Qaidam Basin and each of the major endorheic regions.

Hydrogen and oxygen isotopes (^{2}H, ^{3}H, and ^{18}O) ~~tests~~ were ~~conducted~~ analyzed at the State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, China. A MAT253 mass spectrometer was used to measure the ratios of $^{2}H/^{1}H$ and $^{18}O/^{16}O$, and the results were compared with the Vienna Standard Mean Ocean Water (VSMOW), expressed in δ (‰), with the analytical precision (1σ) of the instrument for these isotopes was lower than ±1‰ and ±0.1‰. To determine the tritium (^{3}H) concentration, the water sample was first concentrated by electrolysis. Following sample enrichment, measurements were carried out using low background liquid scintillation counting (TRI-CARB 3170 TR/SL). The findings were expressed in terms of absolute concentration in tritium units (TU), the detection limit of the instrument was 0.2 TU, and the precision was improved to ~~more~~ less than ± 0.8 TU.

3.2 Hydrograph separation

In the analysis of water sources among hydrological processes, endmember mixing models are widely used. The contribution of each recharge endmember to the mixed water body was estimated with a Bayesian mixing model that considers~~According~~ to the heterogeneity of different end-member isotopes/water chemistry parameters~~, combined with the Bayesian mixing model, the contribution of each recharge end member to the mixed water body can be estimated~~ (Hooper et al., 1990, 2003; Chang et al., 2018). The process is as follows:

$$1=\sum_{i=1}^{n} f_i,\quad C_m^j=\sum_{i=1}^{n} f_i C_i^j, j=1,\dots,n \qquad (1)$$

where f_i represents the proportion of water source i, n represents the number of end-members, and C_m^j represents the level of tracer j in end-member i.

The ~~Stable isotope analysis in R based on~~ Bayesian mixing models (MixSIAR) coded in R can quantify the contributions of more than two potential endmembers (Parnell et al., 2010). In this study, based on the differences in the water body properties and isotopic composition of each endmember, $\delta^{18}O$, δD, and d-excess (d-excess = $\delta D - 8\delta^{18}O$) data were used as parameters in the modeling. The model was calculated~~calculation process was carried out~~ at a fractional increment of 1% and an uncertainty level of 0.1%.

3.3 Water vapor trajectory

The source and transport route of moisture can be monitored based on the water vapor flux field derived from the monthly mean ERA5 reanalysis data (0.25° × 0.25°) of the European Centre for Medium-Range Weather Forecasts (ECMWF, https://www.ecmwf.int/) (Hersbach et al., 2019). ~~In this study, a~~After taking into account that more than 70% of the precipitation in the Qaidam Basin occurs from June to September, the monthly mean ERA5 reanalysis data in this period from 2019 to 2021 were used to analyze the water vapor transport path in and around the study area. Based on the average altitude of >3000 m at the study site, the simulated atmospheric pressure was set to 500 hPa. The majority of the atmospheric water vapor was distributed in the range of 0–2 km above ground, and the simulated height did not have any significant~~remarkable~~ influence on the findings (Li and Garzione, 2017; Yang and Wang, 2020).

4. Results

4.1 Stable H and O isotopes of different water bodies

The spatiotemporal changes of isotopes in the various water bodies in the entire basin are large, the watersheds have distinct characteristics, and considerable differences exist between surface water and groundwater. The $\delta^{18}O$ and δD values extracted from the water samples of each watershed in the study region can be classified into six categories (Figure 3): 1) precipitation; 2) snow meltwater; 3) river water; 4) lake water; 5) phreatic groundwater; and 6) confined groundwater.

In the Qaidam Basin, the sources of precipitation are mainly concentrated on the northern and southern slopes of the Kunlun Mountains and Qilian Mountains, respectively. The ranges of $\delta^{18}O$ and δD of the precipitation samples from the Kunlun Mountains and Qilian Mountains (Zhu et al., 2015) were −23.38‰ to +2.55‰ and −158.64‰ to +30.49‰, respectively. The corresponding fitted Local meteoric water line (LMWL) equation in the Qaidam Basin was $\delta D = 7.48\delta^{18}O + 11.30$ ($R^2 = 0.95$, $n = 74$), where the slope and intercept were similar to the long-term monitoring findings of the Qilian Mountains (Zhao et al., 2011; Gui et al., 2020; Wu et al., 2022; Yang et al., 2023). In the Qaidam Basin, the heavy isotopes present in snow meltwater samples were considerably depleted compared to rainwater. The $\delta^{18}O$ and δD ranges were −19.30‰ to −8.27‰ and −152.02‰ to −53.52‰ respectively, and the fitting trend equation was $\delta D = 7.78\,\delta^{18}O + 10.85$ ($R^2 = 0.83$, $n = 11$), with the slope and intercept lying between LMWL and GMWL (Global meteoric water line).

Among the surface water samples, the $\delta^{18}O$ and δD ranges in river water were −13.51‰ to −5.93‰ and −85.00‰ to −47.50‰ respectively, whereas those in the lake water were more enriched at −4.10‰ to 8.84‰ and −31.05‰ to 22.07‰, respectively. The fitted trend lines of river and lake samples were: $\delta D = 5.97\delta^{18}O - 5.54$ ($R^2 = 0.85$, $n = 92$) and $\delta D = 4.64\delta^{18}O - 16.37$ ($R^2 = 0.99$, $n = 7$), respectively, which were below both the GMWL and LMWL, indicating that the surface water body has undergone varying extents of evaporation, with evaporation from lakes being more enhanced.

In the groundwater samples, the H-O isotopic composition range was wider and considerable differences occurred between phreatic and confined groundwater. The $\delta^{18}O$ and δD value distribution ranges in phreatic groundwater were −12.70‰ to −5.21‰ and −87.38‰ to −42.00‰, respectively, and the fitted trend line was $\delta D = 5.73\delta^{18}O - 9.20$ ($R^2 = 0.83$, n = 185). The phreatic groundwater isotopic composition and slope of the trend line were similar to those of surface water, indicating frequent interactions between the two and substantial evaporative fractionation of some shallow groundwater. The $\delta^{18}O$ and δD ranges in confined groundwater were relatively small and lower in comparison at −12.12‰ to −8.58‰ and −85.00‰ to −51.01‰. The linear regression relationship of the samples fitting ($\delta D = 7.84\delta^{18}O + 12.39$, $R^2 = 0.87$, n = 51) revealed that its slope and intercept were essentially consistent with those of GMWL and LMWL, which suggests the presence of a strong correlation between confined groundwater and atmospheric precipitation in different periods.

Overall, in the Qaidam Basin, the stable H-O isotopic compositions of surface water and groundwater were generally positively skewed. The isotopic composition and trend fitting characteristics both demonstrated that the water samples have undergone varying extents of evaporation during runoff, which reflects the cold and dry climate environmental characteristics of the study area.

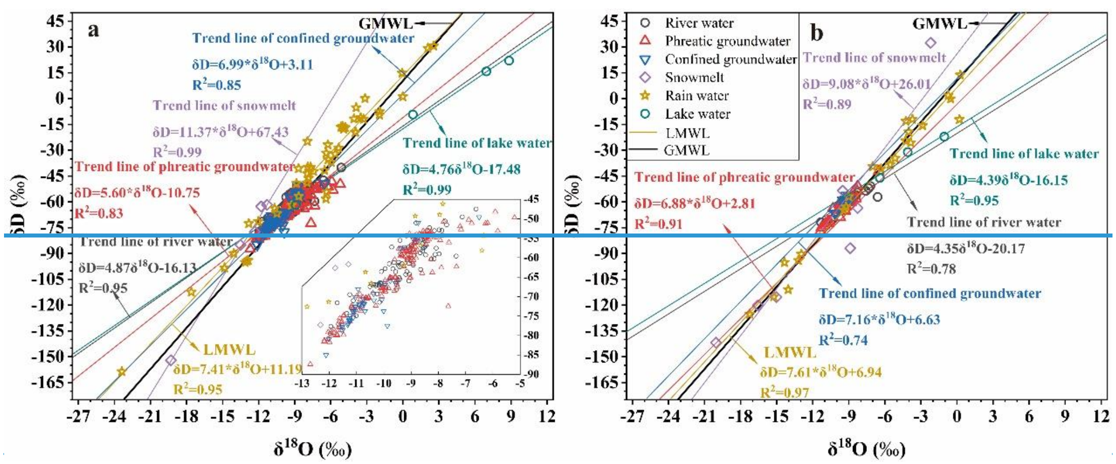


Figure 3. Diagram showing the relationship between $\delta^{18}O$ and δD in different water bodies in the Qaidam Basin (a. Eastern Kunlun Mountains water system; b. Qilian Mountains water system; The data of Rain water and Snowmelt in the Qilian Mountains were from Zhu et al., 2015 and Yang et al., 2021, respectively)

4.2 1 Spatial -and seasonal characteristics of surface water $\delta^{18}O$-δD

In the Qaidam Basin, considerable spatial seasonal and seasonal spatial variations existexist in the stable H-O isotopes of surface water (Figure 43). The isotopic compositions of rivers originating from the Eastern Kunlun Mountains contrast with those from ~~and~~ Qilian Mountains ~~hadshown~~, where the heavy isotopes of the Eastern Kunlun Mountains are -gradually depleted in the direction of west to east, and the reverse holds true for the Qilian Mountains. Of these, the $\delta^{18}O$ and δD values are significantly positive in the southwestern basin ~~and~~ , while significantly negative in the eastern basin. ~~In terms of seasonal variation, a~~Apart from the Nomhon River, all watersheds exhibit~~displayed~~ ~~the~~ a characteristic~~s~~ seasonal variation of enriched in heavy isotope ~~enrichment to varying extents~~ during the wet season relative to the ~~and relative depletion during the~~ dry season. The ~~basin surface water~~ mean $\delta^{18}O$ and δD values in surface water ~~were~~ are more positive~~positively skewed~~ by −0.08‰ to 1.08‰ and 0.6~~3~~‰ to 10.~~58~~6‰, respectively, in the wet season~~s~~. Moreover, the seasonal variations of $\delta^{18}O$ and δD ~~were~~ are more evident ~~pronounced~~ in the downstream river compared to the upstream ~~segment~~. For instance,~~example,~~ the $\delta^{18}O$ value of the downstream Nomhon River ~~was~~ is 3.66‰ higher during the wet season compared to the dry season. These phenomena reflect the differences in the recharge sources of the river during both the wet –and dry seasons and the strong ~~surface~~ evaporation effect in the central basin region. ~~For spatial patterns, the isotopic composition of rivers originating from the Eastern Kunlun Mountains and Qilian Mountains had a contrasting distribution pattern, where the heavy isotopes of the Eastern Kunlun Mountains are gradually depleted in the direction of west to east, and the reverse held true for the Qilian Mountains. Of these, the δ18O and δD values were significantly positively skewed in the southwestern region of the basin and significantly negatively skewed in the eastern region.~~

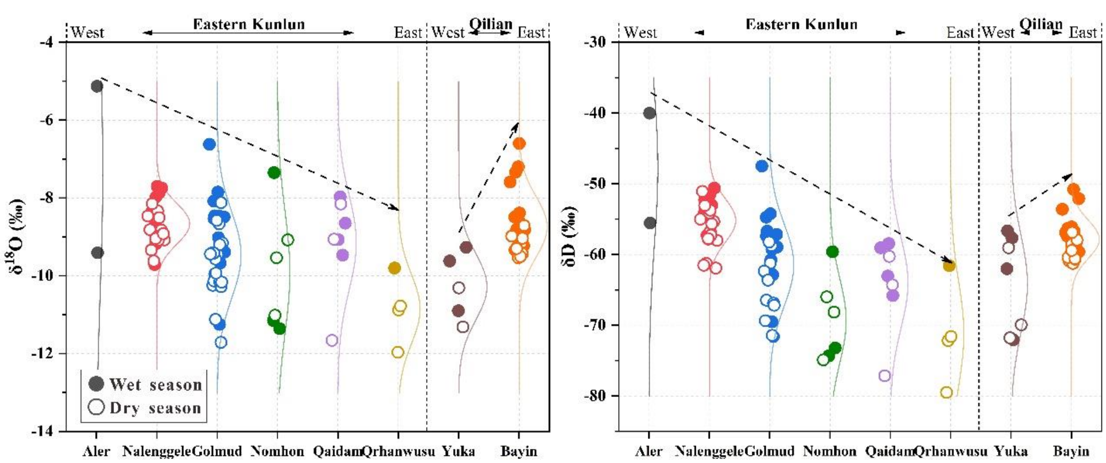


Figure 43. SpatiotemporalSpatial and temporal variations in the H-O isotope composition of Qaidam Basin river water (. Filled and hollow dots indicate wet and dry seasons, respectively; ;—The light lines indicate the trend of $\delta^{18}O$ and δD values from west to east).

4.3 2 Spatial- and seasonal characteristics of groundwater $\delta^{18}O$-δD

The spatial variability of groundwater stable H-O isotopes was is more pronounced compared with river water, although it did appears to follow the same distribution pattern as river water in the watershed basin (Figure 54). In terms of seasons, tThe $\delta^{18}O$ and δD values in the groundwater system were are lower and seasonal fluctuations were smaller compared to that those of in the surface water . because the kinetic fractionation of isotopes caused by evaporation and mixing are weaker in groundwater than in surface water. Specifically, the average seasonal variation of $\delta^{18}O$ in each of the groundwater systems was in the rangeranges of from −0.75‰ to +0.84‰, and the largestmaximum seasonal variations in individual borehole boreholes were are +3.31‰ and −3.16‰, respectively. This suggestsindicates that the groundwater reflects a spatial and temporal average of the surface water isotopic signal, and averaging reduces the variability of the valuesgroundwater isotopic composition was not entirely impacted by surface water infiltration. The region with the greatestlargest seasonal fluctuations of groundwater was is located in the Nalenggele River in the , southwestern basin, and the groundwater $\delta^{18}O$ and δDstable H-O isotopes in wet season were are noticeablysignificantly more positively skewed compared to those of in the dry season. This indicates that groundwater is flowing rapidly and each season, new infiltration displaces the earlier infiltration. TMeanwhile, he adjacent Golmud River, however, has the the region with the smallestleast seasonal variations of in $\delta^{18}O$ and δD is the adjacent Golmud River. In contrast, this suggests that flow is slow. Although there were are no obviousapparent differences in the topography and landforms of between the two adjacent watersheds, significant differences were are observed in the isotope signatures isotopic characteristics of the two., where both surface water and groundwater show much more positive $\delta^{18}O$ and δD values in the Nalenggele River than that of Golmud River catchment. These phenomena reflect the following: 1) the kinetic fractionation of groundwater isotopes caused by evaporation and mixing was smaller than that of surface water isotopes; and 2) substantial differences were detected between the groundwater recharge and surface water groundwater hydraulic interactions in each watershed.

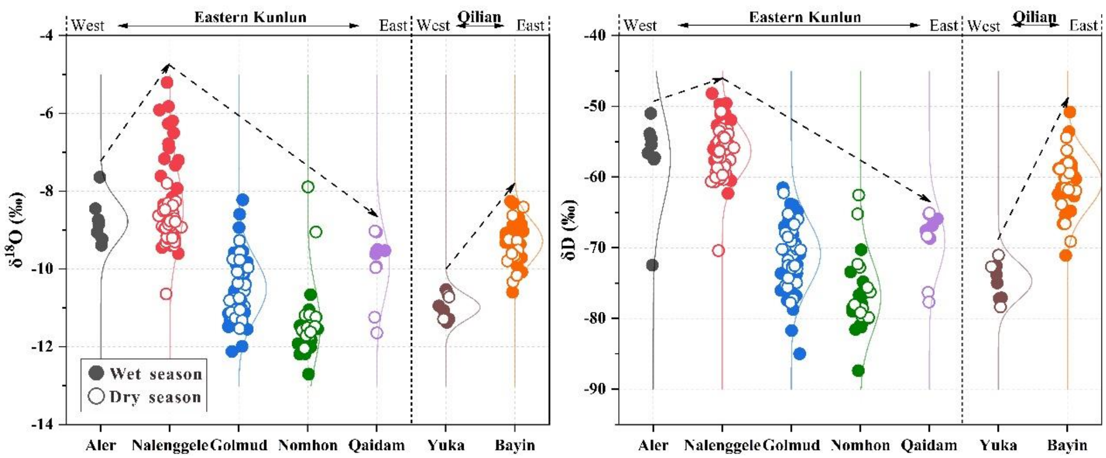


Figure 54. SpatiotemporalSpatial and temporal variations in H-O isotopes in the groundwater of the Qaidam Basin (. Filled and hollow dots indicate wet and dry seasons, respectively; The light lines indicate the trend of δ18O and δD values from west to east).

4.3 Isotopic variations in different water bodies

In the Qaidam Basin, the ranges of $\delta^{18}O$ and δD of the precipitation samples from the Kunlun Mountains and Qilian Mountains are −23.38‰ to +2.55‰ and −158.6‰ to +30.5‰, respectively (Table S1; Zhu et al., 2015). The fitted local meteoric water line (LMWL) equation in the Qaidam Basin is $\delta D = 7.48\delta^{18}O + 11.30$ ($R^2 = 0.95$, n = 74), where the slope and intercept are similar to the long-term monitoring findings of the Qilian Mountains (Figure 5; Zhao et al., 2011; Juan et al., 2020; Wu et al., 2022; Yang et al., 2023). In the Qaidam Basin, the heavy isotopes present in snow meltwater samples are considerably depleted compared to rainwater (Clark and Fritz, 2013). The $\delta^{18}O$ and δD ranges are −19.30‰ to −2.19‰ and −152.0‰ to 32.4‰ respectively, and the fitting trend equation was $\delta D = 9.21\,\delta^{18}O + 31.78$ ($R^2 = 0.89$, n = 12), with the slope and intercept greater than LMWL and GMWL (Global meteoric water line).

The $\delta^{18}O$ and δD ranges in river water are −13.51‰ to −5.93‰ and −85.0‰ to −47.5‰ respectively, whereas those in the lake water are more enriched at −4.10‰ to 8.84‰ and −31.1‰ to 22.1‰, respectively (Figure 5). The fitted trend lines for river and lake samples are: $\delta D = 5.97\delta^{18}O - 5.54$ ($R^2 = 0.85$, n = 92) and $\delta D = 4.64\delta^{18}O - 16.37$ ($R^2 = 0.99$, n = 7), respectively, which are below both the GMWL and LMWL, indicating varying extents of evaporative fractionation in the surface water bodies, with evaporation from lakes being more enhanced. The radioactive ^{3}H concentrations range from 4.2 to 17.8 TU, with a mean value of 12.93 TU (n=23, Table S1).

The H-O isotopic composition ranges in the groundwater samples are wider and considerable differences are observed between phreatic and confined groundwater (Figure 5). The $\delta^{18}O$ and δD values range in phreatic groundwater from −12.70‰ to −5.21‰ and −87.4‰ to −42.0‰, respectively. The fitted trend line is $\delta D = 5.73\delta^{18}O - 9.20$ ($R^2 = 0.83$, $n = 185$). The phreatic groundwater isotopic composition and slope of the trend line are similar to those of surface water, indicating considerable interactions between the two and substantial evaporative fractionation of some shallow groundwater. The $\delta^{18}O$ and δD ranges in confined groundwater are relatively small and lower in comparison at −12.12‰ to −8.58‰ and −85.0‰ to −51.0‰. The linear regression relationship of the samples fitting ($\delta D = 7.84\delta^{18}O + 12.39$, $R^2 = 0.87$, $n = 51$) revealed that its slope and intercept were essentially consistent with those of GMWL and LMWL, suggesting the presence of a strong correlation between confined groundwater and atmospheric precipitation in different periods. Radioactive ^{3}H concentrations detectable in the phreatic and confined groundwater range from 0.22 to 30.35 TU and 0.60 to 12.76 TU, respectively, with mean values of 10.23 TU (n=49) and 7.55 TU (n=10), respectively (Table S1).

Overall, the stable H-O isotopic compositions of surface water and groundwater are generally more enriched in the Qaidam Basin. The isotopic compositions and trend fitting features both demonstrated that the water samples have undergone varying degrees of evaporation during runoff, indicating the cold and dry climate environmental characteristics of the study area.

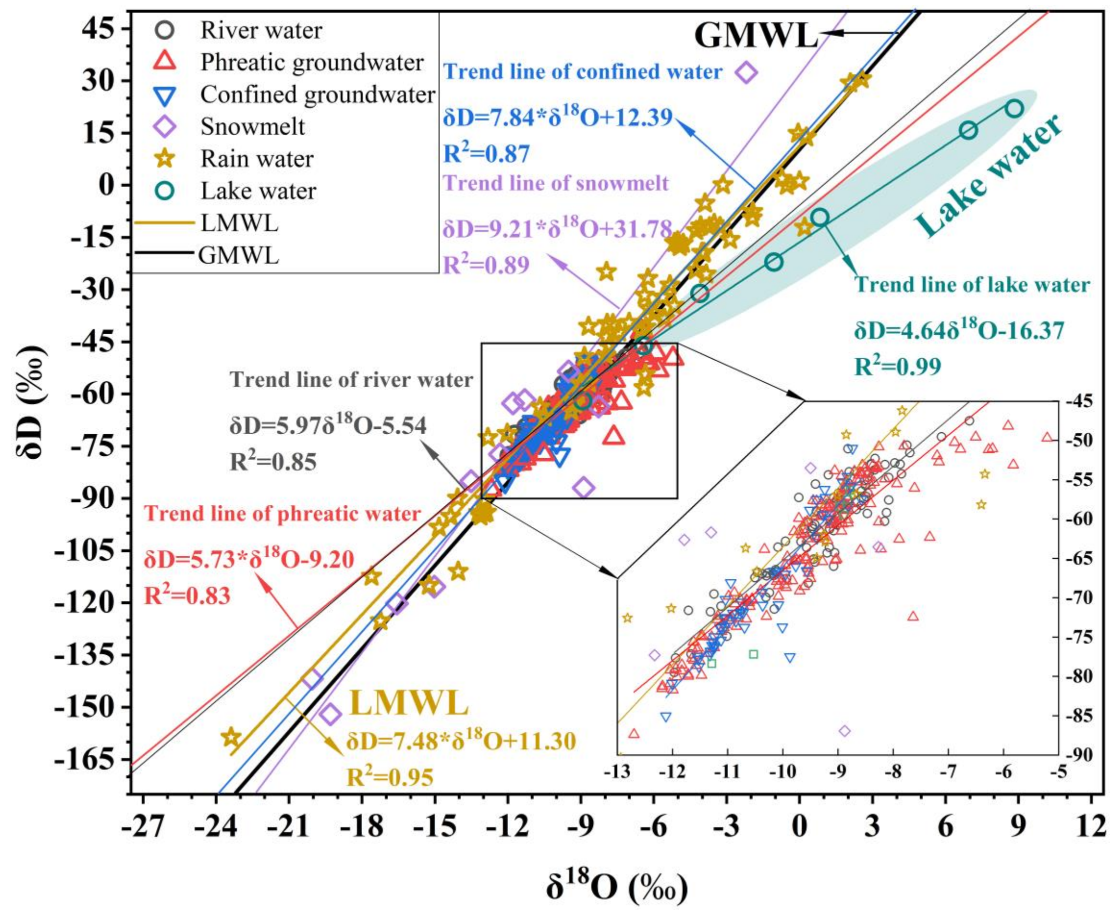


Figure 5. Plot of the relationships between $\delta^{18}O$ and δD in different water bodies from the Qaidam Basin.

5. Discussion

5.1 Water cycle information indicated by surface water isotopes

5.1.1 Atmospheric moisture transport ~~patten~~pattern

To further explain the cause of ~~seasonal~~ spatial and seasonal ~~spatial~~ variations of surface water $\delta^{18}O$ and δD values, ERA5 reanalysis data in the rainy season (June to September) were used to calculate the water vapor flux field in the Qaidam Basin and its surrounding areas as well as track the main trajectories~~paths~~ of the moisture~~water vapor~~ transport~~ation~~ ~~of precipitation~~ (Hersbach et al., 2019). The results show that the mid-latitude westerlies dominate the moisture~~water vapor~~ paths inside and around the basin, and the water vapor flux in the eastern ~~region of the~~ basin is notably greater than that in the western basin (Figure 6; Yang and Wang, 2020)~~region~~. This largely explains the spatial ~~change~~ patterns of river water H-O isotopes (Figure

3), as well as hydrothermal conditiontemperature and precipitation regimes to a large degree (Figure S1). Atmospheric and isotopic tracing data also support these conclusions. For instance,example, the Tanggula Mountains (33°–35° N) serve as the physical and chemical boundary of the Tibetan Plateau, and the westerlies fundamentally govern the northern region, preventing the Indian monsoon from having a significant impact on the Qaidam Basin (Yao et al., 2013; Kang et al. 2019; Wang et al., 2019). Furthermore, d-excess can effectively represent the moisture source properties.where the recycled moisture that enhanced by evaporation over the land surfaceevaporated under conditions of low humidity and moisturewater characterizedcarried by the westerlieswesterly wind isare considered to possess higher d-excess values. The mean d-excess of basin river water samples during the wet season (11.45‰, Table S1) was greater than 10‰, which reflectsassociatesd with the characteristics of an alpine arid continental climate and a moisturewater vapor source devoid of monsoon influences. Higher d-excess values are attributed to westerlies moisture and recycled moisture that is boosted by inland surface evaporation. In contrast, the hinterland of the Tibetan Plateau, south of the Tanggula Mountains, which was subject to significant influences from the Indian monsoon circulation, had summer precipitation and river water d-excess values that ranged from 5‰ to 9‰ with a mean value of 7‰ (Tian et al., 2001). The stark contrasts in the d-excess values between the two regions further support the above inference about the moisturewater vapor sources of the Qaidam Basin.

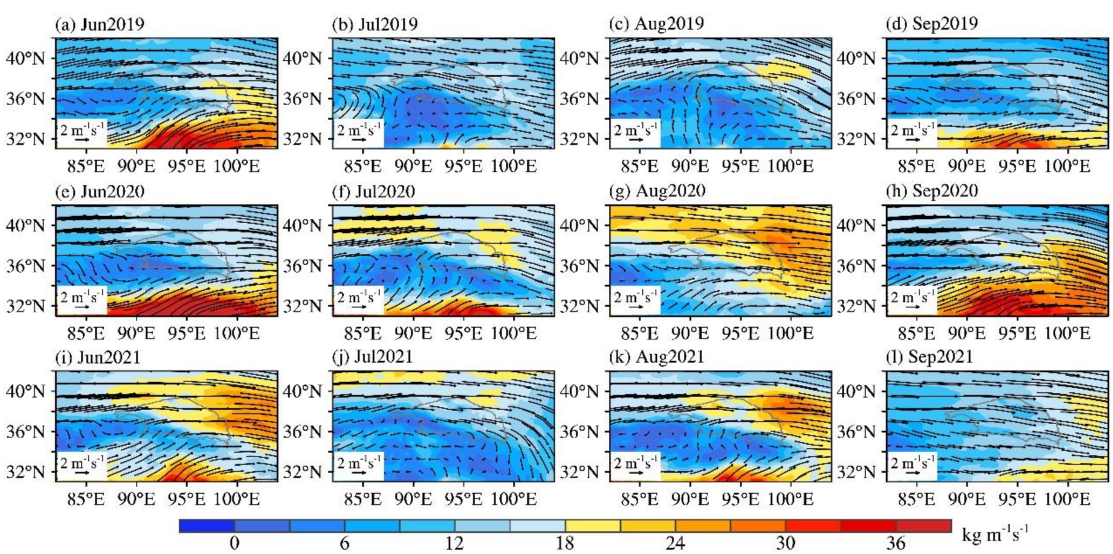


Figure 6. Tropospheric water vapor flux from June to September 2019 to 2021 (below 500 hPa, unit: kg $m^{-1}s^{-1}$).

5.1.2 Isotopic records of surface water to precipitation

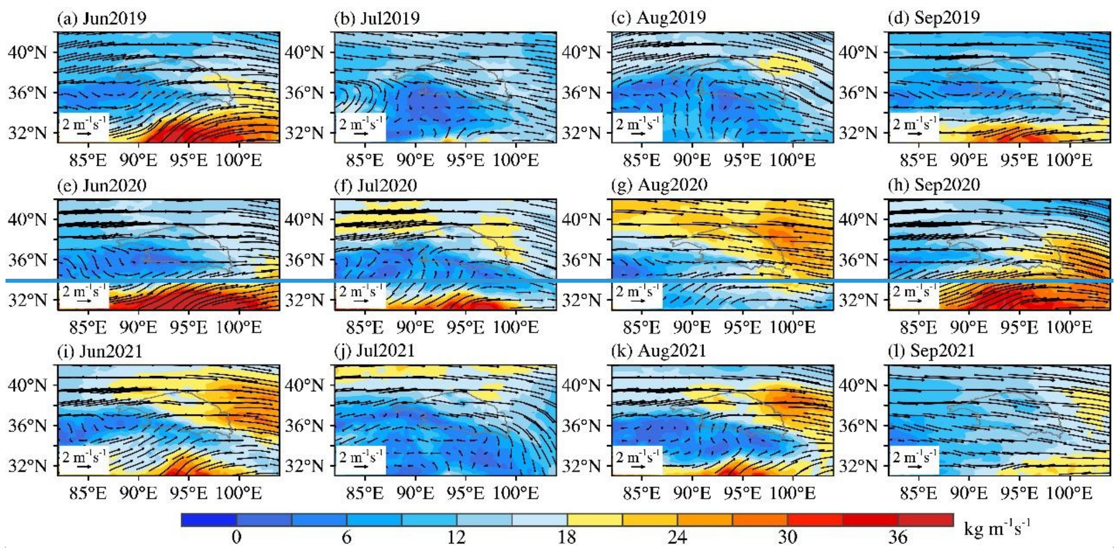
~~Owing~~ Owing to the ~~scant~~ sparse precipitation in the alpine arid region and its concentration in summer (June to September), ~~the~~ surface water isotopic ~~characteristics~~ records ~~of surface water~~ may mimic~~reflect~~ local precipitation characteristics ~~in the respective region~~ during the wet season. ~~The seasonal characteristics of stable H-O isotopes~~ variation ~~in the surface water, which consisted of enrichment during the wet season and depletion during the dry season (Figure 4),~~. On a seasonal basis, the positive correlations between isotopic variations in surface water (Figure 3) ~~isotopes~~ and those ~~of~~in precipitation are extremely strong across most of the basin and its surrounding areas ~~were consistent with the observed~~ or ~~simulated patterns of changes in precipitation isotopes in the basin and its surrounding areas within each year~~ (Liu et al., 2009; Zhao et al., 2011; ~~Gui~~ Juan et al., 2020; Wu et al., 2022). In particular, the $\delta^{18}O$ values ~~at the sampling sites~~ in the mountainous areas ~~on the upper stream~~ of each watershed ~~were~~ are ~~positive~~ higher during ~~the~~ wet season compared to the ~~the~~ dry season, ~~which~~ reflect~~s~~ing the ~~contribution~~ input of precipitation with ~~characterized by~~ heavy isotopic signatures~~that is enriched in heavy isotopes~~ to the river. Moreover, the mean $\delta^{18}O$ and δD values ~~were~~ are higher in watersheds (such as Qaidam and Bayin Rivers) during wet season, with correspondingly excessive rainfall ~~greater precipitation~~ (Figure S1). From this, ~~it can be inferred that the~~ river water ~~stable H-O~~ isotopes of each watershed in the basin ~~were~~ are primarily impacted~~predominantly influenced~~ by summer precipitation during the wet season could be inferred. This is mostly because during ~~largely due to the wet season coinciding with~~ the rainy season, ~~where the~~ relatively ~~more concentrated~~ intensive rainfall events ~~may~~ can create~~directly form~~ surface runoff and rapidly recharge the river.

~~In the Eastern Kunlun Mountains water system, the spatial trend of river water H-O isotopes depletion from west to east (Figure 4) elucidates the variation of precipitation isotopes in relation to the water vapor transport process, which can be attributed to the waning of westerly winds. Along the water vapor transport path, heavy isotopes are preferentially separated in precipitation formation, leading to an augmentation in the continental characteristics of water vapor carried by the air mass, while the precipitation formed by the remaining water vapor undergoes a gradual depletion of isotopes (Yang and Wang, 2020). Meanwhile, the two watersheds in the Qilian Mountains possess contrasting spatial variation characteristics relative to the Eastern Kunlun Mountains water system. Based on the comparison and analysis of the meteorological elements of Delingha and Da Qaidam (refer to Figure 2 for specific location) from 2010 to 2020, the average~~

annual precipitation of Delingha (276.36 mm) was 2.41 times higher than that of Da Qaidam (114.79 mm), and the average annual temperature of Delingha (5.23 °C) was higher than that of Da Qaidam (3.65 °C) by 1.58°C. Since 1961, precipitation in the Bayin River has risen by as much as 25.09 mm/10 a, which was more than six times greater than that of the Yuka River. Owing to the abundance and marked magnitude of increase of precipitation, the seasonal $\delta^{18}O$ variation in the Bayin River was approximately 1.79 times that of the Yuka River. Under similar conditions where ice/snow meltwater recharge was present, the mean $\delta^{18}O$ and δD values of the Bayin River were positively skewed by 1.52‰ and 7.26‰ relative to that of the Yuka River, respectively, which can be attributed to the greater contribution of precipitation with heavy isotopic enrichment characteristics to the river water. Therefore, the spatial and seasonal variations of the river water H-O isotopes in the Qilian Mountains water system can be attributed to the variations in hydrothermal condition and the varying extents of warming and humidification in the watershed.

To further explain the cause of seasonal and spatial variations of surface water $\delta^{18}O$ and δD values, ERA5 reanalysis data in the rainy season (June to September) were used to calculate the water vapor flux field in the Qaidam Basin and its surrounding areas and track the main paths of the water vapor transport of precipitation (Hersbach et al., 2019). The results (Figure 6) demonstrated that the water vapor path in and surrounding the basin is predominantly affected by the mid-latitude westerly air masses (Yang and Wang, 2020) and the water vapor flux in the eastern region of the basin is notably greater than that in the western region. This explains the spatial change patterns of river water H-O isotopes (Figure 4) and hydrothermal conditions to a large degree (Figure S1). The above findings are also supported by atmospheric and isotopic tracing evidences. For example, the Tanggula Mountains (33°–35° N) form the physical and chemical boundary of the Tibetan Plateau, and the northern region is fundamentally under the control of the westerly wind, which hinders the South Asian monsoon from exerting a direct influence on the Qaidam Basin (Yao et al., 2013; Kang et al. 2019; Wang et al., 2019). Furthermore, water vapor source information can be reflected in d-excess, where the recycled moisture that evaporated under conditions of low humidity and water carried by the westerly wind is considered to possess higher d-excess values. The mean d-excess of basin river water samples during the wet season (11.45‰, Table S1) was greater than 10‰, which reflects the characteristics of an alpine arid continental climate and a water vapor source devoid of monsoon influences. In contrast, in the hinterland of the Tibetan Plateau, south of the Tanggula Mountains, which is subject to considerable influences

~~from the South Asian monsoon circulation, the d-excess values of summer precipitation and river water were in the range of 5‰–9‰, with mean value of 7‰ (Tian et al., 2001). The substantial differences in the d-excess values between the two regions also support the above inference about the water vapor sources of the Qaidam Basin.~~



~~**Figure 6.** Tropospheric water vapor flux from June to September 2019 to 2021 (below 500 hPa, unit: kg $m^{-1}s^{-1}$)~~

5.1.3 Climate impact on isotopic spatial and temporal variation

The spatial variation of surface water isotopes of the Eastern Kunlun Mountains water system ~~depletion from west to east~~ (Figure 3) reflects the variation of precipitation isotopes which are strongly influenced by westerlies moisture ~~water vapor transportation~~transport. Heavy isotopes are preferentially separated in raindrops condensation along the westerlies trajectory, and long distance moisture advection leads to heavy isotope depleted precipitation due to rainout (Wang et al., 2016; Yang and Wang, 2020). Meanwhile, the isotope variations in the two watersheds in the Qilian Mountains are opposite to those in the Eastern Kunlun Mountains ~~water system~~. Comparing the meteorological parameters of Delingha and Da Qaidam (refer to Figure S1 for specific location) from 2010 to 2020, the ~~average~~mean annual precipitation of Delingha (276.36 mm) was 2.41 times higher than that of Da Qaidam (114.79 mm), and the ~~average~~mean annual temperature of Delingha (5.23 °C) was 1.58 °C higher than that of Da Qaidam (3.65 °C). Precipitation in the Bayin River has increased by up to 25.09 mm per decade since 1961 (Figure S1). The seasonal $\delta^{18}O$ variation in the Bayin River is roughly 1.79 times that of the Yuka River, due to the marked increase in precipitation in Delingha. Under similar conditions of ice/snow meltwater recharge, the mean $\delta^{18}O$

and δD values of the Bayin River are higher than 1.52‰ and 7.3‰, respectively, relative to that of the Yuka River, which can be attributed to a greater proportional contribution of precipitation with heavy isotopic signatures to the river water. As a result, the change in river water isotopes in the Qilian Mountains can be attributed to the differences in temperature and precipitation regimes, as well as the extents of warming and humidification between the watersheds.

Given the spatiotemporalspatial and temporal variations differences of surface water $\delta^{18}O$-δD (Figure 43), samples of from different water bodies in within each watershed were incorporated into the $\delta^{18}O$-δD plot (Figure 7). The presence of considerable differences in the dual-isotopic spectrumisotope distribution characteristics suggestimplys that seasonal variations changes in the surface water H O isotopes in each watershedwater type may be attributeddue to variabilitydifferences in the proportions of the contribution ratios of precipitation, ice/snow meltwater, and groundwater throughoutduring both the wet and dry seasons. Hence, Equation 1 of the MixSIAR model (Table 1) was employed to estimate the contribution of each potential recharge endmember to the river water (Table 1). The findings revealindicated that in the dry season, groundwater discharge in mountainous areas maintains the base flow in each watershed is maintained by the groundwater discharge in mountainous areas during the dry season, where thewith groundwater contribution of groundwater to base flow may reach up to 97% of the total flow. Various proportions of precipitation, ice/snow meltwater and groundwaterDuring the wet season , recharge the river water in each watershed is recharged byduring the wet season different proportions of precipitation, ice/snow meltwater and groundwater. For example, in the area with the most abundantgreatest annual precipitation amount rainfall, the contribution of summer precipitation to the Bayin River during the wet season may reach 84% during the wet season. The westerly water vapor forms more precipitation as a result of obstruction from landforms in the eastern region of the basin, in contrast, as the source area of the Bayin River is in close proximity to the eastern region of Qilian Mountains, although the summer monsoon is likened to 'an arrow at the end of its flight' (a spent force), the latter continues to contribute more than 22% of the oceanic water vapor to the nearby areas (Wu et al., 2022). The topographic obstruction and strong convection form abundant precipitation, rendering the proportion of precipitation in the surface runoff in the eastern basin region appreciably higher than that in other areas. Thus, variabilitydifferences in the proportional contributions proportions of contribution ratio of each recharge end-member during wet and dry seasons are the main factors responsible for the seasonal variations in surface water isotopes in each watershed.

In summary, the spatial ~~patterns seasonal variations~~ and seasonal variations ~~spatial patterns~~ of surface water stable ~~H O~~ isotopes are caused by~~a consequence of~~ the interaction~~combined effects~~ of ~~the extent of~~ regional warming and humidification trends~~warmth and humidity in the region~~, the intensity of ~~the~~ mid-latitude westerlies moisture transport~~ation~~~~westerly wind water vapor transport~~, and local hydrometeorological conditions.

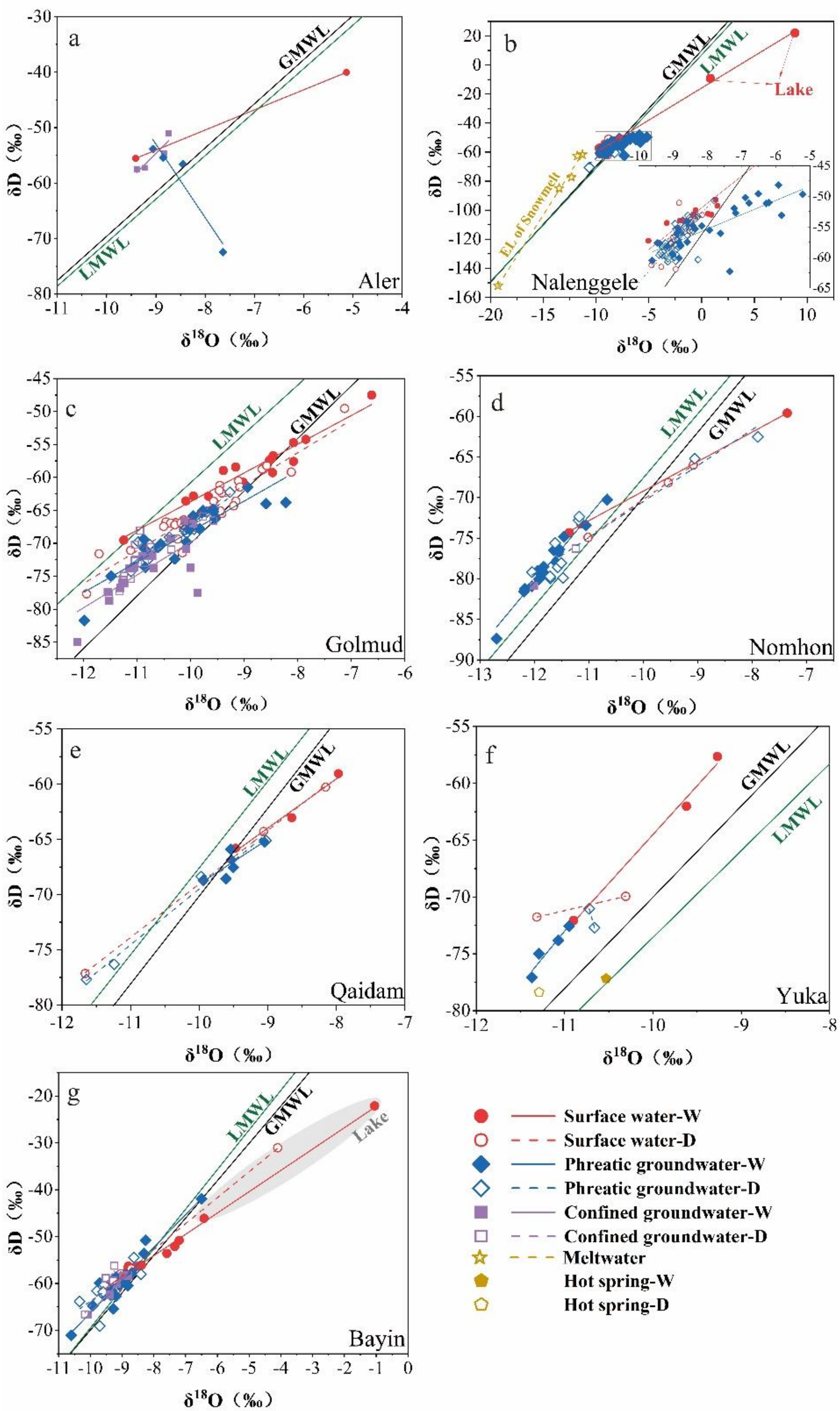


Figure 7. δ^{18}O-δD plots ~~during dry-wet seasons and~~ in different water bodies in each watershed of the Qaidam Basin during dry and wet seasons ~~(~~. W and D represent wet and dry seasons, respectively~~)~~. Data source of LMWLs: a and b: Xu et al., 2017; c: this study; d and e: Xiao et al., 2017; f: Zhu et al., 2015; g: Tian et al., 2001.

Table 1. Contribution ratios of endmembers to river water during the wet and dry seasons based on δ18O and d-excess (Unit: %; W and D represent wet ~~season~~ and dry seasons, respectively).

	Endmember	Groundwater	Meltwater	Tributary	Precipitation
Nalengele-W	Mean	0.41		0.47	0.12
	Max	0.60		0.74	0.13
	Min	0.18		0.27	0.08
	SD	0.12		0.13	0.02
Nalengele-D	Mean	0.90	0.10		
	Max	0.97	0.27		
	Min	0.73	0.03		
	SD	0.07	0.07		
Golmud-W	Mean	0.31	0.34	0.25	0.10
	Max	0.36	0.39	0.32	0.12
	Min	0.28	0.29	0.20	0.08
	SD	0.03	0.04	0.05	0.01
Golmud-D	Mean	0.32	0.25	0.42	
	Max	0.46	0.45	0.70	
	Min	0.19	0.11	0.21	
	SD	0.09	0.10	0.17	
Yuka-W	Mean	0.62	0.23		0.15
	Max	0.76	0.29		0.18
	Min	0.55	0.15		0.10
	SD	0.10	0.06		0.04
Bayin-W	Mean	0.26	0.04	0.25	0.45
	Max	0.35	0.05	0.43	0.84
	Min	0.08	0.02	0.06	0.23
	SD	0.08	0.01	0.11	0.19

5.2 Multi-sources of groundwater recharge and circulation mechanism~~Sources and spatial patterns of groundwater recharge~~

~~The s~~Seasonal variations in groundwater aquifer H-O isotopes in each watershed suggest~~s~~ that ~~differences exist in~~ their recharge sources, forms, and rates fluctuate. The $\delta^{18}O$-δD correlations~~relationships~~ of different seasons and ~~different~~ types of water samples can be used to deduce~~elucidate~~ the groundwater source compositions and recharge patterns. According to the seasonal variations in groundwater $\delta^{18}O$-δD in each watershed (Figure 4) and the dual-isotopic spectrum of different water bodies within the watershed (Figure 7), ~~The~~ the Qaidam Basin groundwater systems can be ~~classified~~divided into three recharge types~~of recharges according to the seasonal changes in groundwater $\delta^{18}O$-δD in each watershed (Figure 5) as well as the δ^{18}O-~~

~~δD relationship of different water bodies within the watershed (Figure 7)~~: modern precipitation and glacier snow melt water dominated recharge and fossil water as well.

5.2.1 ~~Heavy p~~Precipitation~~ in the wet season ~~-dominated recharge

In the Nalenggele River, which is situated in the southwestern basin, and the Qaidam and Bayin Rivers in the eastern basin, groundwater $\delta^{18}O$ and δD values ~~were ~~are markedly positive~~ly skewed~~ ~~during the~~in wet season and negative in dry season (Figure 5). The groundwater isotope data ~~distribution ~~in the majority of the wet season~~s~~ clusters near~~was closer to~~ the LMWL and GMWL compared to that during the dry season (Figures 7b, 7e, and 7g),~~. Moreover,~~ indicating the isotopic signatures~~characteristics~~ ~~were ~~are similar ~~closer ~~to the river water and summer precipitation in the same period (Table S1; Zhu et al., 2015), with different trends in evaporation ~~(Figures 7b, 7e and 7g)~~. These results suggest~~ indicate the~~ ~~contribution of ~~precipitation recharge ~~to ~~s groundwater during the wet season~~s~~. The ~~relatively ~~significant~~marked~~ seasonal variations of H-O isotopes ~~also demonstrate~~show -that the aquifers in the eastern and southwestern Qaidam Basin have ~~a ~~relatively rapid groundwater circulation~~cycle~~ and ~~present ~~seasonal recharge. There is an abundance and notable rise in precipitation ~~In ~~in the eastern basin~~, there is an abundance and notable rise in precipitation ~~(Figure S1). ~~,~~ An interesting finding was that ~~which ~~increased~~ing~~ precipitation has directly caused~~led to~~ a rise of 5 m in water level and an ~~surface ~~area expansion of 1.59 times in a lake ~~at ~~near the headwaters~~source~~ of the Nalenggele River in the southwestern basin from 1995 to 2015 (Chen et al., 2019). The abundant Precipitation observed in the eastern basin headwater ~~This further indicates the abundant precipitation in the headwater may ~~may also be a potential source for the rapid seasonal ~~recharge of ~~groundwater recharge associated with ~~the~~ rapid warming ~~climate warming ~~and humidification. Furthermore,~~Additionally,~~ the tectonic conditions of the recharge area are ~~considered~~believed to enhance~~are factors that are in favor of driving~~ seasonal groundwater recharge. The three watersheds coincide with collision zones of intensive neotectonic movement, where a considerable number of deep faults and other volcanic channels have developed within recharge areas (Figure 2; Tan et al., 2021). ~~These three watersheds happened to be situated in the collision zone (Figure 2), where neotectonic movement is strong, and there are substantial developments of deep fractures and faults in the recharge area. I~~I~~t ~~t can be concluded~~inferred from the aforementioned~~ that favorable hydrological and tectonic conditions facilitate~~promote~~ the formation of directly~~ and~~ rapid~~ recharge of ~~ groundwater recharge of precipitation and meltwater through bedrock fissures at high altitudes under the large hydraulic heads (>1000 m) from precipitation and meltwater at higher altitudes, resulting in significantsubstantial seasonal variationschanges in the groundwater H-O isotopes in these regions (Tan et al., 2021).

5.2.2 Glacial Glacier -snow melt water -dominated recharge

In the Nomhon and Yuka Rivers, situated located in the central middle region of the basin region, groundwater H-O isotopes were are more depleted during in the wet season compared tothan in the dry season (Table S1; Figure 54). Figures 7d and 7f also show that the majority Most of the $\delta^{18}O$–δD data for the groundwater samples in these two watersheds were are observed in the lower left of the LMWL and GMWL (Figures 7d and 7f.), and These these values were far away from the LMWL and GMWL, and were are more negative more negatively skewed relative to river water, with characteristics parallelbeing closer to the those measured in snow-melt water obtained fromobserved in the high-altitude Eastern Kunlun Mountain (Figure 35; Yang et al., 2016). This demonstrates shows that the groundwater recharged by ice/snow meltwater is more isotopically depleted depleted in heavy isotopes, during both the wet– and dry seasons, despite the fact that precipitation contributes less to the aquiferand the contribution of precipitation to the aquifer was relatively small. Similarly, non-monsoonal meltwater control of hydrological processes in monsoonal groundwater systems has also been observed on the eastern margin of the Tibetan Plateau Similarly, on the eastern margin of the Tibetan Plateau, the phenomenon where the non-monsoon meltwater controls the monsoon groundwater system hydrological process has been observed (Kong et al., 2019). The isotope signals suggestedindicated that isotopically depleted ice/snow meltwater depleted in the heavy isotopes in the source regionarea was released as a result of due to elevated summer temperaturesthe rising temperature in summer, and was further depleted in the groundwater after mixing with groundwater recharged by seasonal meltwaterand following the mixing of groundwater with the seasonal meltwater recharge, the groundwater was further depleted in heavy isotopes. Furthermore, owing due to the scarcelow precipitation in these two watersheds (61.39 and 121.78 mm, respectively, Figure S1), and that even the fewer precipitation events occurred in 2020, was even lower. Under extremely arid climate, the seasonal direct recharge to the aquifer from the limited precipitation was negligible in this extremely arid climate. GRACE data also showed that the melting of solid water in the source area due to climate warming was a key factor driving the increase in the groundwater storage of the Qaidam Basin (Xiang et al., 2016). This further supports the inference that groundwater isotopic depletion during the wet season stems from the seasonal melting recharge of the cryosphere.

5.2.3 Fossil water -dominated recharge

In the Golmud River, the mean $\delta^{18}O$ value during the wet season was is 0.33‰ higher during the wet season than that during the dry season, and with insignificant seasonal changes were not apparent, indicating that the a limited share of seasonal groundwater recharge and a slow renewal rateproportion of seasonal groundwater recharge was small and the renewal rate was slow. The groundwater H-O isotope data of the groundwater lay mainlywere mainly located between the LMWL and GMWL (Figure 7c), indicating implying that the predominantmain recharge source was is different periodsthe atmospheric precipitation (Beyerle et al., 1998)seasons. Furthermore,In addition, the groundwater $\delta^{18}O$ and δD values in the alluvial fan belt exhibited a gradually decreased negatively skewed trend along the flow path (Figures 8a and 8b). For this watershed, A a prominent feature of this watershed is the sizeable storage of confined groundwater, which is constantlycontinuously emanating discharging at the front edge of the alluvial fan. Confined groundwater $\delta^{18}O$ and δD values arepossesses more negative $\delta^{18}O$ and δD values that are more negative than those of phreatic groundwater, and the mean $\delta^{18}O$ values are similar during the wet and dry seasons, with minor seasonal variation (Table S1)during the wet dry seasons are consistent, without any seasonal changes. The substantial differences in isotopic characteristics between phreatic and confined groundwaters (Table S1) suggest that there are potential differences in their recharge sources. It is We hypothesizespeculated that phreatic groundwater is predominantly recharged primarily by ice/snow meltwater, while confined groundwater is slowly and stably recharged and may be sustained by precipitation with low $\delta^{18}O$ and δD values or fossil water formed under during the relatively cold climatic conditions climate periods (Xiao et al., 2018). This scenario is in fact observed in deep confined groundwater in many areas in the world (Ma et al., 2009; Jasechko et al., 2017).

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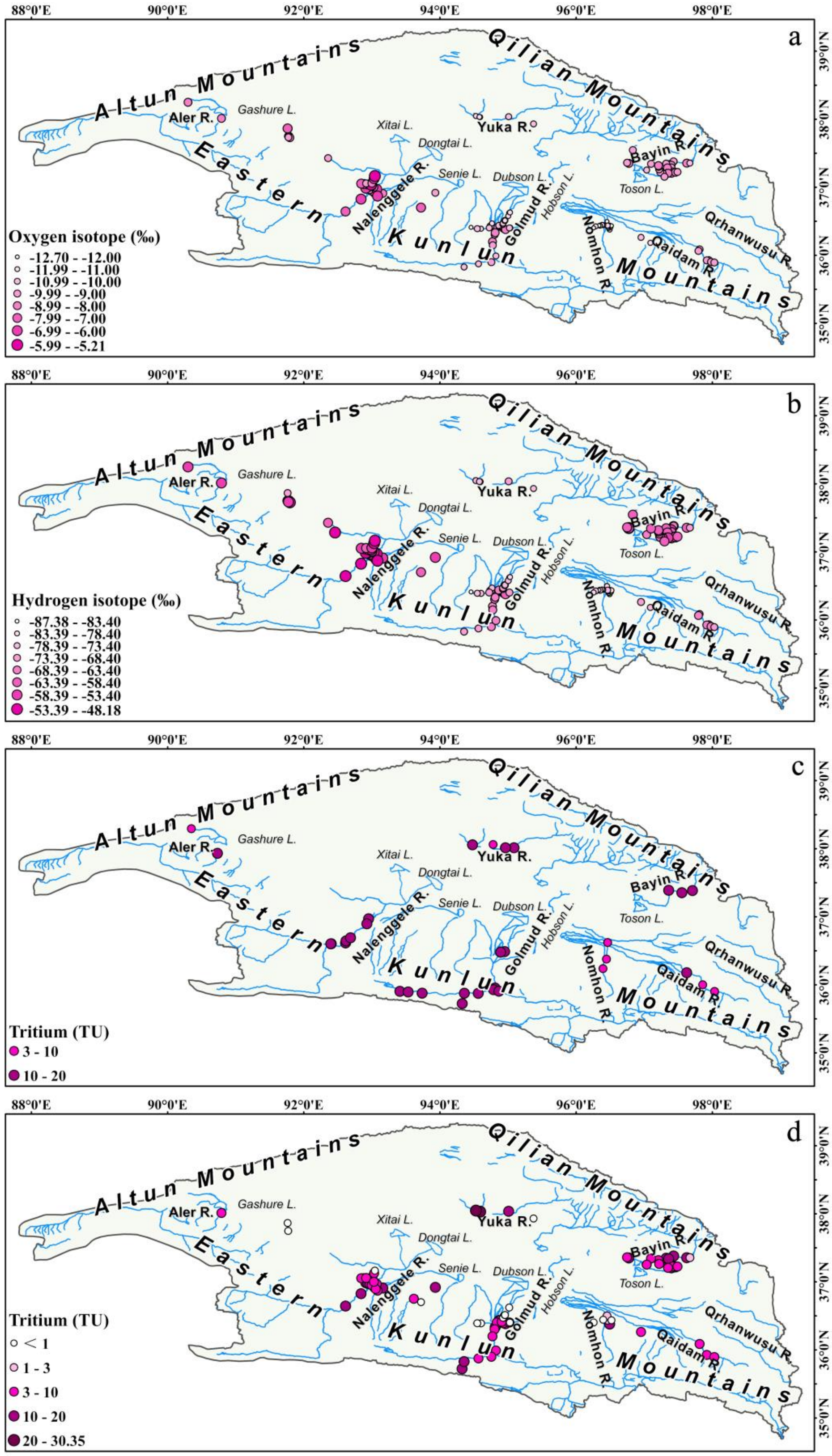

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Hobson L.
Nomhon R.
Qaidam R.
Qrhanwusu R.
Oxygen isotope (‰)
-12.70 - -12.00
-11.99 - -11.00
-10.99 - -10.00
-9.99 - -9.00
-8.99 - -8.00
-7.99 - -7.00
-6.99 - -6.00
-5.99 - -5.21
Hydrogen isotope (‰)
-87.38 - -83.40
-83.39 - -78.40
-78.39 - -73.40
-73.39 - -68.40
-68.39 - -63.40
-63.39 - -58.40
-58.39 - -53.40
-53.39 - -48.18
Tritium (TU)
3 - 10
10 - 20
Tritium (TU)
< 1
1 - 3
3 - 10
10 - 20
20 - 30.35

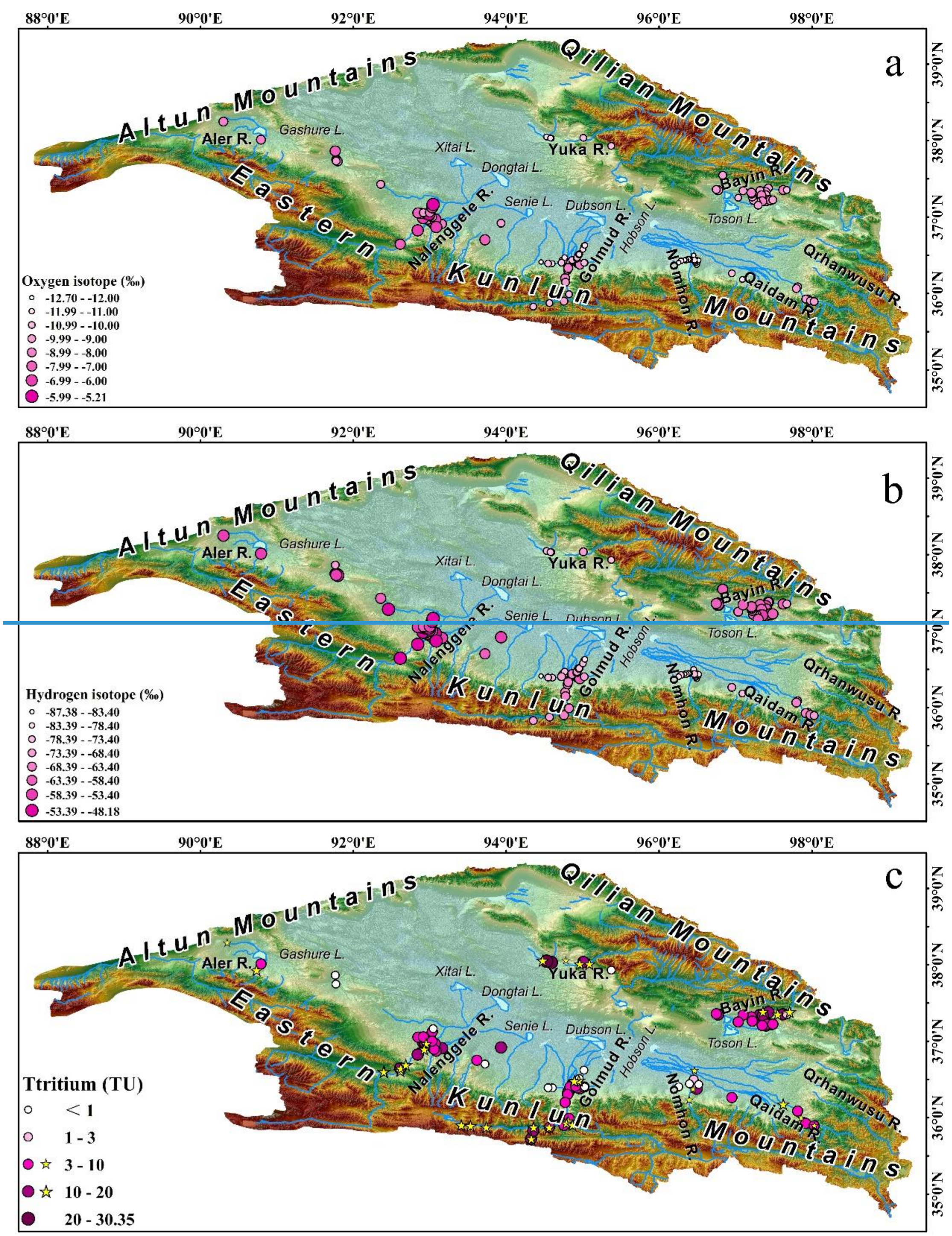


Figure 8. Spatial distribution of ~~groundwater~~ $\delta^{18}O$ (a) and δD (b) in groundwater ~~,~~ and tritium concentrations in ~~and~~ surface water (c)~~–~~ and groundwater ~~^{3}H~~ (~~c~~d) ~~concentrations~~ during the wet season. ~~(Circle and asterisk represent groundwater and surface water, respectively)~~

5..32.4 Mechanism governing water cycle in alpine mountain-basin systemWater cycle mechanism

RBeing a direct constituent of water molecules, radioactive ^{3}H, tritium, with a half-life of 12.32 years, can be used to estimate the migration time of younger water. Particularly , in mixed water bodies consisting of younger water and fossil water, ^{3}H can be used to effectively characterizetrace groundwater age and renewal rate in water bodies consisting of a mix of younger water and fossil water (Stewart et al., 2017; Xiao et al., 2018; Chatterjee et al., 2019; Shi et al., 2021). In accordance with the significantconsiderable differences in δ^{18}O-δD of the variousdifferent water bodies in each watershed (Figures 7, 8a, and 8b), the scale and extent of the groundwater recharge in the Qaidam Basin were is further constraineddetermined withusing the ^{3}H (Figures 8c and 8d) concentration. The spatial pattern of ^{3}H concentration spatial distribution pattern revealsindicated that groundwater recharge rates varied significantly there were considerable differences in groundwater recharge rates at both intra- and inter-watershed scales (Figures 8c and 8d). Thus, the groundwater system was is dominated by both regional and local recharge.

At the watershed scale, the ^{3}H concentration of the phreatic groundwater is significantly higher in alluvial fan areas in the alluvial fan zone nearalong the river channel and mountain pass was considerably higher (Table S1; Figures 8c and 8d), and approximatesclose to that of the river water. These results This indicate suggests that there is a close hydraulic connectionhydraulic interactions occurred between the surface water and groundwater, and that the aquifer also receives river water via through vertical infiltration and lateral runoff recharge. THence, this portion of groundwater is therefore dominated bymostly seasonal seasonal modern water recharge, which is younger, and has a relatively rather rapid more rapid renewal rate. The ^{3}H concentrations in the periphery of phreatic and confined groundwater ^{3}H concentrations at the edge of the alluvial fan wereare typicallylargely below less than 3 TU or lower than the detection limit, indicating that which ^{3}H is dead in comparison to was inconsistent with that near the river channel. These findings suggest that these aquifers are predominantly mostly recharged by lateral runoffflow, consisting primarily of sub−modern water (>60 years) or fossil water, with limited mixing of modern precipitation and seasonal meltwater, and a slow renewal rate., which consists largely of submodern water (>60 years) or fossil water, and the mixing proportion of modern precipitation and seasonal meltwater is relatively low, with a slow renewal rate. This situation is especially evidentparticularly apparent in Golmud and Nomhon Rivers (Liu et al., 2014; Cui et al., 2015; Xiao et al., 2017, 2018), highlightingwhich also further reflects the importance of fossil water content in rechargingmaintaining the aquifer in extremely arid regions.

At the basin scale, radioactive ^{3}H data is concentration characteristics are consistent with the water cycle information indicated by the seasonal variationschanges in stable H-O isotopes. Seasonal variations in $\delta^{18}O$ and δD values correspond to higher average ^{3}H concentration In inthe phreatic groundwater systems situated in the eastern and southwestern basin regions, ^{2}H and ^{18}O are relatively enriched during the wet season, ^{3}H has a relatively higher average concentration, revealing that seasonal groundwater recharge is more significantnoticeable, and that groundwater age is overall younger (<60 years). Based on river seepage, modern meltwater and precipitation may potentially also infiltrate through preferential flow pathsfavorable structural water passage channels, such as fault zones developed on a large scale in the recharge area, resulting inresulting in rapid aquifer recharge to the aquifer (Figure 9b; Tan et al., 2021). The contrary was observed in the phreatic groundwater systems in of the western Qilian Mountains and central middle Eastern Kunlun Mountains, were relatively depleted in ^{2}H and ^{18}O during the wet season, where the depletion in heavy isotopes during wet season, accompanied by low the ^{3}H concentrations were correspondingly low, and meant these aquiferssystems were primarilymainly received recharged from by seasonal ice/snow meltwater. In contrastHowever, the groundwater renewal rate was relatively slow, owing todue to less and more the steadyrelatively stable meltwater recharge of meltwater by comparison, the groundwater renewal rate was relatively slow (Figure 9c).

In confined groundwater, heavy H-O isotope depletion is greatest, with most samples having very low ^{3}H concentrations (<3 TU), indicating a very slow recharge rate.The depletion of heavy H-O isotope was greatest in confined groundwater, and the ^{3}H concentration of the majority of the samples was very low (<3 TU) or fall below the detection limit, which indicates that the confined groundwater recharge rate is very slow. Furthermore, most of the confined groundwater was largely overover 100 years old and consisted mainly predominantly of submodern groundwater or fossil water (Xiao et al., 2018). In the Golmud River, the effect of H-O isotope seasonal changes in most of the confined groundwater was relatively small or showed almost no detectable change. However, the confined groundwater in the discharge overflow zone continued to dischargecontinued to spontaneously emanate after nearly a half a century of extractionmining, and the hydraulic water pressure heads did not decreasedecrease, which suggestimplyings that modern precipitation or ice/snow meltwater may recharges deep confined groundwater. Some confined groundwaters possess discerniblerecognizable seasonal isotopic seasonal effects, and the existence of a certain proportion of ongoing continuous recharge, even on a seasonal scale, cannot be excludedruled out. LIn addition, large karst springs have also developed in the mountainous areas of the Golmud River. Moreover, a large karst spring (KLSQ-1) was observed near the mountain pass, with a flow rate as high as 224.7 L/s. In mountainous areas, wWell-formed karst cavities caves and fissures provide conduits to enable thefor direct infiltration of precipitation or meltwater infiltration. Following With deep circulation, precipitation and meltwater generate regional subsurface flow that recharges the confined groundwater in the overflow zone in the long term, allowing continuous flow under a precipitation and meltwater give rise to regional subsurface runoff, which recharges confined groundwater in the overflow zone over a long distance, thus causing it to flow continuously under the effect of a large hydraulic head (approximately about 1,000 m) (Figure 9d). Moreover, the H-O isotopic signals of confined groundwater in part of the alluvial fan front in the Golmud and Bayin Rivers , the H-O isotopic signals of some confined groundwaters at the front edge of the alluvial fan wereare largely similaressentially consistent with that those of the nearby phreatic groundwater, and thewith ^{3}H concentrations was close to 10 TU. These findings also suggest that confined groundwater recharge may have occurred through aquitard or by leakage recharge in nearby skylights.the confined groundwater may pass through the aquitard or leakage recharge occurs in the local skylights.

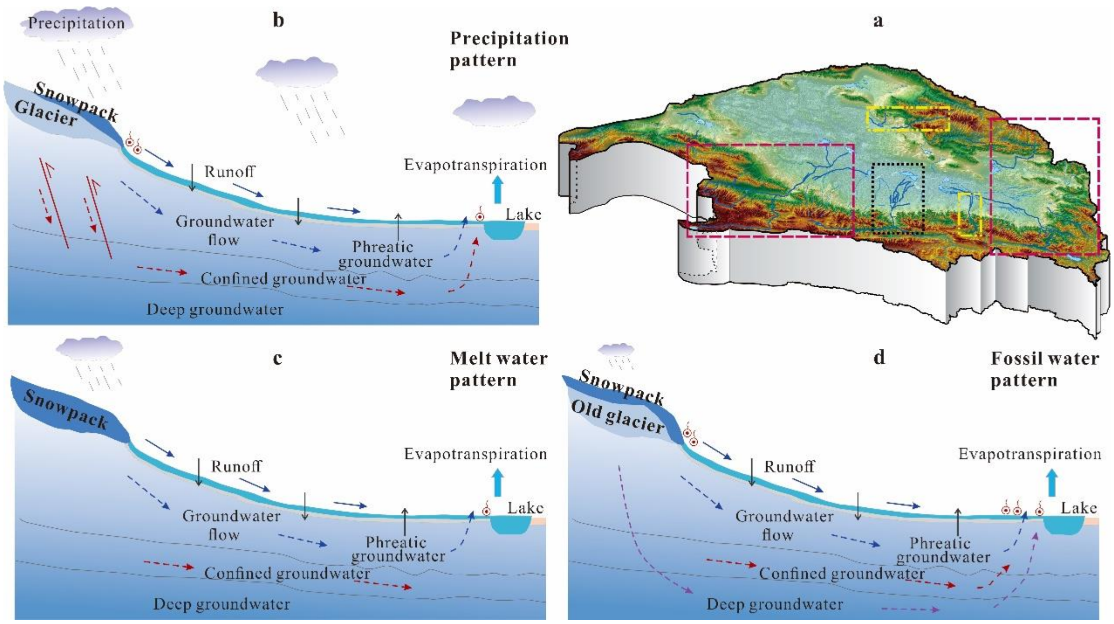


Figure 9. Schematic diagram of the Qaidam Basin water cycle model (b represents the purple~~blue~~ dashed box; c represents the yellow dashed box; and d represents the black dashed box).

5.~~4~~ 3 Isotope hydrology responses to climate change and indication of water cycle trends ~~under climate change~~

~~Since the 1980s, t~~The Qaidam Basin has experienced rapid warming at a rate more than twice ~~of~~ the global average since the 1980s (Wang et al., 2014; Kuang and Jiao, 2016; Yao et al., 2022). Since ~~1960~~1961, the 10- and 30-year mean temperature and precipitation ~~average annual temperature and precipitation variations~~changes and ~~increasing~~ rising rates ~~over every 10 and 30 years~~ at eight meteorological stations in the basin ~~(Figure 10a)~~ have ~~and continuous air temperature and precipitation change trends at two representative meteorological stations in the north and south (Delingha and Golmud) (Figure 10b) have~~ demonstrated~~shown~~ that the current~~present~~ warming and humidification trends in ~~the~~ this ~~northeastern Tibetan Plateau~~basin, northeastern Tibetan Plateau, are continuously strengthening ~~are continuously strengthening~~ (Figure 10). Changes in surface water and groundwater isotopes in the Qaidam Basin reflect different sensitivities to climate change at both seasonal and multi-year scales. Previously, it was assumed~~the general assumptions were~~ that the isotopic composition of the surface water and groundwater systems did not vary with time, at least on interannual intervals~~scales~~, and was ~~relatively~~ rather stable (Boutt et al., 2019). However, isotopic variability in water bodies over the past 40 years ~~, the isotopic variations of water bodies have demonstrated~~ suggests that there is a variable degree of interannual variability in surface water and groundwater isotopes, with interannual variability in mean $\delta^{18}O$ values greater than 3‰ (Figure 11). varying degrees of interannual differences in surface water and groundwater isotopes exist and interannual variations in the average $\delta^{18}O$ value are greater than 3‰ (Figure 11). Therefore, isotopic changes reflect different extents of sensitivity to climate change, regardless of the seasonal or multi-year scale. The spatiotemporalspatial and temporal variability of isotopic signals can be ascribed to differences in the extent of warming and humidification across the basinsin each watershed. Wang et al. (2014) highlighted that while the Qaidam Basin has experienced rapid warming in over the past 50 years, the extent of warming and humidification have been markedly asynchronous in different regionsin different regions is noticeably not in sync, where thewith rates of temperature increaserise ranginged from 0.31 to 0.89 ℃ per decade/10a and the rates of rate of rainfall increase increase ranged from 1.77 to 25.09 mm per decade/10a (Figure S1). The correlation between $\delta^{18}O$ of watershed surface groundwater and temperature and precipitation showed (Figure 12) that the multi-year scale $\delta^{18}O$ variations in the basin surface water and groundwater had a more significant positive correlation with precipitation in the same period than temperature (Figures 12b and 12d). It is noteworthy thatOf note, surface water was is more responsivesensitive to precipitation (Figures 12a and 12b) , whereaswhile groundwater was is more sensitive to temperature (FiguresFigure 12) 12a and 12c). This phenomenon suggests that the rise inincreased precipitation rainfall may influence affect the water cycle by promoting slope runoff and groundwater infiltration in mountainous regions areas, and indicates that the warming will lead tocause the ablation of solid water ablation at higher elevations,altitudes to thereby accelerate accelerating the groundwater recharge of to aquifers through bedrock fissures. In addition, elegantThe GRACE and remote sensing monitoring findings suggestedalso demonstrated that the increase in terrestrial water storage in the Qaidam Basin was strongly correlated with increased is closely linked to the rise in precipitationrainfall and glacier meltwater recharge (Song et al., 2014; Jiao et al., 2015; Xiang et al., 2016; Wei et al., 2021; Zou et al., 2022), which fully supporteds the isotope-based conjecture. Furthermore, a recent study foundresearch demonstrates that the accelerated conversion of ice and snow on the Tibetan Plateau into liquid water on the Tibetan Plateau has led to an imbalance in the "Asia Water Tower", with the Qaidam Basin being one of the major regions experiencing an key regionsincrease in where liquid water has grown (Yao et al., 2022). The consistency of data on H-O The isotopes, remote sensing and hydrometeorology data are consistent with the observation shows that the Qaidam

Basin is the most rapid and substantial warming ~~a~~ region in the Tibetan Plateau ~~with the most rapid and substantial warming~~. Global warming affects the basin by redistributing ~~causing a redistribution of~~ precipitation and melting ice and snow in high elevations ~~altitude areas~~, resulting in ~~a rise in~~ groundwater storage increase and ~~an~~ lakes expansion ~~of the area of lakes, among other effects~~. ~~Additionally, the corresponding rise in precipitation in the mountainous areas is able to supplement the rapidly melting ice and snow to a certain degree. This~~ The trend of increasing water storage ~~increase~~ in the Qaidam Basin is likely to continue in the 21st century. The highly coupled results~~findings~~ of different observation methods further emphasize the sensitivity and potential of water ~~stable~~ isotopes in tracing water cycles and climate change.

~~Due to~~Under the influence~~effects~~ of climate change and the intensive ~~intensification of~~ cryosphere retreat, runoff has changed ~~considerably~~ dramatically on the Tibetan Plateau, ~~which~~ with significant effects on ~~drastically impacted~~ the ~~spatiotemporal~~spatial and temporal ~~distribution of~~ water resources distribution (Wang et al., 2021). ~~Based on our observation results, it can be speculated that with continued rapid warming and humidification, the water resources of the watershed with substantial seasonal recharge may manifest as follows:~~ The rapid changes in water resources in the Qaidam Basin are likely because:

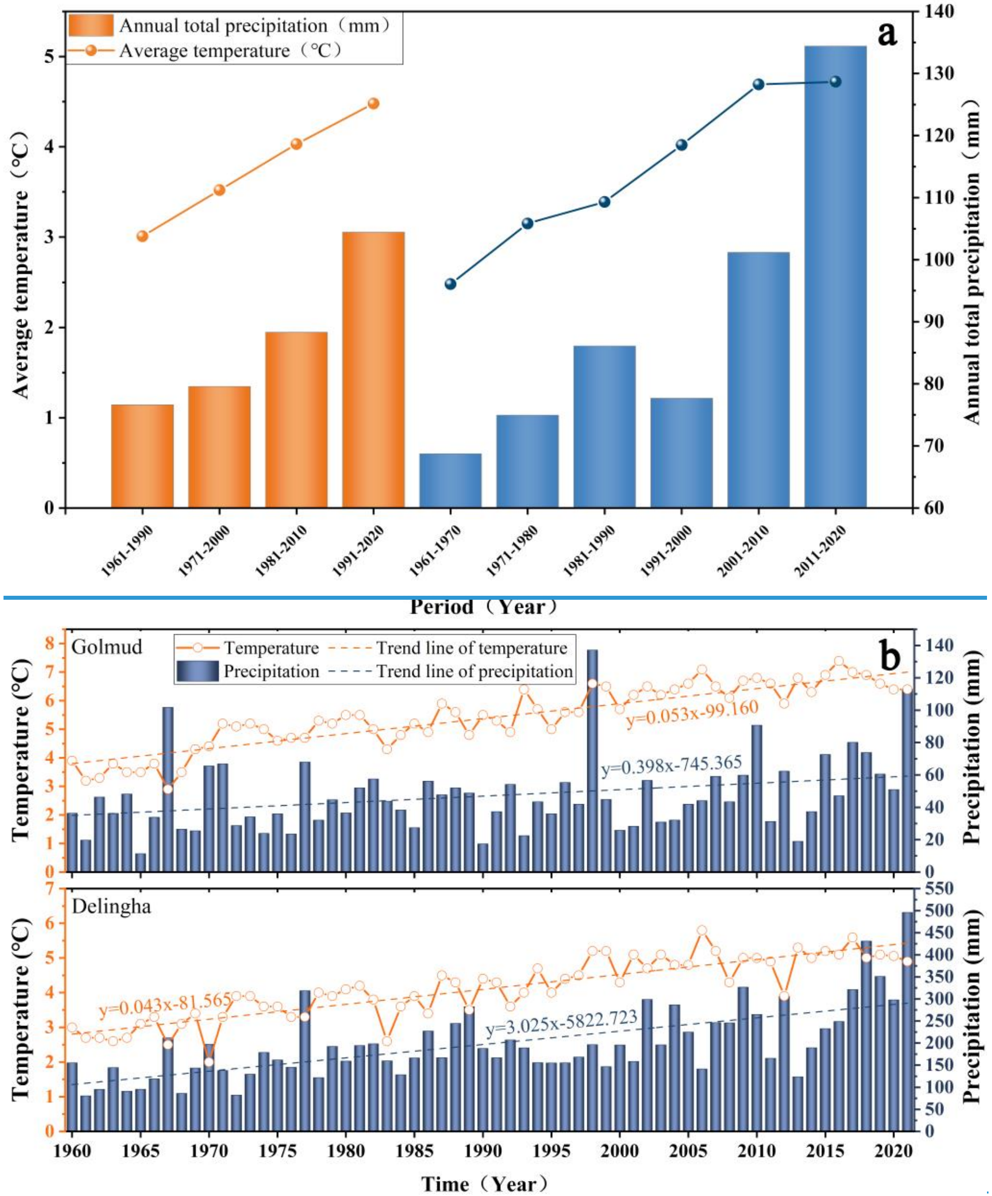
1) ~~The amount of~~ The surface water and groundwater resources will ~~considerably~~ increase significantly in the short term (in recent decades) ~~-~~ due to continued rapid warming and wetting~~because of the shift of snow line and rapid melting of ice and snow coupled with the increase in precipitation~~. For example, water storage in the Bayin and Qaidam Rivers in the eastern basin is ~~,~~likely to continue to increase with a high renewal capacity in the long term under the influence of sustained climate change and the abundant and significantly increasing precipitation~~as a result of the abundant and marked increase in precipitation and strong water resource renewal capability, the water reserves may sustain an increasing trend in the long term under the influence of continuous climate warming~~. This phenomenon has been verified in many regions of the Tibetan Plateau ~~and~~ as well as some alpine watersheds in high-latitude Switzerland (Xiang et al., 2016; Malard et al., 2016; Shi et al., 2021).

~~Moreover, t~~2) The decadal scale climatic oscillation ~~cyclical nature of climate change also~~ suggests that the massive shrinking cryosphere~~cryosphere retreat on a large scale~~ may not sustain surface~~be sustainable for watershed surface -~~ water and groundwater recharge in the basin (Wang et al., 2023). It is expected that water resources in the southwestern basin (e.g., Nalenggele River) may continue to increase for a certain period followed by a large-scale decrease under future climate change scenarios. This is a general trend that has occurred in the Tibetan Plateau as well as regions around the world with large-scale glacial coverage area in alpine watersheds. ~~It was reported that the glaciers~~ Glaciers in the southwestern basin are reported to be ~~continuously~~ losing mass regularly (−0.2 to −0.5 m/a), a trend that ~~and this trend has substantially~~ has increased substantially from 2018 to 2020, notably~~particularly~~ ~~in~~ at the headwaters of Nalenggele River, where ~~the~~ glacier elevation has been reduced by 5.42 m since 2000 (Shen et al., 2022). However, ~~as a result of the low precipitation in the southwestern basin,~~ completing~~achieving~~ the hydrologic budget~~equilibrium in recharge~~ will ~~remains~~ remain a challenge given strong decoupling between ~~the~~ rapid melting of ice and snow caused by ~~climate~~ warming versus scarce precipitation in the southwestern basin, even if precipitation continuously ~~continues to~~ increases in the future.

~~This meansthat in the future climate change scenario, water resources in the southwestern basin watershed (such as Nalenggele River) may continue to rise for a certain period before showing a large-scale decrease. This trend of initial increase followed by decrease is common in the Tibetan Plateau or regions with relatively little precipitation in alpine watersheds around the world. Furthermore,~~ 3) ~~in~~ In the ~~watersheds of the central~~middle basin (Nomhon, Golmud, and Yuka Rivers), there is ~~a~~ long-term large-scale groundwater mining during the agriculture and industry development, accompanied by strong local evaporation. ~~while~~ The sparse precipitation in the source area led to a melt dependence, although the surface~~-~~ water and groundwater recharge here ~~is~~ are relatively stable.~~,~~

~~the long-term large-scale exploitation of groundwater in these three areas during the industrial and agricultural development processes has decreased the precipitation in the source area and led to a reliance on ice and snow melting. Moreover,~~ 4) ~~a~~ Future ~~decline~~ ~~in~~ groundwater level ~~fluctuations in the future is~~ dropping seems to be inevitable in the basin with glacier retreat and reducing of melt water in the mountainous source area. ~~Data monitoring~~ Monitoring ~~of the~~ data from five shallow groundwater boreholes ~~in~~ along the alluvial fan belt of the Golmud River ~~showed~~ shows that ~~the~~ groundwater levels ~~has~~ have fluctuated since 2011, ~~and reduced~~ declining by an average of −1.18 m/a ~~since 2011~~ (Figure S2).

Therefore, Whether whether the enhancedincrease in water resource renewal capacity and water storage in the Qaidam Basin can remain stay stable in the future is a scientific issue that is worthy of consideringconsideration in the future.



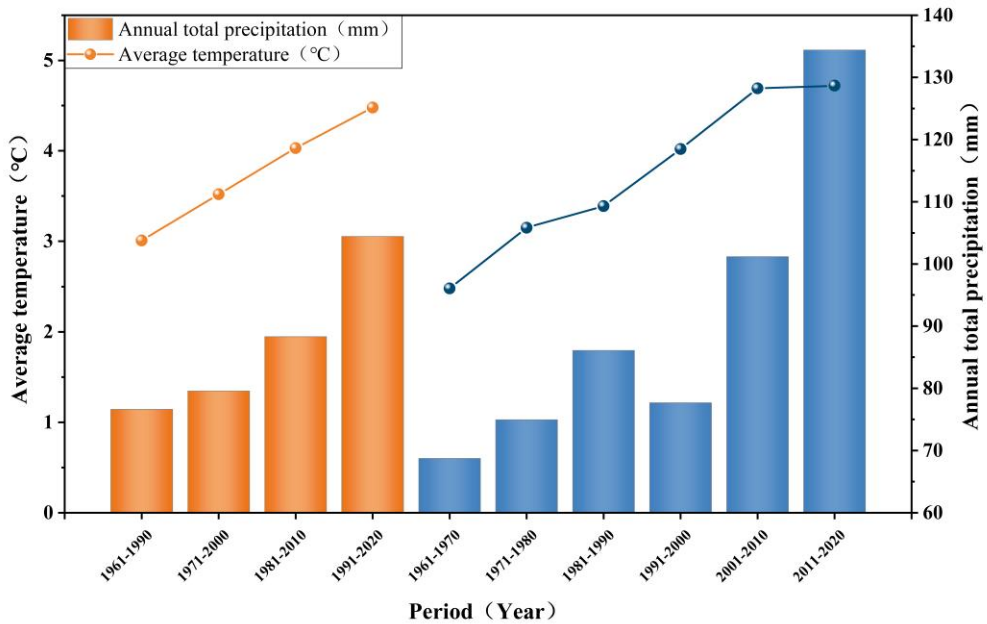


Figure 10. Average temperature and precipitation in the Qaidam Basin every 30 years and 10 years from ~~1960~~ 1961 to 2020~~. (a); interannual changes in temperature and precipitation at the Golmud and Delingha meteorological stations (b)~~

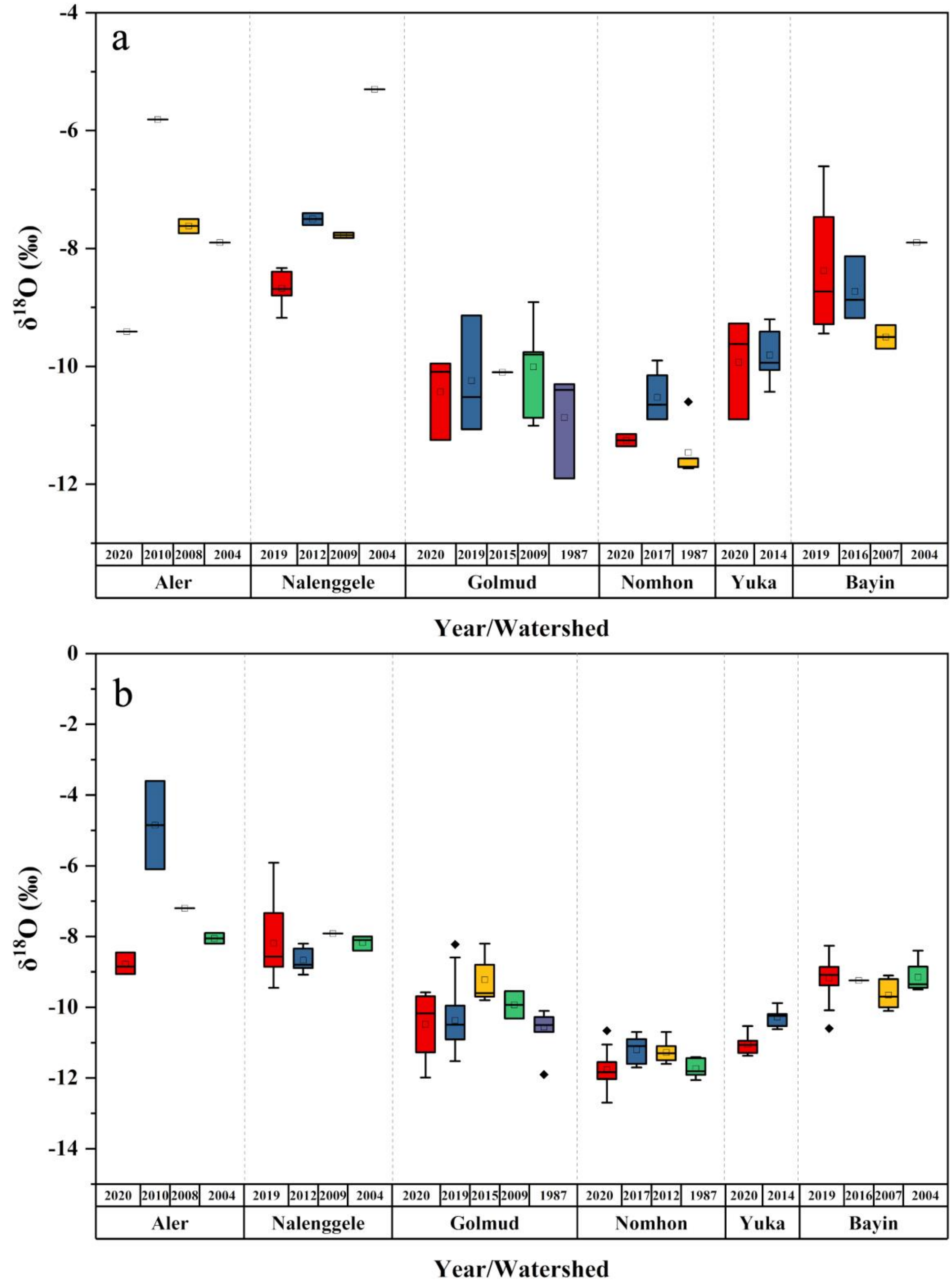


Figure 11. Interannual variations in the river water (a) and groundwater (b) $\delta^{18}O$ in the Qaidam Basin. (Date source: Aler: 2004, Wang et al., 2008; 2008, Tan et al., 2009; 2010, Ye et al., 2015. Nalenggele: 2004, Wang et al., 2008; 2009, Tan et al., 2012; 2012, Xu et al., 2017. Golmud: 1987, Wang et al., 2008; 2009,

Tan et al., 2012; 2015, Xiao et al., 2018. Nomhon: 1987, Wang et al., 2008; 2012, Cui et al., 2015; 2017, Zhao et al., 2018. Yuka: 2014, Zhu, 2015. Bayin: 2004, Wang et al., 2008; 2007, He et al., 2016; 2016, Wen et al.,2018.)

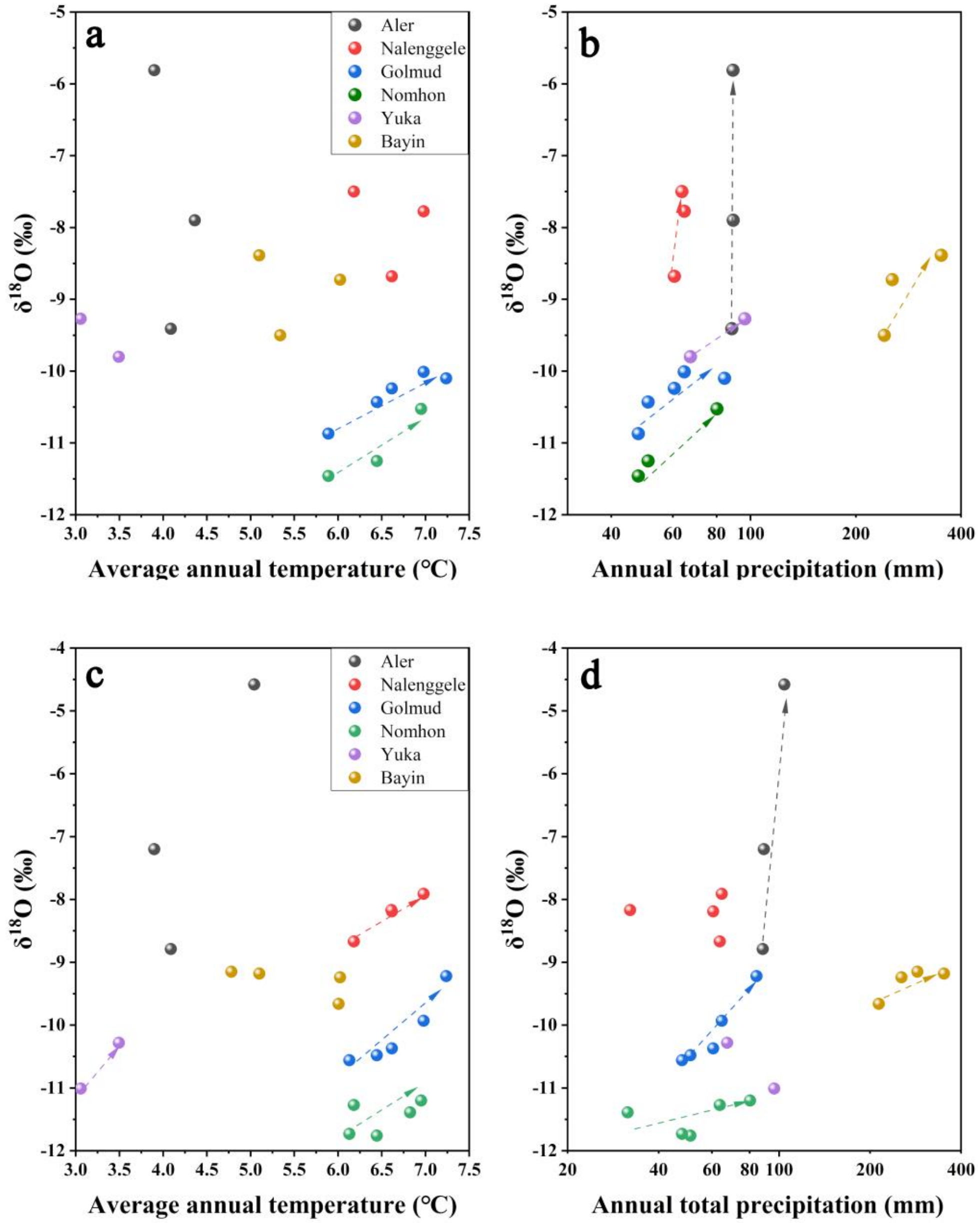


Figure 12. Surface water $\delta^{18}O$ and temperature (a) and precipitation (b); Groundwater $\delta^{18}O$ and temperature (c) and precipitation (d) in the Qaidam Basin. (The light lines indicate $\delta^{18}O$ change with temperature and precipitation.)

6. Conclusion

(1) The contribution of precipitation and ice/snow meltwater is the main factor that drives the accelerated water cycle in the Qaidam Basin. The spatiotemporalspatial and temporal variations of $\delta^{18}O$ and δD in surface water and groundwater $\delta^{18}O$ and δD inof the Qaidam Basin reflect their dynamic hydrological responses to climate change, water sources, climate warming, and local temperature and precipitation regimesneotectonic movements, especially precipitation, at interannual and seasonal scales.

(21) The mean values of surface water $\delta^{18}O$ and δD in the Eastern Kunlun Mountains gradually decrease eastward, whereas the opposite is true for the Qilian Mountains river system, reflecting the intensity of westerlies moisture transport and the influence of local climatic conditions, respectively. Surface water H-O isotopes are enriched during the wet season and relatively depleted during the dry season with a remarkable evaporation effect. The mean values of surface water $\delta^{18}O$ and δD in the Eastern Kunlun Mountains water system are gradually decreased negatively skewed from west to east, and the reverse holds true for the Qilian Mountains water system. Surface water is enriched in heavy H-O isotopes during the wet season and is relatively depleted during the dry season. The base flow is maintained by groundwater recharge during the dry season, andwhile receiving varying proportions of groundwater (26%–62%), ice/snow meltwater (23%–47%) and precipitation (10%–45%) are received during the wet season. The seasonal isotopic variability isdifferences of isotope are determined by the quantity of precipitation level and its gradient increase in the watershedbasin, with precipitation in the Qilian Mountains contributing more to rivers than in the eastern Kunlun Mountains. and the spatial change patterns reflect the influence of water vapor transport intensity of the westerly path and local climatic conditions. The base flow is maintained by groundwater recharge during the dry season, and varying proportions of groundwater (26%–62%), ice/snow meltwater (23%–47%) and precipitation (10%–45%) are received during the wet season. The contribution of precipitation to surface rivers in the Qilian Mountains is greater than that of the Eastern Kunlun Mountains.

(2) The key factor accelerating groundwater circulation in the Qaidam Basin is the contribution of precipitation and meltwater produced by climate change. The phreatic groundwater systems located in the collision and convergent convergence zone of different several mountain ranges is are distinguishedcharacterized by enriched H-O isotopes during wet season, high

~~concentrations of radioactive~~ ^{3}H concentrations, and marked rapid seasonal recharge ~~during the wet season~~. Modern precipitation~~meltwater~~ and meltwater ~~precipitation are able to~~can infiltrate through favorable structural conduits (e.g., large-scale active fault zones) ~~water channel passages, such as large-scale active fault zones, giving rise to~~resulting in rapid groundwater recharge. In contrast, the ~~phreatic~~ groundwater systems in the western ~~region of the~~ Qilian Mountains and the ~~central~~ middle ~~region of~~ Eastern Kunlun Mountains ~~have~~ are depleted in H-O isotopes during wet season and ~~low~~ ^{3}H concentrations are low ~~during the wet season~~, and ~~they~~ are primarily~~mainly~~ slowly recharged by seasonal ice/snow meltwater, which consisted ~~which consists~~ of modern water and submodern water (>60 years) ~~maintained together~~. The confined groundwater is considerably depleted in H-O isotopes, and for the most part exhibits imperceptible ~~a majority has no apparent~~ seasonal changes. ~~The~~ ^{3}H concentrations ~~is~~ are very low ~~or below the detection limit~~, and ~~the~~ recharge is quite ~~relatively~~ slow, dominated by~~with~~ fossil water ~~dominated~~.

(3) Warming climate ~~Climate warming~~ has exerted a substantial impact on the hydrological processes across~~throughout~~ the ~~whole~~ basin, accelerating~~thereby driving~~ water cycle ~~acceleration~~ and raising~~increases in~~ water storage uncertainties~~fluctuations~~ in the eastern and southwestern basin ~~regions via~~ through the increase ~~in~~d precipitation and melting of glaciers and snow. However, this increasing trend of water resources in the basin seems to be unsustainable. ~~the cyclical nature of climate change suggests that this trend is unsustainable. As precipitation increases and solid water ablation in mountainous regions becomes severely out of balance, t~~The southwestern basin ~~may~~ could suffer~~face~~ a rapid ~~decline~~ loss in total water resources in the future as precipitation increases and solid water ablation in mountainous areas becoming severely out of balance undergone climatic extreme changes.

Author Contribution

Conceptualization: Yu Zhang, Hongbing Tan; Funding acquisition: Xiying Zhang; Investigation: Peixin Cong; Resources: Wenbo Rao; Visualization: Dongping Shi; Writing–original draft: Yu Zhang; Writing–review & editing: Hongbing Tan.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The complete list of isotopes and their values is available in Table S1 in Supporting Information. The meteorological data can be obtained on China Meteorological Data Network (http://data.cma.cn). The monthly mean ERA5 reanalysis data (0.25° × 0.25°) can be obtained from European Centre for Medium-Range Weather Forecasts (ECMWF, https://www.ecmwf.int/).

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