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An Analysis of Surface Water–Groundwater Interactions Based on Isotopic Data from the Kaidu River Basin, South Tianshan Mountain

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Abstract: The unique climate conditions and water source composition in the Tianshan Mountain provide a good experimental site for verifying the relationships between water resources and climate change on a larger scale. With the help of water isotopes (D, ¹⁸O), a more reliable conceptual model of groundwater systems can be constructed on both local and regional scales, especially in areas that are susceptible to climate change and under pressure from intensive human activities. In this paper, we present $\delta^{18}\text{O}$, δD , d-excess, RWLs and altitude effects of river water and groundwater based on the data derived from our network of stable isotope sampling sites along the Kaidu River. Stable isotope mass balance was applied to study the interactions between groundwater and surface water and to quantify the recharge proportions between bodies of water in typical regions. The results showed that the Kaidu River is composed of precipitation, ice and snow melt, baseflow and groundwater. The percentage of groundwater increased with the distance between upstream (the runoff producing area) and the leading edge of the glacier. The two recharge areas are the spring overflow from the mountain area to the alluvial layer of the inclined plain and the leading edge of the alluvial plains to areas with fine soil. The groundwater recharge ratio is about 23% in high mountain areas but 46% or more in the middle and lower reaches. These results generated a more comprehensive understanding of the hydrological cycle of inland rivers in arid regions.

Keywords: stable isotopes; baseflow; groundwater; mass balance



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1. Introduction

Presently, the demand on water resources exceeds its supply capacity in many parts of the world. This is especially true for arid regions. As the result of a worldwide increase in human water consumption, the pressure on existing water resources is intensifying; thus, the sustainable exploitation of water resources is of great importance [1]. Groundwater is a resource but also a living ecosystem [2]. Groundwater circulation controls the water quality and ecosystem dynamics in groundwater-dependent ecosystems [3,4]. In polar and alpine regions, groundwater is also the most significant source of other hydrological systems, such as surface water [5]. Water containing stable isotopes (¹⁸O, D) exhibits systematic temporal and spatial variations as a result of the isotope fractionation events that accompany changes in the water cycle and the diffusion stages [6]. Thus, isotopic techniques can be used conveniently and have been applied successfully to study the origins, dynamics, evaporation and mixing processes between surface and groundwater sources [7–13]. However, a comprehensive circulation model of groundwater has not yet been established due to the complicated mechanisms involved in groundwater recharge.

To create such a model, research on isotopic fractionation is necessary, first to trace changes in exploitation intensity and second to understand the interconnecting feedbacks between surface water and groundwater systems [14].

The Tianshan Mountain Range, located at the border between China and Kyrgyzstan, offers the most typical and complete mountain vertical natural zone spectrum in the temperate zones of the world. In this area, water mostly originates from the mountain region and is a key factor of energy and mass circulation; additionally, the studied area is highly sensitive to global climate change. This kind of unique climate condition and water resource composition will inevitably have an impact on regional natural resources, which also provides a good experimental site for verifying the relationships between water resources and climate change on a larger scale. In arid and semiarid areas, isotope hydrological separation provides a quantitative method of differentiating the recharge types of rivers, which is important for water resource management in the ungauged basins. Examples of these applications include the study of surface water and groundwater replenishment in small watersheds [15–20]. A review of published papers showed that the current knowledge in the understanding of water circulation isotopes and the quantitative evaluation of water recycling in mountain–plains areas are still lacking [21]. The Tianshan range is called “the water tower of Central Asia” because it plays a pivotal role in the water cycle. In this area, the quantity and quality of groundwater control the state of riparian vegetation. Currently, the charge regime of this riparian groundwater system under natural conditions is not still fully understood, and it is still unclear how the recharge regime has been affected by cross-catchment water diversion.

Based on the collected stable water isotope data, the goals of the current study are: (1) to estimate the groundwater recharge and illustrate the hydrological connection and the frequent conversion relationship between surface water and groundwater; (2) to evaluate the recharge rate of groundwater in the runoffs from alpine oasis regions (defined in Figure 1) to the plain desert regions. Collectively, these results provide insights into groundwater resources and river basin management for the Kaidu River Basin and other watersheds sharing a similar environment in Central Asia.

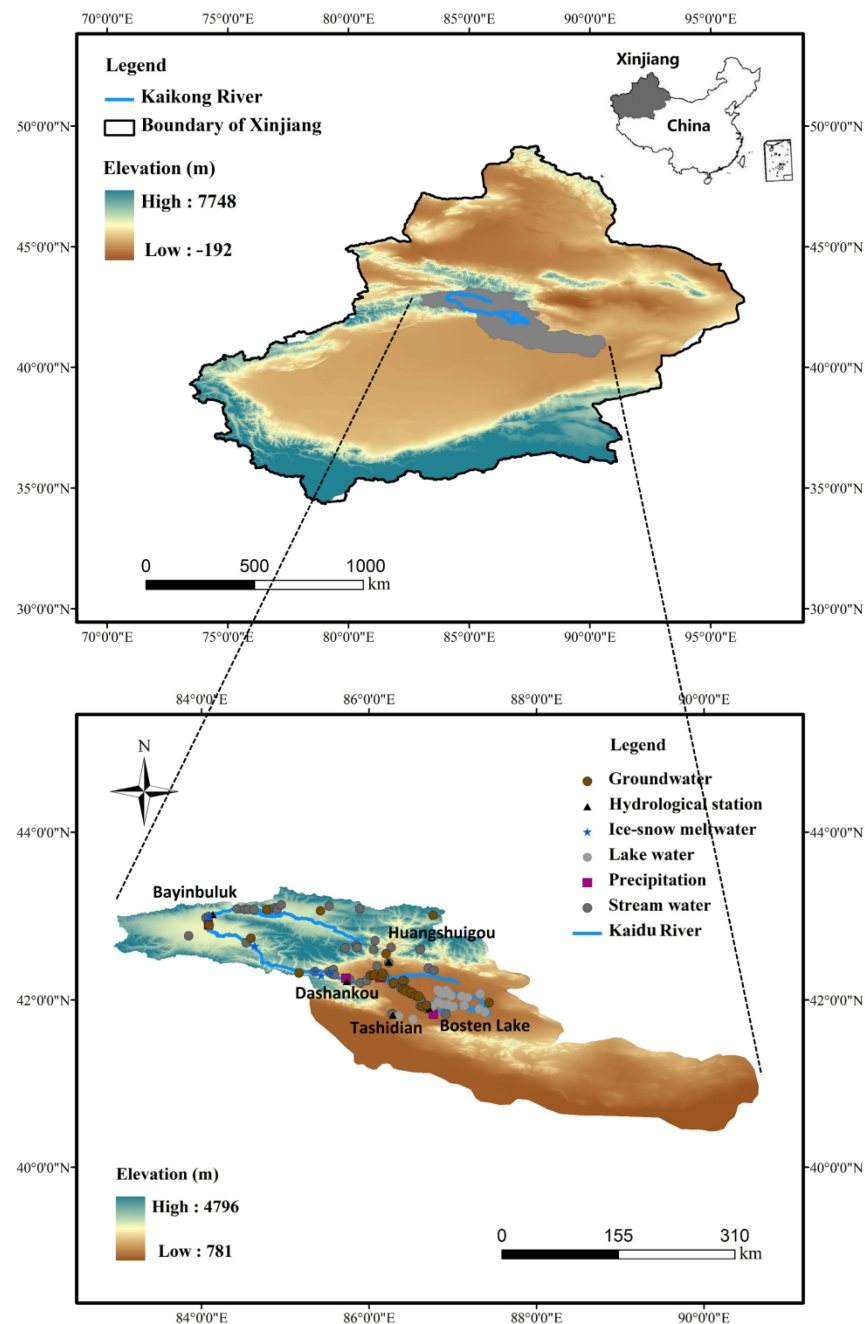


Figure 1. The locations of the sampling sites including geographical features of the study area. The Kaidu River (Kaikong River as shown in the map) Basin is located in Southern Xinjiang, PR China.

2. Materials and Methods

2.1. Meteorological and Hydrological Conditions of the Studied Area

The study area is focused on the Kaidu River Basin of South Tianshan Mountain, which spans $42^{\circ}43'–43^{\circ}21' N$ and $82^{\circ}58'–86^{\circ}05' E$, with nearly 610 km in length, and about 22,000 square kilometers in area. Tianshan Mountain is located deep inland (Figure 1), has a temperate continental arid climate and a landscape of mountains and basins with glaciers and rivers. Unique biota and ecological processes have made it the most typical representative of large mountainous ecosystems in the arid and temperate regions of the world. The Köppen–Geiger climate classification of Tianshan Mountain include BWk (cold arid climate), ET (polar tundra climate) and Dwc (snow dry winter and cool summer climate) [22]. The area is situated deep inland, the precipitation is concentrated between

April and September and the melting water is most abundant between April and May (with the air temperature rising above -4.5 degrees, runoff forms on the surface). The rivers are influenced by seasonal water quantity and have wet–dry periodic cycles. The Kaidu River (Figure 1) is the third largest river in Tianshan Mountain range. It originates from Ilenhabilga Mountain in the central part of the Tianshan range (more than 4000 m above sea level); flows through Hejing, Yanqi and Bohu, which are three counties in the Bayinguleng Mongolian autonomous prefecture upstream and ends at Bosten Lake. The annual average runoff is 3.362 billion cubic meters, the average flow rate is $112 \text{ m}^3/\text{s}$ and the maximum flood peak flow rate is $883 \text{ m}^3/\text{s}$. The wet period of Kaidu River is April–September, and the dry season is October–March. In the data collected at Dashankou Station and Huangshuigou Station, spring (March to May) runoff accounted for 23.3% and 14.0% of the river's contents, respectively; summer (June to August) runoff accounted for 45.0% and 57.3%, respectively; autumn (September to November) runoff accounted for 20.9% and 18.6%, respectively; and winter (December to February) runoff accounted for 10.8% and 10.1%, respectively (Figure 2). Groundwater is mainly found in the aquifers in the diluvial and alluvial layers in the mountainous areas and plains. The sediments of the phreatic aquifer in the mountainous areas consist of gravel, gradually changing to soil with descending altitude then from soil to clay from the northwest to the southeast of the plain area.

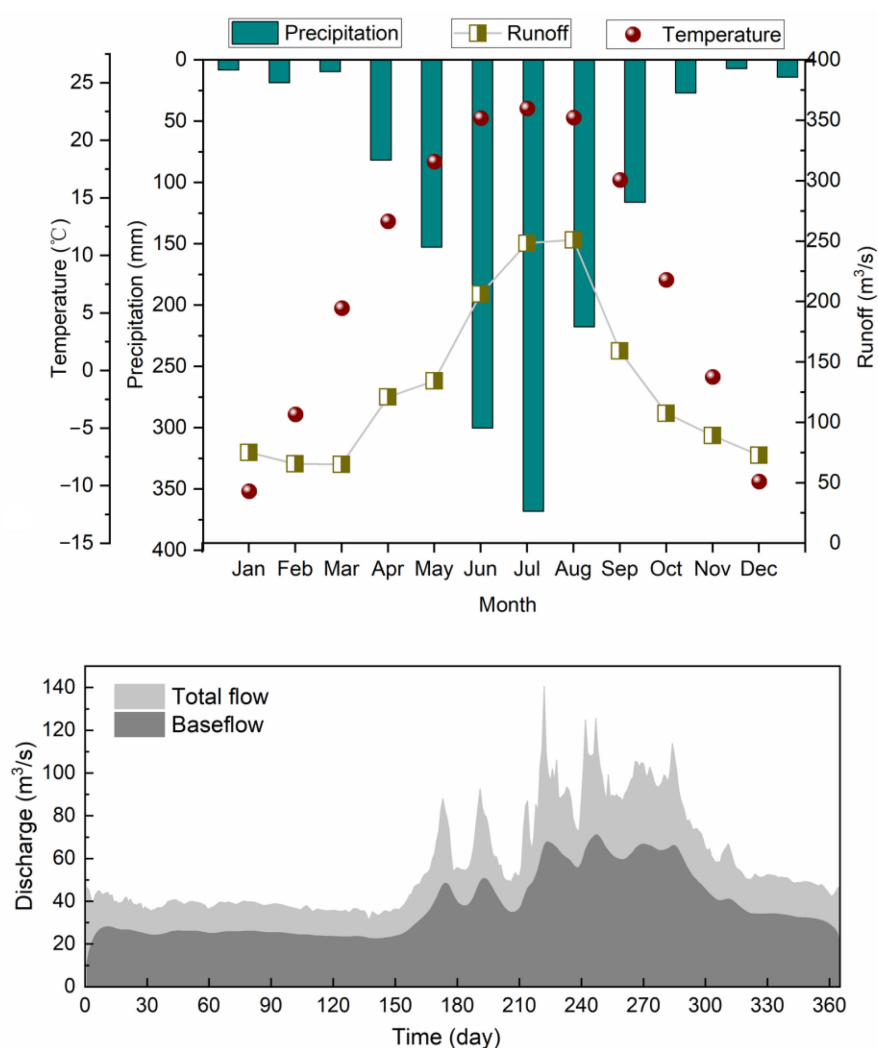


Figure 2. Monthly variations in temperature, precipitation, runoff and baseflow in the Kaidu River. The data for temperature and precipitation are from 2000 to 2018, and the data for runoff are from 1972 to 2012. The baseflow separation of the Kaidu River is the multiyear average.

2.2. Sampling and Data Analysis

Stable isotope surveys were conducted seasonally between January 2017 and June 2018 in the Kaidu River Basin, with a total of 279 water samples collected from 4 distinct geological regions: high mountain area, middle mountain area, oasis area and Bosten lake (Table 1 and Figure 1). Water samples, including precipitation, surface water, groundwater, spring water, baseflow and ice and snow melt were collected along the Kaidu River; the sampling sites were selected within the junction of the main river's principal course and its tributaries. The corresponding parameters, air temperature, precipitation, humidity and rate of flow, were also measured at the sampling sites at the time of collection. River water was collected on a seasonal basis whenever possible from January 2014 to June 2016 at hydrological stations (Figure 1, solid triangles). The precipitation was sampled with a submerged inlet tube (i.e., tube-dip-in samplers) to prevent evaporation during the sampling period (by event, Figure 1, squares) [23]. Groundwater was sampled from wells in both dry and wet seasons (Figure 1, brown solid circles); ice and snow melt were collected underneath the snowpack at the tongue of Tianshan Mountain (Figure 1, solid stars); samples from smaller bodies of surface water in the basin (springs, baseflow, lakes, ponds) were collected whenever possible. The watershed was divided into different regions according to the topographic environment, where the different types of samples are shown in Table 1.

Table 1. The statistics for $\delta^{18}\text{O}$, δD , and deuterium excess of different types of water from the Kaidu River (recharge areas of the source to downstream).

Sampling Region	Water Type	No.	$\delta^{18}\text{O}(\text{‰ V-SMOW})$			$\delta^{18}\text{O}$ Std. Dev	$\delta\text{D}(\text{‰ V-SMOW})$			δD Std. Dev	D-Excess Mean (‰)
			Max	Min	Mean		Max	Min	Mean		
Mountain area	Ice-snowmelt	70	−17.80	−20.12	−18.96	0.02	−140.25	−147.91	−144.08	0.10	7.60
	Precipitation		−3.63	−4.98	−4.73	0.04	−46.89	−52.22	−49.05	0.75	−13.82
	River water		15.82	−13.73	−8.22	0.07	−14.07	−81.43	−62.26	0.69	4.05
	Groundwater		8.96	−11.37	−7.25	0.04	−31.65	−72.72	−60.05	0.68	−2.23
Oasis area	Precipitation	120	−3.87	−6.61	−5.24	0.06	−53.12	−54.65	−53.88	1.28	−11.96
	River water		−5.73	−13.94	−10.45	0.07	−45.88	−97.96	−69.84	0.93	13.79
	Groundwater		−7.97	−10.62	−9.37	0.10	−60.27	−70.07	−64.90	0.72	10.05
Lake	Lake water	89	−0.25	−9.99	−2.79	0.06	−14.12	−66.03	−27.77	0.64	−5.43
	Groundwater		−9.93	−10.90	−10.51	0.07	−61.66	−72.49	−69.00	0.94	15.08

Note: Max, maximum value; Min, minimum value; No., number of samples; Std. Dev, standard deviation; oasis area, Yanqi Basin Oasis (one of fifteen independent oases of Xinjiang that is spawned by the mainstream of Kaidu River and Bosten Lake); D-excess, deuterium excess.

2.3. Oxygen and Hydrogen Isotopic Measurement

All water samples were filtered through 0.45 μm cellulose acetate membrane filters, collected into injection bottles and kept $<4^\circ\text{C}$ but above freezing until analysis. The Los Gatos Research liquid water isotope analyzer's (LWIA-24d) off-axis cavity-enhanced absorption spectroscopy technique was used to measure the isotopic compositions of the water samples. To avoid the memory effect that is associated with continuous-flow methods, each sample was measured 6 times, and the first 2 measurements were discarded. Data were processed using LWIA Post software (Version 3.1.0.9, Los Gatos Research, Inc., Los Gatos, CA, USA; www.lgrinc.com, accessed on 8 June 2022). We used USGS47 ($\delta\text{D} = -150.2\text{‰}$, $\delta^{18}\text{O} = -19.8\text{‰}$), USGS45 ($\delta\text{D} = -10.3\text{‰}$, $\delta^{18}\text{O} = -2.238\text{‰}$), W-43156 ($\delta\text{D} = -112.8\text{‰}$, $\delta^{18}\text{O} = -14.42\text{‰}$), W-32633 ($\delta\text{D} = -58\text{‰}$, $\delta^{18}\text{O} = -8.95\text{‰}$), and W-115143A ($\delta\text{D} = -4.8\text{‰}$, $\delta^{18}\text{O} = -1.19\text{‰}$) as isotopic reference materials. Corrections of $\delta^{18}\text{O}$ and δD were performed by calculating the differences between the measured and known values for the standard samples. The measured isotope signatures were expressed as parts per thousand (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) using δ notation. The measurements' accuracies were $\pm 1\text{‰}$ for δD and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$.

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

R_{sample} and R_{SMOW} represent isotopic ratios of D:H or $^{18}\text{O}:^{16}\text{O}$ of the samples and VSMOW, respectively.

Deuterium excess (d-excess) was defined in a previous work in order to highlight the variability of isotopes [24]. The isotopic values create a linear relationship between $\delta^{18}\text{O}$ and δD with a global mean slope of 8:

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

The Global Meteoric Water Line (GMWL) defined by Gouy [25] was applied as a reference for precipitation, and Local Meteoric Waters Lines (LMWL) were adopted from Pang [26].

2.4. Hydrograph Separation and Data Analysis

2.4.1. Baseflow Digital Filter

Hydrograph separation was conducted using recursive digital filtering (RDF) [27]. The filter parameter was fixed at 0.925 [28]. The algorithm separates baseflow from total stream flow by passing the filter over the stream flow record three consecutive times (forwards, backwards, and forwards again). The output of the filter is constrained such that the separated flow cannot take negative values and is no greater than the total flow. The RDF process can be represented as:

$$Q_d(t) = \beta Q_d(t-1) + \frac{1+\beta}{2} [Q(t) - Q(t-1)] \quad (3)$$

where Q_d (m^3/s) is the filtered quick streamflow; Q (m^3/s) is the total streamflow; t is the time step (day) and β is a filter parameter. The filtered baseflow Q_b can then be obtained by:

$$Q_b(t) = Q(t) - Q_d(t) \quad (4)$$

The calculated digital filter baseflow was then compared with two tracer-based, linear mixing approaches in a model based on Bayesian theory (MixSIAR).

2.4.2. End-Member Mixing Analysis (EMMA)

The streamflow is usually divided into different combinations of water components, such as event and pre-event water or event water, pre-event water, and the total precipitation mixture of the previous events. In this study, end-member mixing analysis (EMMA) [29] is applied for the identification of water sources and their contributions to the river;

$$\sum_{i=1}^n C_{i f_i}^j = C_{t_j}^j, \quad j = 1, \dots, k \quad (5)$$

$$\sum_{i=1}^n f_i = 1 \quad (6)$$

Here, C_i^j is the tracer j incorporated in the component i . EMMA solves n simultaneous Equations (5) and (6) with the least squares method using $n-1$ tracers. The tracers we used were $\delta^{18}\text{O}$ and δD . These tracers were measured in each potential source, referred to as endmembers, and in the target water body.

2.4.3. Bayesian Mixing Model (MixSIAR)

MixSIAR incorporates many advances from previous software packages (IsoSource, MixSIR, SIAR, IsotopeR) [30,31]. The model was applied to stable isotope data to determine the relative contributions of each water source to the mainstream and tributaries. Alpine catchments are defined as catchments where ice and snowmelt water contribute to recharging [32]. The runoff is mainly composed of land flow and groundwater derived from precipitation and ice and snow melt. As noted earlier, isotope values of river water,

ice and snow melt and groundwater differ greatly in the mountainous segments of the river as they gradually seep into the river [33]. The proportion of groundwater discharged into surface water is calculated solely based on oxygen isotopes and can be calculated by the two-component model derived using Equations (5) and (6). In the river below the Dashankou Station section, groundwater is mainly composed of surface water, and two-component hydrograph separation was used for water from the mainstream and nearby groundwater. However, if two confluence flows converged at one site, it was better to treat them as branching water rather than as upstreams, and a three-component hydrograph separation was carried out. A three-component model produced using Equations (5) and (6) was used to deduce a formula for calculating the proportion of groundwater in river runoffs to verify the results for the source region. Data analyses were conducted using JAGS and R software 4.1.0.

2.4.4. Meteorological Data Collection and Analysis

Instrumental climate records of the meteorological stations near the sample sites were obtained from the China National Climatic Data Center (<http://data.cma.cn>, accessed on 8 June 2022), including monthly mean temperature, monthly minimum temperature, monthly maximum temperature, relative humidity and total monthly precipitation.

Data processing (linear regression) and statistical analysis (Pearson's correlation coefficients, *t*-test) were performed with software package R (RStudio, version 4.1.0) and the Statistical Package for Social Sciences (version 13.0, SPSS, IBM, Armonk, NY, USA). The level of significance was set at $p \leq 0.05$.

3. Results

3.1. Temporal and Spatial Variations in Water Isotopes

The results showed that the $\delta^{18}\text{O}$ isotopes were more enriched away from the source in the flow direction in the first 100 km and started to deplete after the first 100 km (Figure 3a). However, this trend is not statistically significant. For groundwater, heavy isotopes also showed a nonsignificant fluctuation similar to the river water (Figure 3b), implying the potential connectivity between river water and groundwater. The mean $\delta^{18}\text{O}$ of -10.45‰ in the oasis area reflects greater depletion of heavier isotopes compared with the mean groundwater $\delta^{18}\text{O}$ of -9.37‰ (Table 1).

The total runoff often reaches a maximum in spring and/or summer. Precipitation in the Kaidu River also exhibits significant seasonal variation, most of which occurred during the summer months. It receives 50–70% of the annual precipitation in the summer (Figure 2). Due to the temperature effect, the ice and snow melt water isotopes are always depleted earlier than those of precipitation and runoff. Isotopes of groundwater exhibit considerable similarities to the weighted average precipitation. Mountainous areas receive much less precipitation in winter, which only accounts for about 5–15% of the annual total. In contrast, the seasonal precipitation distribution in plain areas is more uniform, with a slight increase in spring and summer. Thus, there are significant isotopic differences between each component.

River d-excess values exhibit remarkable spatial variation in surface water. The values of water samples from mountainous areas are greater than those from oases and riparian zones. The highest d-excess values were found at sites with altitude >1600 m, in the oasis area and downstream of the river (Figure 3a,b). The surface water and groundwater in the mid-mountain regions exhibited intermediate d-excess, and a significant correlation was found between d-excess and the distance from the source ($R = 0.52$, $p < 0.05$). The d-excess of the groundwater in the oasis area showed relatively stable trends (not significant), which may be caused by different proportions of water component inputs in groundwater and the drainage to the surface water (Figure 3b). A significant correlation between elevation and river water d-excess was observed ($R = 0.46$, $p < 0.05$). Lower d-excess values in low-elevation areas were found because of the higher evaporation rates. The variations in

surface water and groundwater d-excess can be interpreted as the attenuation of d-excess during the infiltration of precipitation and ice and snow melt.

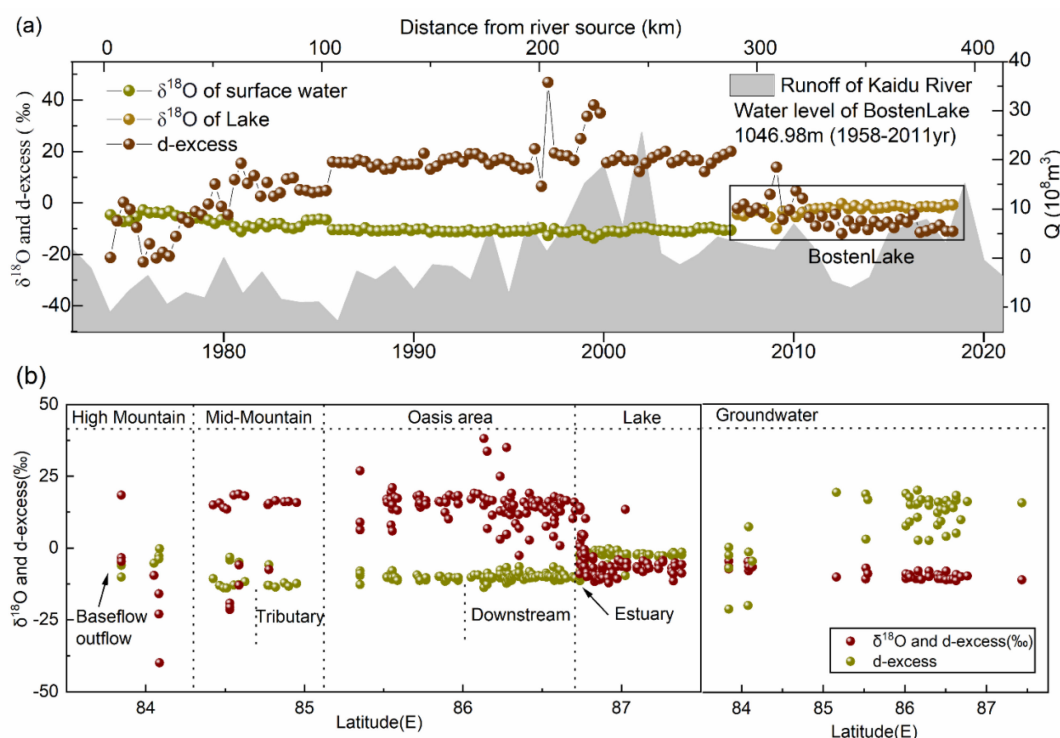


Figure 3. (a) $\delta^{18}\text{O}$ (circles, ‰) and d-excess (triangles, ‰) fluctuations at sample sites vs. distance from river source (left and upper axis) and time series of discharge (solid line, 10^8 m^3) of the Kaidu River. Yellow circles denote lake isotope measurements during the ice-free period. (b) Spatial variations in $\delta^{18}\text{O}$ of river water and groundwater.

The river water and groundwater samples are distributed in the vicinity of the Global Meteoric Water Line (GMWL) and in a centralized manner, in contrast to Local Meteoric Water Line (LMWL, $\delta D = 7.05\delta^{18}\text{O} + 0.6$) (Figure 4a) [26]. The maximum $\delta^{18}\text{O}$ and δD appeared in the dry season months, with the highest $\delta^{18}\text{O}$ and δD being -2.7‰ and -44.9‰ , respectively. Minimum values appeared during the wet season months, with the lowest $\delta^{18}\text{O}$ and δD of -14.65‰ and -112.11‰ , respectively. Generally, a seasonal difference could be observed, with lower $\delta^{18}\text{O}$ and δD in the wet season and higher values in the dry season (Figure 4a). Stable isotopic compositions for surface water samples during the wet season (from mountainous and oasis zone) were similar and located above or close to the GMWL, but the data from the dry season are located below the GMWL and LMWL, suggesting that the effect of evaporation is significant during recharge. According to the relationship between $\delta^{18}\text{O}$ and δD , most of the isotopic data points of the groundwater are close to the LMWL; the stable isotope data provided no evidence of evaporative concentration in groundwater. Several sample points of B1–B2 were sequestered from other points (gray circles, Figure 4a); these samples were collected from baseflow in the wet season, which indicated that surface water generated in the Bayinbuluke region (B1–B2) was significantly different in isotopic values from the water from downstream, which in turn indicates that the constitutions of the water sources are different.

Spatially, the river water was more depleted in heavy isotopes in the upper reaches than in the middle and lower reaches (Figure 4b), further indicating that the effects of evaporative fractionation increase towards downstream. For the mid-mountain (midstreams), although the river water was more depleted in heavy isotopes downstream, the slope of the RWL was overall lower than that of the high mountain area (upstreams) (Figure 4b). As the sampling time covered both the wet and dry seasons, the groundwater samples were

distributed among the river water samples and located near the river water line, which indicated that there is considerable similarity among these water samples, especially in oasis areas.

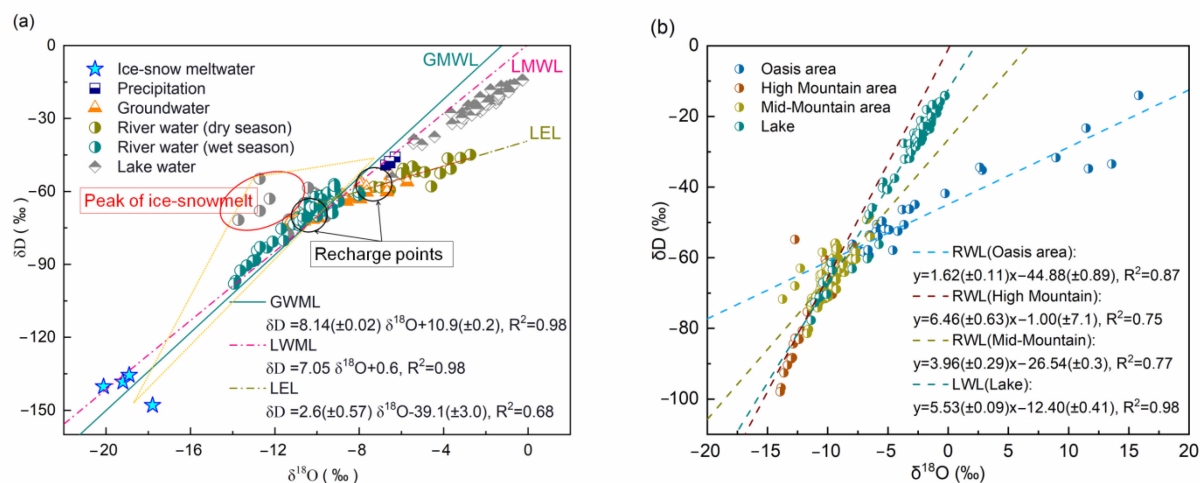


Figure 4. (a) Water component relationships displayed by the bivariate plot of δD versus $\delta^{18}O$ in the Kaidu River Basin, river water, precipitation, ice and snow melt and groundwater relative to GMWL. (b) River water samples from the high mountain area, mid-mountain area, oasis area and lake. (GMWL: global meteoric water line; LMWL: local meteoric water line; LEL: local evaporation line; RWL: river water line; LWL: lake water line). Both the slopes and the intercepts of the four regression lines presented in (b) are statistically different from each other (Tukey's multiple comparison test).

3.2. Surface Water–Groundwater Interaction

The combination of the isotopic evidence showed that the Kaidu River water is composed of precipitation, ice and snow melt, baseflow and groundwater, and the groundwater recharge gradually increases from source to the midstream and decreases at some regions due to artificial drainage (Table 2). Then, the groundwater ratio first decreased and then increased again: the ratio was about 20% at the distance of 150 km from the river source but increased to 42% at the mountain mouth station (Figure 3a and Table 2).

Table 2. The mean concentrations of tracers in different water types and the fractions of groundwater discharged to the surface.

Along Kaidu River	Region	Water Type				Per (%)
		C_r (‰)	C_u (‰)	C_{u2} (‰)	C_g (‰)	
A. High mountain	B1	−4.89	−3.66	/	−8.96	23
	B2	−3.19	−0.25	−13.59	−7.94	28
	K1	−5.48	−4.58	/	−6.52	46
	K2	−5.27	−4.19	/	−6.64	44
B. Mid-mountain	K3	−10.26	−10.29	/	−10.15	21
	T1	−10.32	−10.37	−10.29	−10.15	23
	T2	−10.05	−10.00	/	−10.12	42
	T3	−8.99	−10.26	−9.93	−10.12	12
C. Oasis area	D1	−10.07	−10.14	−10.01	−10.90	−9
	D2	−9.95	−10.03	−10.26	−10.72	−12
	D3	−8.42	−9.03	/	−10.98	−31
	D4	−9.92	−10.20	/	−10.63	−65
D. Lake	L1	−10.08	−2.27	/	−10.12	99
	L2	−10.03	−1.45	/	−10.72	93
	L3	−10.03	−1.45	/	−10.72	93

Note: C_r , runoff; C_u , upstreams; C_{u2} , up-tributaries; C_g , groundwater; Per, percentage.

Table 2 shows that the contribution of groundwater increased with the distance between the upstream (runoff producing area) and the leading edge of the glacier. At the point of 41 km, the proportion of groundwater exceeded 55%, and the importance of ice

and snow melt indicates that the warm and dry climate could cause significant changes in the hydrology of the Kaidu River Basin and thus affect the rational utilization of water resources in the short term.

After the flow reached the oasis region, groundwater decreased and began to present a more complicated relationship with the surface water. In several specific regions such as T3, B1 and K3, during dry seasons, groundwater was the major contributor to the baseflow and may have been recharged by a mixture of ice and snow melt and rain; during the wet season, water is discharged to the river by spring or through faults in the alpine valley. In most watersheds along the Kaidu River (such as D1–D4), river water was continuously pumped out for agricultural use, which resulted in a decrease in the amount of water seeping into the ground. As a result, the recharge of groundwater decreased and in extreme cases even changed the interaction between groundwater and surface water. The basement of the basin is part of the Bayin–Gobi Formation, whose rock consists of gneiss, schist, granitoid and glacial deposits. Deep groundwater exploitation was carried out for irrigation, and the recharge source was reduced, which resulted in some environmental problems such as the reduction of groundwater levels, the exhaustion of groundwater resources and the degeneration of vegetation (Figure 5). Groundwater and upstream accounted for 93% of the Bosten Lake water. Moreover, the groundwater was observed to have a similar composition as the lake water. Based on the predicted future trend of climate change, the inflows of the Bosten Lake are expected to be reduced as a result of decreasing river runoff volume and lower groundwater level.

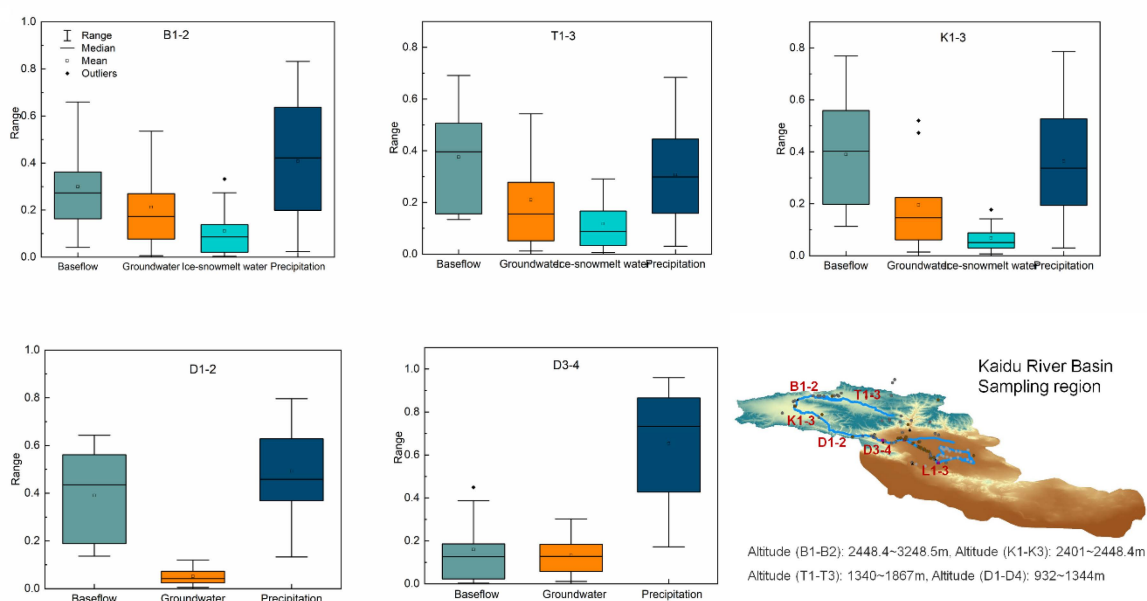


Figure 5. The MixSIAR-derived source water contributions to the mainstream at the outlet (B1–B2), tributary (T1–T3), midstream (K1–K3) and downstream (D1–D4). The boxplots represent the distributions of potential source water contributions derived by a Bayesian approach for MixSIAR. The boxes show the medians and 25th/75th percentiles, with the whiskers indicating the 5th/95th percentiles. The crosses point out absolute extreme values. Baseflow (light cyan), groundwater (orange), ice and snow melt (blue) and precipitation (navy blue).

4. Discussion

Through classification analysis, there are three interactive processes within river flow (Table 2 and Figure 6). From the snow line of Tianshan to the mountain pass stations, the bedrock fissure water receives precipitation, and the deuterium value of the fissure water increases. The fissure water recharges surface water through output by springs, and the deuterium content of the river water increases to exceed that of groundwater. After that, the river water is recharged by local precipitation, and 70% to 80% of this surface runoff

recharges the groundwater from piedmont, so the deuterium value of groundwater became slightly elevated, although it was still lower than the river water deuterium values.

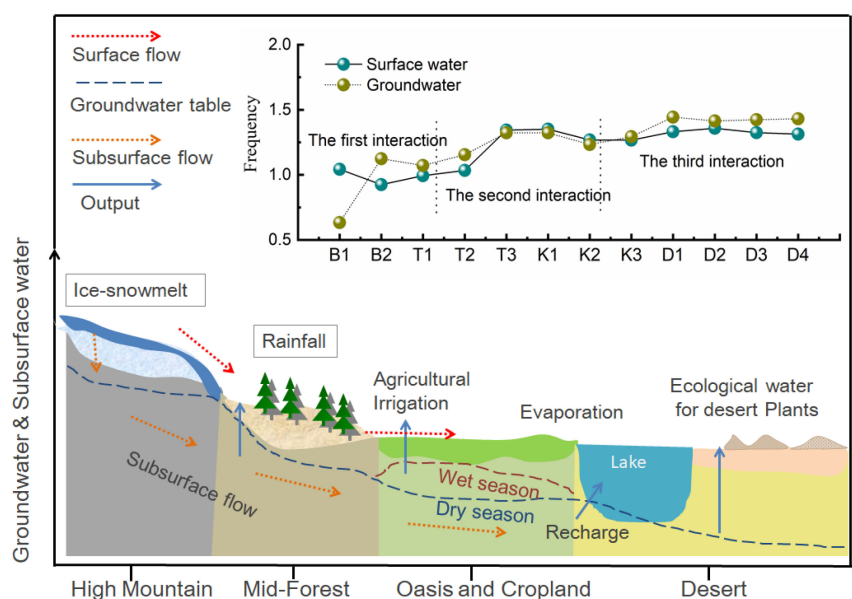


Figure 6. Sketch of hydrologic cycle in Kaidu River basin, groundwater and surface water interaction relationship based on mass balance.

In the middle reaches of the basin (mid-mountain areas), the vegetation is well preserved. As a result, soil erosion is not very pronounced, and the flow directions of groundwater and surface water are identical. On the temporal scale, there were three different transforming relationships between the surface water and groundwater that were strongly influenced by agricultural and domestic water consumption around the sampling sites. Consequently, more frequent water transformation and differentiation in proportions occurred. This is indicated by the sudden increase in isotope ratios in the midstream sampling points.

In the oasis area, groundwater migrates from the alluvial fan to the alluvial plain under the action of hydraulic gradient. In the front of the alluvial fan, a groundwater overflow zone is formed due to the finer particles of aquifer and the weaker water conductivity. Groundwater overflows the surface in the form of springs along the gully and converges into or forms a river and transforms into surface water. Springs or baseflow with low deuterium values from grasslands recharge the river water, resulting in a sharp decline in the deuterium values of river water, making them lower than the values for groundwater. For the midstream regions, groundwater recharge surface water, and along the flow direction, the deuterium value of groundwater approaches that of the river, between 62–65‰. The situation reverts to surface water recharging groundwater in several areas with human activity. In the downstream area, the mainstream of the river was still the main source of groundwater. Near lakes, the deuterium value of groundwater was around 70‰, far lower than river water (Table 2 and Figure 6). Flow of artesian groundwater to lake water was visible in the Bosten Lake area.

The Kaidu River is dependent on spring ice and snow melt and summer precipitation, and since the increasing runoff due to globe climate change, the baseflow index from the mountain mouth has indicated a complicated structure of groundwater recharge and discharge [34,35]. Figure 3a shows how the runoff of Kaidu River experienced an increasing trend over the past few decades, while Bosten Lake's water level continued to decrease an average of 1046.98 m from sea level. Over the past 50 years, despite the considerable increase in baseflow, the area's baseflow index has shown a decreasing trend [34]. A small rise of temperature in summer may lead to the melting of larger amounts of glacier, thus

increasing the amount of groundwater recharge and baseflow. The surface water in the wet season was generally a mixture of precipitation, ice and snow melt, baseflow and groundwater, with different isotopic compositions. Groundwater has a uniform isotope characteristic and exhibits moderate $\delta^{18}\text{O}$, δD , and d-excess [36].

In general, the types of rock layer affect groundwater flow in the catchments, while the discharge of groundwater can happen through faults, which provide hydraulic connections to the spring in shallow aquifers or impermeable strata across the layers [37]. The Kaidu River fault zone is a strike-slip zone, since the layer consists mainly of gravel, which lead to high hydraulic conductivity, a suitable condition for pumping groundwater [38]. When recharge water enters the aquifer, the groundwater depth is increased and then kept stable, because groundwater continues to dissipate due to the capillary effect. If there is no direct recharge, no isotopic fractionation in the remaining waterbody will occur. Since groundwater comes from infiltrated precipitation and ice melt, isotope values of the groundwater are between the values of the abovementioned two sources. Though isotope values in river water varied considerably at different locations, the origins of the enrichment are almost always the groundwater and ice melt. This indicates that there were hydraulic connections among river water, groundwater, ice melt and precipitation and that similar water sources existed for both groundwater and river water. A correspondence between precipitation and groundwater samples during the wet season was revealed. The latter was within the range of the isotopic values of the precipitation and ice and snow melt samples, which indicates that the influence of these factors on groundwater during the wet season is significant, similar to the results of precipitation-groundwater systems found by H. Tan et al. [39]. There is no evidence of an evaporative component in groundwater. Evaporation is a systematic enrichment of the isotopic content of ^{18}O and D relative to the composition of the precipitation source. This suggest that precipitation is abundant and that the evaporation is low in the wet season, so that evaporation has little influence on the isotopic composition of groundwater.

5. Conclusions

In this paper, we presented $\delta^{18}\text{O}$ and δD , d-excess, RWLs and altitude effects for river water and groundwater based on the data from our network of stable isotope sampling sites in the Kaidu River Basin. The aim of this study is to improve the understanding of the effect of baseflow on river water in dry seasons in northwestern China. The stable isotope mass balance method was used to study the conversion between groundwater and surface water and to quantify the recharge proportions between bodies of water in typical regions. The Kaidu River is composed of precipitation, ice and snow melt, baseflow and groundwater. With increased distance between upstream (the runoff producing area) and the leading edge of the glacier, the contribution of groundwater to the rivers also increased. According to the distribution characteristics of surface water, two groundwater recharge areas were identified. The first recharge area was the spring overflow from the mountainous areas to the alluvial layer of the inclined plain, where the baseflow and groundwater discharge became the main source of runoff. The second recharge area reached from the leading edge of the alluvial plains to areas with fine soil. The groundwater recharge ratio was processed via a spatial scale. It is only about 23% in high mountain areas but accounted for 46% or more in the middle and lower reaches. These data contribute to the further elaboration of detailed hydrological separation, which can be used to describe the supply relationships in similar basins in the arid areas of central Asia. Further studies should focus on the sources of aquifer recharge and the responses of groundwater to various groundwater extraction activities.

6. Patents

The following is a patent resulting from the work reported in this manuscript: ZL 2021 2 1210432.7, Name: Water Samplers. Inventor name: Yuting FAN and Tong LI.

Author Contributions: Conceptualization, Y.F.; methodology, Y.F.; software, S.Y.; validation, S.Y. and S.J.; formal analysis, Y.W. (Ye Wu); investigation, Y.W. (Yun Wang); resources, S.Y.; data curation, Y.F.; writing—original draft preparation, Y.F.; writing—review and editing, Y.W. (Ye Wu); project administration, H.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The water stable isotope data used to support the findings of this study are available from the corresponding author upon request (because hydrological data of this study are divided into classified data).

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