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Groundwater recharge in the oasis-desert areas of northern Tarim Basin, Northwest China

Weihua Wang, Yaning Chen and Wanrui Wang

ABSTRACT

Groundwater is an important source for maintaining desert ecological processes in arid areas. With the increasing intensity of climate change and human activities, the rivers in Tarim Basin are severely dried-up. Aiming at the dried-up river, vegetation degradation and oasis maintenance in the middle and lower reaches of dried-up river basin, groundwater recharge and groundwater-surface water interaction have become hotspots, but are not well known. We examined spatial distributions and controlling factors of groundwater stable isotopes and recharge at oasis scale using data from 247 samples surveyed in the four headwaters in the northern Tarim Basin. Stable isotopes of surface water and groundwater were different from each other, and varied among sampling sites. Surface water and groundwater isotopes generally became enriched towards the east throughout the study area, while surface water isotopes showed enrichment towards the upstream direction within each catchment, mainly due to cultivated area expansion. Surface water mainly originated from precipitation, groundwater, and meltwater, while shallow groundwater derived from lateral groundwater flow, river and irrigated water infiltration, and little precipitation. The mainstream water was directly recharged by the headwaters. The results could provide a new insight into groundwater cycling in oases of dried-up river basins, which is helpful for regional groundwater management.

Key words | dried-up river basin, electrical conductivity, groundwater recharge, stable isotopes, Tarim River Basin

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HIGHLIGHTS

- Groundwater recharge in the oasis-desert areas of northern Tarim Basin was examined.
- Shallow groundwater mainly originated from lateral groundwater flow and infiltrating river and irrigation water.
- Human activities greatly impact the groundwater recharge.

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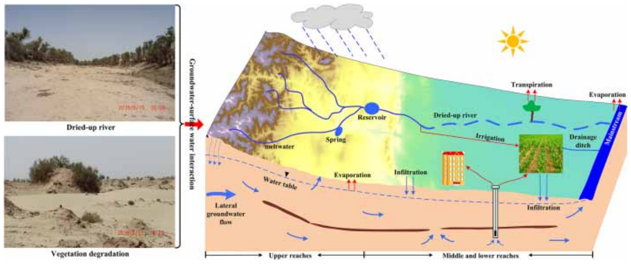
GRAPHICAL ABSTRACT



INTRODUCTION

In arid climates, oases are the habitat of human life and the centers of economic development (Gonçalvès *et al.* 2013). Groundwater resource sustainability in arid regions is crucial for residential, industrial, agricultural, and ecological uses due to limited surface water resources and little precipitation (Gleeson *et al.* 2010; Scanlon *et al.* 2012; Cao *et al.* 2013; Taylor *et al.* 2013; Lezzaik *et al.* 2018; Zou *et al.* 2019; Duan *et al.* 2020), especially in these oasis areas (Wang *et al.* 2018; Chen *et al.* 2019b). In the past decades, groundwater in arid regions has depleted across the world (Rodell *et al.* 2009; Wada *et al.* 2010; Zhang *et al.* 2014b; Shakya *et al.* 2019), and could be exacerbated by climate warming and anthropogenic activities (Jiao *et al.* 2015; Liu *et al.* 2018; Bibi *et al.* 2019; de Graaf *et al.* 2019). The Tarim River is the largest inland river in China, and the Tarim Basin is the core area for construction of the 'Silk Road Economic Belt' (Chen *et al.* 2009, 2019b). Increasing population, expanding irrigated farmland, and increasing farming activity in recent decades have resulted in overexploitation and utilization of groundwater for irrigation in oasis regions of the Tarim Basin (Chen *et al.* 2006a, 2019b; Zhang *et al.* 2014b; Guo *et al.* 2019a). Groundwater depletion in the regions is further challenging regional water and ecological security, causing severe cutoff of river channels and ecological degradation in the downstream (Chen *et al.* 2006a, 2019b, 2019c). Therefore, it is essential to improve our understanding of groundwater sources and recharge mechanisms to uniformly regulate water resources in the arid oasis region of the Tarim Basin, focusing on water resources preservation, ecosystem restoration and sustainable economic development (Pang *et al.* 2010; Steward & Allen 2016).

At the watershed scale in the Tarim Basin, groundwater is an important source of agricultural irrigation and maintaining ecological processes in arid desert oasis regions (Pang *et al.* 2010; Chen *et al.* 2019b). Previous studies on the groundwater in the Tarim River, using hydrological models, stable isotopic data, and hydrological monitoring methods, have investigated groundwater table dynamics (Chen *et al.* 2010; Zhou *et al.* 2019), groundwater recharge and circulation (Wu *et al.* 2008; Pang *et al.* 2010), groundwater salinization and hydrogeochemical evolution (Chen *et al.* 2005; Hasan *et al.* 2011), the interaction between groundwater and stream water (Chen *et al.* 2018; Xue *et al.* 2019), and its relationship with riparian vegetation (Chen *et al.* 2008, 2010; Pang *et al.* 2010). Most of the studies focused on the middle and lower reaches of the Tarim River, but few studies have been made on groundwater in the headwaters, especially in the dried-up river basin. Moreover, these previous studies have largely relied upon point-scale sampling to examine the precipitation-surface-groundwater relationship (Zhou *et al.* 2019). In fact, underlying surface characteristics (soil properties, hydrogeological conditions) and resultant hydrological processes are spatially heterogeneous, which could hardly be captured by point-scale investigation (Li *et al.* 2019b). It is also difficult to use point-based samples to interpret the groundwater–surface water relationship at the watershed scale (Li *et al.* 2019b). Furthermore, using large-scale surface water and groundwater samples to examine groundwater sources, residence time, storage, and flow pathways at the watershed scale could reflect the influence of large-scale environmental factors such as climate and hydrogeology (Sophocleous 2002;

McGuire & McDonnell 2006; Timsic & Patterson 2014; Li *et al.* 2019b). Compared with point-based water samples, information gleaned from watershed-scale studies are arguably more helpful to the efficient management and utilization of water resources (Li *et al.* 2019b). However, groundwater cycling, especially the recharge mechanisms at watershed scale, are still not well known in arid oases of the dried-up river basin in the Tarim Basin due to lack of field observations, and also may be neglected when implementing efficient water resource management strategies in the regions (Chen *et al.* 2019b).

Stable isotope tracing provides an efficient way of investigating water cycles (Bowen *et al.* 2012; Gibson *et al.* 2017). Stable water isotope compositions (^{2}H and ^{18}O) exhibit significant differences among precipitation, groundwater and surface water, behave conservatively and their concentrations are not influenced by geochemical reactions in aquifers (Craig 1961; Richards *et al.* 2018). Hence, isotopic methods have been widely used independently or in combination with geochemical and hydrometric methods to elucidate hydrological processes, including tracing water recharge, flow paths, moisture recycling, residence times and the biogeochemical cycle (Chen *et al.* 2006b; Pang *et al.* 2010; Peng *et al.* 2012; Li *et al.* 2019a). For arid regions with limited continuous field observation of hydrological processes, water stable isotope tracing is particularly useful for studying the origin and cycle of surface water and groundwater (Huang *et al.* 2013; Jasechko *et al.* 2017; Li *et al.* 2019a), which could provide direct information on the water cycle and circumvent substantial uncertainties in hydrological simulation (Gibson *et al.* 2017). Using stable isotope analysis, Li *et al.* (2019b) found that streamflow was sourced from similar groundwater reserves across four large catchments in China's Loess Plateau.

We examined the spatial distributions and controlling factors of groundwater stable isotopes and sources of groundwater in oasis areas of four headwaters in the northern Tarim Basin at the catchment scale using data from 247 water samples surveyed during the period July and November 2018. The objectives of our study were to analyze the spatial distributions of groundwater isotopes in the oases, to examine the influence of environmental factors on groundwater isotopic values, and to determine the sources of groundwater. The result would be expected to advance our understanding of the regional groundwater cycle mechanism, and provide a theoretical foundation for regional water resources management in arid desert oasis regions of the dried-up river basin in Tarim Basin.

DATA AND METHODS

Study area

The Tarim Basin is located in the northwest arid region of China, with an area of 1.02×10^6 km^2. It is flanked by the Tianshan Mountains to the north and the Kunlun Mountains to the south (Figure 1(a)), and is characterized by a typical temperate arid continental climate (Wang *et al.* 2019). Over the past few decades, this area has developed into a typical oasis agricultural area, and the cultivated land distributed in the oasis area on the edge of the desert is mainly irrigated by groundwater and surface water (Wang *et al.* 2019). The headwaters in the Tarim River Basin are mainly supplied by glacier-snow meltwater and precipitation in the Tianshan Mountains, and the wet season in the region occurs from July to September (Pang *et al.* 2010). This study focused on the oasis-desert areas of four headwaters in the northern Tarim Basin, that is, the Dina River, Weigan-Kuqa River, Akesu River, Yarkand River, and the mainstream of Tarim River (Figure 1(a)). The four headwaters cover a large area (18.69×10^4 km^2) with variable physical conditions, such as climate, topography, soil, vegetation, and hydrogeology (Table 1). The elevation in the study area ranged from 868 to 8,354 m above sea level, mean annual air temperature ranged from 1.8 to 7.5 °C, and mean annual precipitation was 119–248 mm (Figure 1 and Table 1; data from the Chinese National Meteorological Centre (2018)). Precipitation in the region has a seasonal distribution, with 70% occurring from June to October (Fang *et al.* 2018).

The study region is covered by sediments of different hydrogeologic units, including pore water in friable rocks, pore-fissure water in clastic rocks, fissure-karstic water in carbonate rocks, fissure-karstic water in carbonate-clastic rocks, fissure water in magmatic rocks, fissure water in metamorphic rocks, and glacier-snow cover (Figure 1(e)). The hydrogeological conditions in the oasis-desert areas are mainly dominated by pore water in friable rocks with

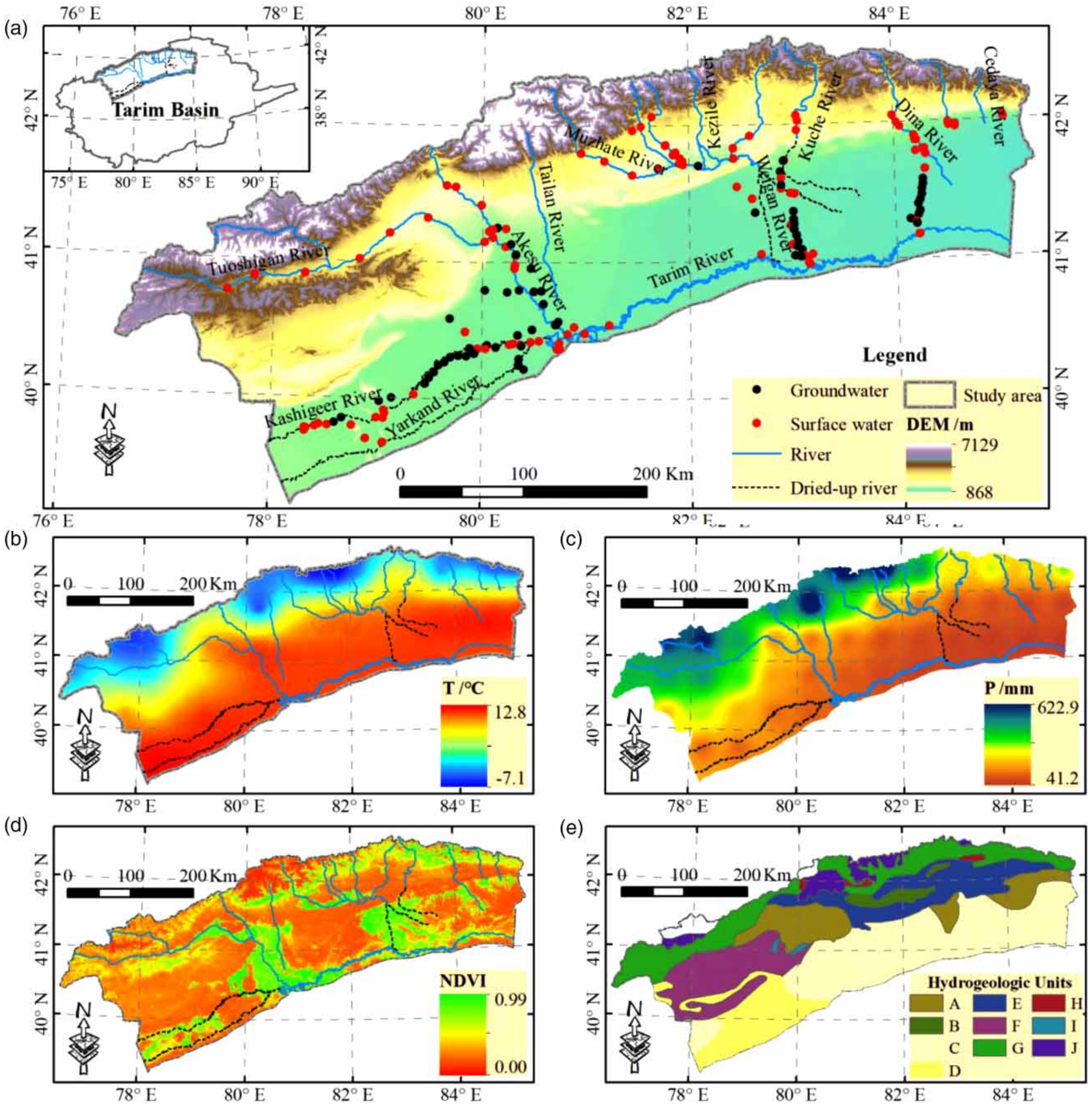


Figure 1 | The location of study region and water stable isotopic sampling sites in the northern Tarim Basin of China. (a) The location of study region and water stable isotopic sampling sites; (b) mean annual air temperature (T); (c) mean annual precipitation (P); (d) the normalized difference vegetation index (NDVI) in 2018; and (e) regional hydrogeological map: A – friable rock, pore water, strong water-abundance; B – friable rock, pore water, moderate water-abundance; C – friable rock, pore water, weak water-abundance; D – friable rock, pore water, very weak water-abundance; E – clastic rock, pore-fissure water, weak water-abundance; F – carbonate rock, fissure-karstic water, moderate water-abundance; G – carbonate-clastic rock, fissure-karstic water, moderate water-abundance; H – magmatic rock, fissure water, moderate water-abundance; I – metamorphic rock, fissure water, weak water-abundance; J – glacier, snow cover.

weak water-abundance for Dina River, Weigan-Kuqa River, and Akesu River, and are dominated by pore water in friable rocks with very weak water-abundance for Yarkand River (Figure 1(e)). In general, the water abundance of aquifer systems in the oasis regions is better than that in the desert regions (Figure 1(e)). The large spatial heterogeneity of hydrogeological conditions in the study area influences the occurrence, distribution and flow of groundwater (Pang *et al.* 2010). The natural vegetation that exists in the oasis-desert areas is mainly distributed along the river (Figure 1(d)), and mainly depends on shallow groundwater for maintenance (Chen *et al.* 2019b).

Table 1 | Basic information on the four headwaters in the northern Tarim Basin

Catchment	Area (km^2)	Elevation (m)	Runoff ($\times 10^8$ m^3)	MAP (mm)	MAT (°C)
Dina	11,393	868–4,661	3.5	141.8	7.3
Weigan-Kuqa	42,667	932–6,830	29.5	189.1	7.5
Akesu	50,646	1,013–7,129	77.2	248.4	6.4
Yarkand	82,193	1,021–8,354	54.6	118.8	1.8

MAP: mean annual precipitation during 1999–2018; MAT: mean annual air temperature during 1999–2018.

Field data

Water samples of surface water and groundwater were collected during the period between July and November 2018 from 207 sites in the oasis areas of northern Tarim Basin (Dina River, Weigan-Kuqa River, Akesu River, Yarkand River, and the mainstream of Tarim River), which falls in the growing season and the non-growing season, respectively (Zhou *et al.* 2019). The sampling sites for surface water and groundwater are shown in Figure 1(a). In total, we collected 110 groundwater samples and 137 surface water samples. Groundwater samples were collected from boreholes (long-term observation wells), springs, and pumped wells (domestic wells, irrigation wells, or industrial wells), including shallow groundwater (<20 m deep), middle groundwater (20–100 m deep), and deep groundwater (>100 m deep) (Wang *et al.* 2013). All water samples were collected manually and filtered through a 0.22 μm nylon filter, and then stored in 100-mL high-density polyethylene bottles and refrigerated at 4 °C before analysis to prevent evaporation fractionation.

Laboratory analysis

Stable water isotope compositions (^{2}H and ^{18}O) of the samples were measured using a LGR DLT-100 liquid water isotope analyzer (Los Gatos Research, Inc., USA) at the State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. The stable isotope contents were expressed in delta per million notation (δ, ‰), which was relative to the Vienna Standard Mean Ocean Water (VSMOW) (where $\delta = (R_{sample}/R_{VSMOW} - 1) \times 1000$). The measurement precision of the liquid water isotope analyzer was ±0.8‰ for δ^2H and ±0.1‰ for δ^{18}O. In addition, electrical conductivity (EC) was used as another main indicator in our analysis and evaluation of the groundwater source. EC was measured *in situ* using a conductivity meter, with measurement accuracy of 0.01 μs/cm (Chen *et al.* 2019a).

RESULTS AND DISCUSSION

Spatial distributions of groundwater stable isotopes

For the oasis areas of northern Tarim Basin (Dina River, Weigan-Kuqa River, Akesu River, Yarkand River, and the mainstream of Tarim River), surface water was generally more enriched isotopically than groundwater (Table 2). The mean isotopes of surface water were –52.0 and –8.2‰ for δ^2H and δ^{18}O, respectively, and the mean values of groundwater were –60.2 and –8.7‰ for δ^2H and δ^{18}O, respectively, which were similar to the observations by Sun (2015) for Weigan-Kuqa, Chen *et al.* (2019a) for Akesu, Wu *et al.* (2008) for Yarkand, and Pang *et al.* (2010) for the mainstream. For the oasis-desert areas of the four headwaters in northern Tarim Basin, the mean isotopes of both surface water and groundwater generally become enriched towards the east (Table 2). The largest range of stable isotopic values for surface water samples were observed in Akesu River and may be due to the longest river length (Figure 1) by increasing the evaporation period leading to more enriched isotopes (Li *et al.* 2019b). However, the largest range of stable isotopic values for groundwater samples was observed in Dina River, which may be attributed to more complex recharge mechanisms (Li *et al.* 2019b) or hydrogeological conditions (Hale & McDonnell 2016), and further research on this aspect is needed.

Furthermore, we assessed the relationship between water isotopic values and climate conditions (precipitation amount and air temperature) at the scale of the northern Tarim Basin to better understand the drivers of the spatial distribution of water isotopes. For the whole study area, the isotope values of surface water were significantly negatively correlated with mean annual precipitation amount (MAP) ($\delta^{18}O = -0.006MAP - 7.395$ ($n = 137,\ R^2 = 0.126,\ p < 0.001$)) and positively correlated with mean annual air

Table 2 | Stable isotope compositions for surface water and groundwater samples in the oasis areas of northern Tarim Basin

			δ^2H(‰)			$\delta^{18}O$(‰)		
Water type	**Location**	**n**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**
Surface water	Dina	18	−34.6	−54.7	−41.1	−5.7	−7.7	−7.1
	Weigan-Kuqa	36	−36.4	−75.1	−55.1	−4.9	−11.7	−8.9
	Akesu	50	−23.8	−76.4	−57.9	−3.5	−11.6	−9.0
	Yarkand	20	−33.5	−64.9	−46.5	−3.6	−9.9	−6.6
	Mainstream	13	−35.3	−76.6	−52.7	−5.2	−10.3	−7.9
Groundwater	Dina	16	−17.2	−68.3	−47.2	−0.9	−10.2	−6.1
	Weigan-Kuqa	21	−52.0	−83.9	−67.4	−8.3	−12.2	−10.0
	Akesu	38	−51.6	−77.1	−66.9	−7.0	−11.6	−9.9
	Yarkand	25	−53.0	−85.8	−68.7	−7.5	−12.1	−9.7
	Mainstream	10	−49.7	−77.5	−60.9	−6.9	−11.3	−8.7

temperature (MAT) ($\delta^{18}O = 0.142MAT - 9.577$ ($n = 137$, $R^2 = 0.086, p < 0.01$)), while the isotope values of groundwater were negatively related to MAP ($\delta^{18}O = -0.029MAP - 6.784$ ($n = 110$, $R^2 = 0.163, p < 0.001$)) and positively related to MAT ($\delta^{18}O = 0.390MAT - 13.657$ ($n = 110, R^2 = 0.008, p > 0.1$)). These were consistent with the temperature effect and precipitation amount effect (Craig 1961; Clark & Fritz 1997). This suggested that climate conditions may control the spatial variation of water isotopes for the catchments with similar underlying surface conditions (Li *et al.* 2019b).

The spatial distributions of surface water and groundwater isotopes varied among the sampling sites within northern Tarim Basin (Figure 2). For the groundwater isotopes within each catchment, a spatial trend in the downstream direction was not obvious, the Dina and Akesu River showed enriched isotopes toward the downstream, while the other two rivers showed depleted isotopes toward the downstream (Figure 2). However, within each catchment, except for the Akesu River, surface water isotopes showed enrichment towards the upstream direction (Figure 2). This may be because the three rivers were dried-up river basins, in which more than 90% of the upstream river water was transported for irrigation, leading to more depleted isotopes in channel water by reducing the evaporation period and increasing groundwater withdrawal (Wu *et al.* 2008). However, the Akesu River was not a dried-up river basin, the much longer river length may lead to longer evaporation, and thus in turn lead to more enriched isotopes in the downstream river water (Li *et al.* 2019b). Furthermore, we assessed the relationship between water isotopic values and sampling site location (longitude and latitude) within each catchment in the study area. As shown in Figure 2, the stable isotopic values of surface water were negatively correlated to latitude and positively correlated with longitude in three catchments. Groundwater isotopic values were positively correlated to latitude and negatively correlated with longitude in three catchments. Furthermore, as shown in Figure 1, most headwaters flow southwards, except for Yarkand River flowing eastwards, air temperature increases and precipitation decreases in the downstream direction, while elevation and latitude both decrease in that direction. In summary, the relationships between surface water isotopic values and their locations were the result of the spatially variable climate (Li *et al.* 2019b) and human activities (Guo *et al.* 2019a).

In addition, this study evaluated the relationships between water isotopic values and vegetation coverage within the oasis areas of northern Tarim Basin. As we all know, the vegetation in an arid oasis area mainly depends on the irrigation of stream water and extracted groundwater (Wang *et al.* 2013). That is, in general, the greater the irrigation water amount from human activities, the greater the vegetation coverage in an arid oasis, indicating that vegetation coverage could indirectly reflect human activity to some extent (Li *et al.* 2018). For the four headwaters in the northern Tarim Basin (Figure 1), stream water isotopic values were positively correlated with the normalized difference vegetation index (NDVI, the grid NDVI values of the sampling

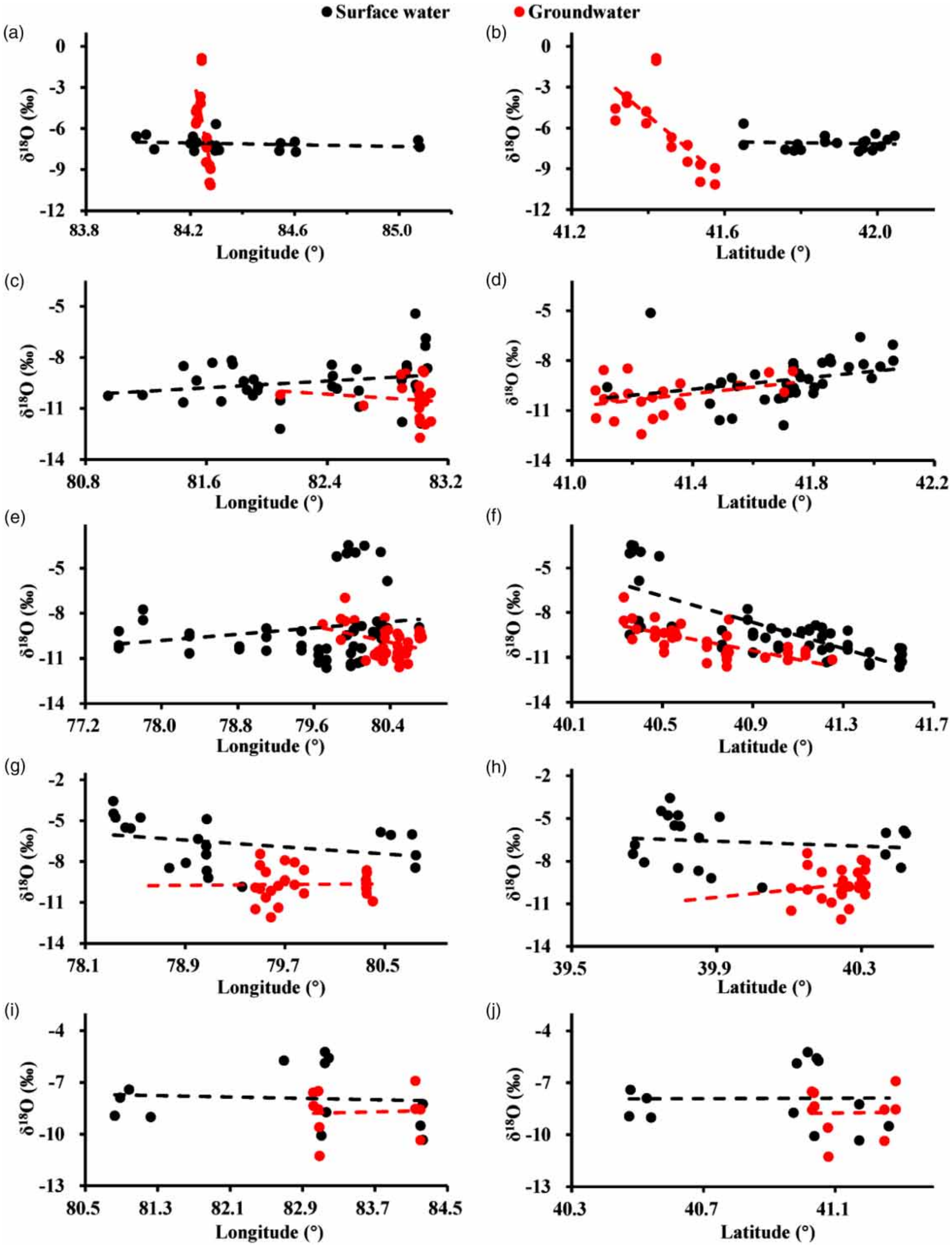


Figure 2 | Spatial distributions of oxygen stable isotope for surface water and groundwater samples in the oasis areas of northern Tarim Basin: (a) and (b) for Dina, (c) and (d) for Weigan-Kuqa, (e) and (f) for Akesu, (g) and (h) for Yarkand, (i) and (j) for Mainstream.

sites) ($\delta^{18}O = 2.662NDVI - 9.277$ ($n = 137$, $R^2 = 0.072$, $p < 0.01$)), while groundwater isotopic values were significantly negatively related to NDVI ($\delta^{18}O = -3.210NDVI - 8.121$ ($n = 110$, $R^2 = 0.144$, $p < 0.001$)). This indicates that for regions with similar climatic and geological conditions, human activity accounts for water isotopic variations (Guo *et al.* 2019a). In summary, climate and human activities jointly control the spatial distribution of surface water and groundwater isotopes in the arid oasis areas (Guo *et al.* 2019b; Li *et al.* 2019b).

Sources of groundwater

Figure 3 illustrates the stable isotopes of surface water and groundwater samples in the oasis-desert areas of northern Tarim Basin. Water samples (surface water and groundwater) in the study area had a wide range of δ^{18}O and δ^2H, and different water components showed different isotopes (Table 2 and Figure 3). Surface water and groundwater isotopes for the whole study area ranged from –85.8 to –17.2‰ for δ^2H and from –12.2 to –0.9‰ for δ^{18}O in the whole sampling period, laying on both sides of the global meteoric water line (GMWL) (Figure 3). Furthermore, the local meteoric water line (LMWL) for the Xiehela Hydrological Station ($\delta^2H = 7.74\delta^{18}O + 5.37$) and Shaliguilank Hydrological Station ($\delta^2H = 7.64\delta^{18}O + 4.93$) in the Akesu River from Sun (2015) were used to explore the interaction relationships between precipitation and surface water and groundwater in northern Tarim Basin (Figure 3). The slopes and intercepts of the two LMWLs were both smaller than that of GMWL, probably due to the effects of moisture recycling and subcloud evaporation on the precipitation formation in the region (Pang *et al.* 2011). The surface water and groundwater samples were located on both sides of the LMWL (Figure 3), indicating that surface water and shallow groundwater were affected by strong evaporation in such an arid environment (Guo *et al.* 2019a; Li *et al.* 2019b), and surface water mainly originated from precipitation, groundwater, and meltwater in the wet season in this region, while groundwater was the most important contributor to river runoff in the oasis region (Chen *et al.* 2018). In addition, as shown in Figure 3, the surface water evaporation line had greater slope and intercept ($\delta^2H = 5.93\delta^{18}O - 3.64$ ($R^2 = 0.90,\ n = 137$)) than that for the groundwater evaporation line ($\delta^2H = 5.57\delta^{18}O - 12.59$ ($R^2 = 0.89,\ n = 110$)), but the differences were small. In general, the d-excess values of groundwater were smaller than those of surface water in our study area, and the stable isotopic values of surface water were slightly larger than those of groundwater, but the differences were not significant (Figure 3). The smaller d-excess and lower slope of groundwater suggested that groundwater undergoes stronger evaporation than surface water, which is evidence that surface water recharged shallow groundwater in the oasis region (Li *et al.* 2019b). At the same time, the nonsignificant differences in isotopic values, slope, and d-excess among the water components implied frequent exchange and interactions between surface water and shallow groundwater in the desert oasis areas of northern Tarim Basin (Chen *et al.* 2019c; Wang *et al.* 2019).

Figure 4 shows the relationship between δ^{18}O and δ^2H for groundwater and surface water in the four headwaters of northern Tarim Basin. The stable isotopic data for surface water within each catchment exhibited a great range (Figure 4(a) and Table 2), the Akesu River water samples tended to be lower than the other catchments in δ^{18}O (–9.0‰) and δ^2H (–57.9‰), while the Yarkand River

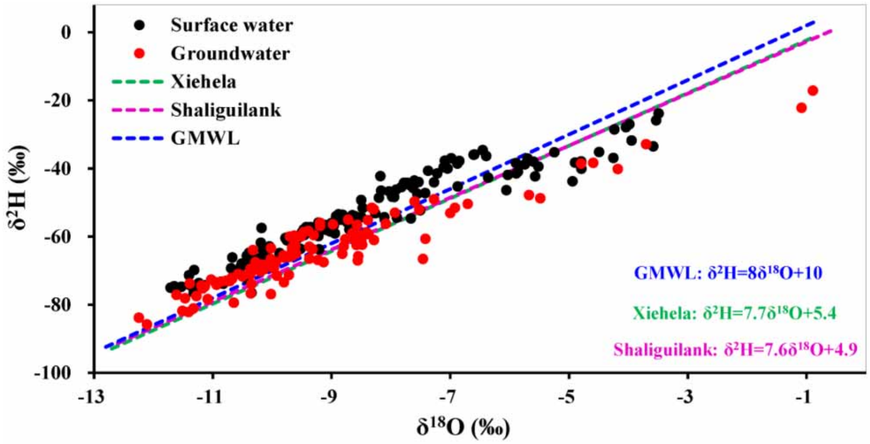


Figure 3 | Stable isotopic compositions (δ^{18}O and δ^2H) of surface water and groundwater from the oasis-desert areas of northern Tarim Basin, northwest China. GMWL, global meteoric water line. Xiehela and Shaliguilank, local meteoric water line for the Xiehela Hydrological Station and Shaliguilank Hydrological Station in the Aksu River basin, respectively (data from Sun (2015)).

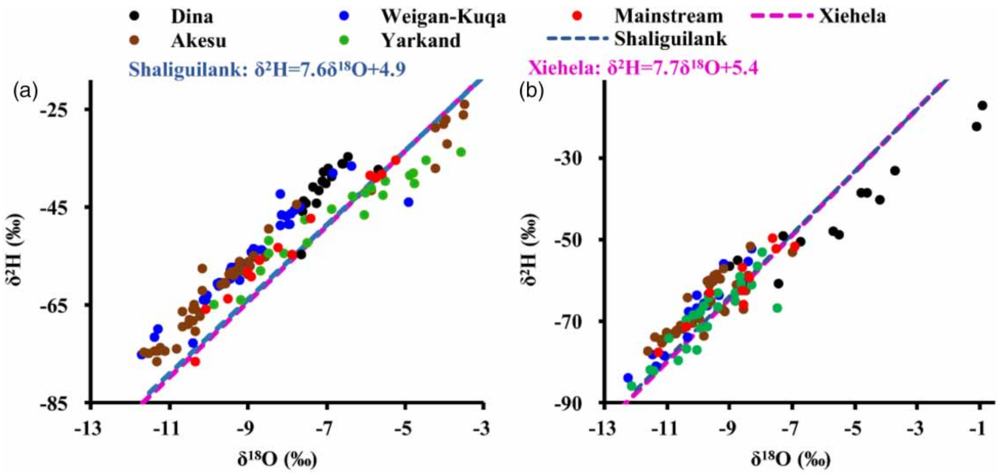


Figure 4 | Stable isotopic compositions (δ^{18}O and δ^{2}H) of sampled surface water and groundwater from the oasis-desert areas of northern Tarim Basin: (a) surface water, (b) groundwater. The purple and blue dotted lines represent the local meteoric water line (LMWL) for the Xiehela Hydrological Station and Shaliguilank Hydrological Station in the Aksu River basin, respectively (data from Sun (2015)).

samples tended to be higher than the other catchments in δ^{18}O (–6.6‰) and δ^{2}H (–46.5‰) due to strong evaporative enrichment of the surface water samples mainly collected from the middle and lower reaches (Wu *et al.* 2008). Similarly, the stable isotopic values of groundwater differed among the four catchments in our study area, the Dina River water samples tended to be heavier than the other catchments in isotopic values, while the Akesu River samples exhibited the smallest isotope range (Figure 4(b) and Table 2). This may be because Akesu River was not a dried-up river basin, while the other rivers were dried-up in recent decades (Chen & Xu 2004). For the oasis area of dried-up river basin in arid regions, agricultural irrigation water mainly comes from canal water and overexploited groundwater during the growing season (Wang *et al.* 2019), while groundwater was mainly recharged by river infiltration and irrigated water infiltration (Wang *et al.* 2013; Guo *et al.* 2019a). This implied that groundwater interacted with surface water frequently during the growing season in the oasis area of dried-up river basin, resulting in a larger range of groundwater isotopic values than that in the Akesu River (Sun 2015; Guo *et al.* 2019a). Additionally, the evaporation lines (EL) of groundwater in the oasis areas of the four headwaters were not parallel to the LMWL (Figure 4(b)), indicating that the shallow groundwater did not only originate from precipitation of the year (Evaristo *et al.* 2015), but was also recharged from lateral groundwater flow (Guo *et al.* 2019a). In addition, the relationships between shallow groundwater isotopes and environmental factors, discussed in the previous sections, further supported the contributions from local precipitation, irrigated water infiltration, and lateral groundwater flow (Guo *et al.* 2019b; Li *et al.* 2019a). Consequently, shallow groundwater in the oasis region of northern Tarim Basin may be derived from lateral groundwater flow and little precipitation in the dry season, while it was from river infiltration, irrigated water infiltration, lateral groundwater flow, and little precipitation in the wet season (Chen *et al.* 2018; Wang *et al.* 2019). In summary, compared to the not dried-up river basin, the stable isotopes of surface water and groundwater exhibited a larger range in the oasis areas of dried-up river basin in northern Tarim Basin, possibly due to climate conditions and human activities (Guo *et al.* 2019b; Li *et al.* 2019b).

The differences of stable isotopic values between surface water and groundwater samples within each catchment in our study area were significant (Figure 5). For the Dina River, the stable isotopic values of surface water samples were concentrated in a small range (Figure 5), indicating that the sources of surface water samples were generally identical during the study period (Guo *et al.* 2019a). δ^{18}O and δ^{2}H values of groundwater in the Dina River oasis exhibited a relatively large range, and mean values of shallow groundwater were close to that in surface water, indicating a strong interaction between surface water and

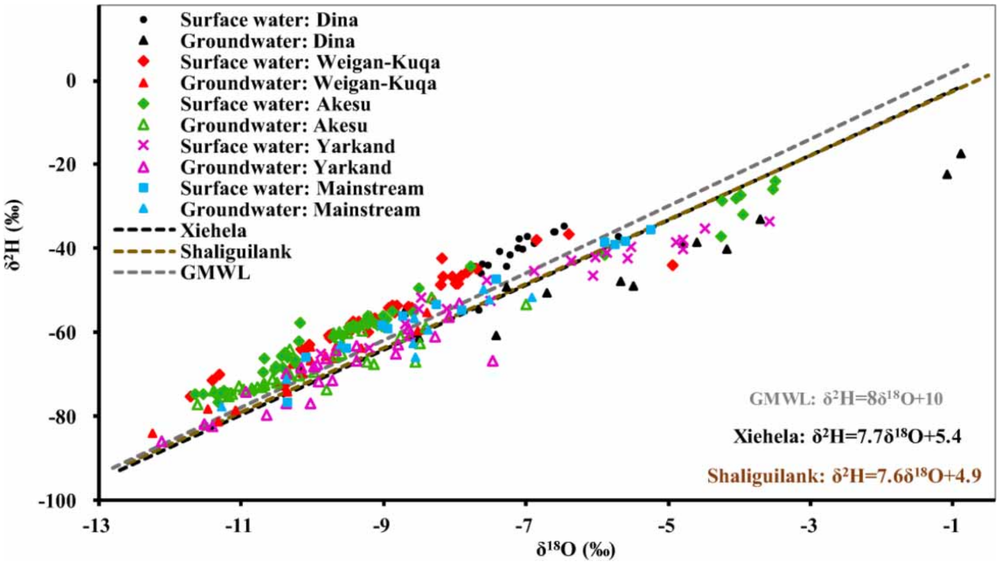


Figure 5 | Stable isotopic compositions (δ^{18}O and δ^2H) of surface water and groundwater from the oasis-desert areas of northern Tarim Basin (the stable isotope composition of surface water and groundwater were separated by catchment).

groundwater in this region (Sun 2015). For the other three headwaters (Weigan-Kuqa, Akesu, and Yarkand), compared to shallow groundwater, δ^{18}O and δ^2H of surface water samples exhibited larger values and larger ranges (Figure 5), indicating that surface water may experience strong evaporation due to long flow paths and was supplied by multiple water sources (precipitation, meltwater, and lateral groundwater) (Li *et al.* 2019b), also suggesting shallow groundwater in the arid oasis areas was supplied by deep groundwater due to irrigated water infiltration from agricultural pumping deep groundwater for irrigation (Chen *et al.* 2019c). In addition, δ^{18}O and δ^2H values for the mainstream water samples (both surface water and groundwater) lay between that of the four headwaters (Figure 5), suggesting that the mainstream water was directly recharged by water from the four headwaters (Sun 2015), and δ^{18}O and δ^2H values of surface water and shallow groundwater in the mainstream exhibited a large range, suggesting strong evaporation processes and frequent interaction between surface water and groundwater in the region (Sun 2015). Additionally, the air temperature in our study area was almost below 0 °C in the dry season (Figure 1), indicating that little meltwater and precipitation recharged the streamflow, this in turn confirmed that the small amount of runoff in the dry season primarily originated from lateral groundwater (Chen *et al.* 2018). Furthermore, the stable isotopic values of surface water showed slight seasonal variations in the sampling period, with more positive values in the wet season and more negative values in the dry season, and this may be attributed to evaporative enrichment in the wet season and groundwater discharge in the dry season (Chen *et al.* 2018). Similarly, the stable isotopes of shallow groundwater also exhibited significant seasonal difference in the sampling period within the four headwaters, with more depleted isotopes in the dry season and more enriched isotopes in the wet season, mainly because shallow groundwater was recharged by evaporated surface water infiltration in the desert oasis region in the wet season (Sun 2015). However, this study did not address this aspect, and further studies on this topic are needed.

Electrical conductivity (EC) of the surface water and groundwater samples are presented in Figure 6, and vary significantly among water compositions (surface water and groundwater) within each catchment in the oasis areas of northern Tarim Basin. EC values of the sampled waters from the oasis areas were characterized by a high degree of variability, ranging from 0.35 to 50.00 ms/cm, indicating significant variations in surface water and groundwater quality in the oasis regions, ranging from fresh to saline (Wang *et al.* 2013). The EC values for shallow groundwater were

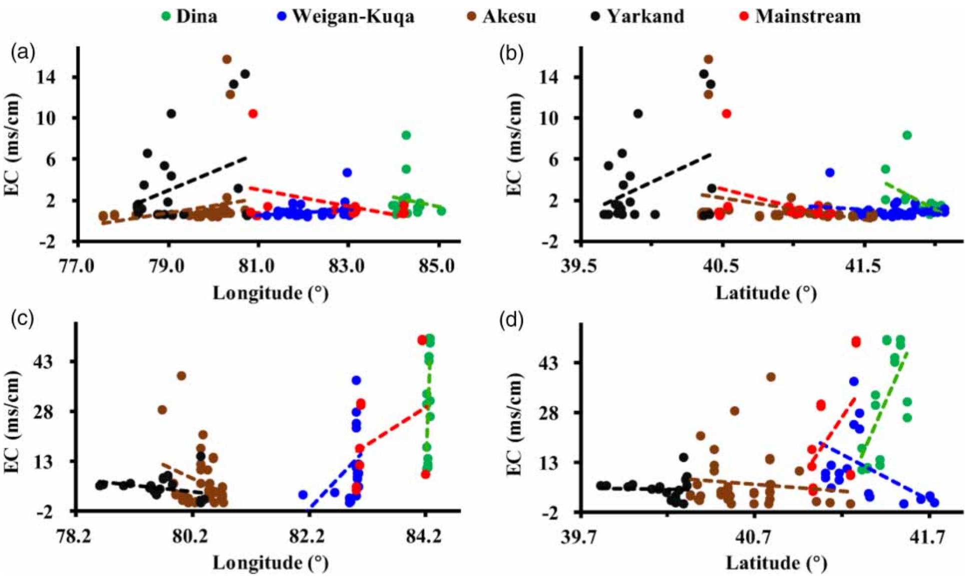


Figure 6 | Spatial distributions of electrical conductivity (EC) for surface water and groundwater samples in the oasis areas of northern Tarim Basin: (a) and (b) for surface water, (c) and (d) for groundwater.

much higher (0.57–50.00 ms/cm) than that for surface water (0.35–15.66 ms/cm), mainly due to the significant evaporative concentration within the oasis areas in our study region (Wang *et al.* 2013). EC values of deep groundwater in the oasis areas were generally smaller than those of shallow groundwater due to the different recharge sources of different aquifers (Guo *et al.* 2019b), probably because the shallow groundwater was primarily supplied by river water and irrigated water infiltration, while precipitation and lateral groundwater flow were the primary sources of deep groundwater (Wang *et al.* 2013; Guo *et al.* 2019b). Furthermore, the mainstream water EC was also high and lay between that of the four headwaters (Figure 6), indicating that the mainstream water was directly recharged by water from the four headwaters (river water, lateral groundwater, and salt water from drainage system) (Sun 2015), which was consistent with the above conclusions derived from the water stable isotopic data. Generally, the EC values for surface water and groundwater within each catchment, except for the Dina River, increased along the flow pathways (Figure 6), suggesting the occurrence of evaporation in such an arid environment (Chen *et al.* 2006b; Wang *et al.* 2013). For the Dina River, the EC values in the upper reaches were higher than those in the lower reaches (Figure 6), probably because groundwater in the upper reaches was recharged by river infiltration dissolving a large amount of soluble salts (leaching), while shallow groundwater in the lower reaches was primarily supplied by irrigated water and river infiltration (dilution and evaporation) (Chen *et al.* 2006b).

Implications for groundwater resources management

The above analyses showed that in the wet season, surface water was mainly recharged from precipitation, meltwater, and groundwater, while shallow groundwater was mainly recharged from river infiltration, irrigated water infiltration, and lateral groundwater flow in the desert oasis areas. In the dry season, stream runoff primarily originated from lateral groundwater flow, while shallow groundwater in the desert oasis region was also primarily recharged from lateral groundwater flow and little local precipitation. Furthermore, shallow groundwater in the oasis areas was primarily supplied by river water and irrigated water infiltration, while precipitation and lateral groundwater flow were the primary sources of deep groundwater (Wang *et al.* 2013; Guo *et al.* 2019b). The mainstream water was directly recharged by water from the four headwaters, mainly including river water, lateral groundwater, and salt water from the drainage system (Sun 2015). At the same time, surface water and shallow groundwater undergo strong evaporation processes during water cycling in such arid climate conditions (Chen *et al.* 2019c), and both climate change and human activities significantly affected surface water and groundwater cycling in the arid oasis areas of northern Tarim Basin (Chen *et al.* 2019c; Guo *et al.* 2019a; Li *et al.* 2019b). Figure 7 summarizes the frequent interaction between surface water and groundwater in the typical dried-up river basin of northern Tarim Basin. Additionally, the contributions of different sources (precipitation, river infiltration, lateral groundwater flow, and irrigated water infiltration) in each catchment to groundwater may not be equal (Chen *et al.* 2006b; Guo *et al.* 2019b). Further study is needed to quantify the contributions of each source to groundwater and identify the influence of climate and human activities on groundwater isotopes in the oasis area.

As mentioned above, river infiltration, irrigated water infiltration, and lateral groundwater flow were the main sources of shallow groundwater in the desert oasis areas, which have important implications for regional groundwater resource management. The amount of infiltration from river and irrigated water to shallow groundwater has gradually decreased in the past decades, mainly due to the increased canal water use coefficient and popularized water-saving irrigation technology in the arid oasis region (Han & Feng 2016). Meanwhile, overexploitation and utilization of deep groundwater for irrigation in the oasis region could lead to the decrease of semi-confined or confined groundwater levels (a slow decline), thus causing a gradual decrease in the recharge of lateral groundwater flow to shallow groundwater (Guo *et al.* 2019b). This in turn resulted in a downward trend in shallow groundwater levels in this region in recent decades (Chen *et al.* 2019b). Therefore, close attention should be paid to river runoff inputs, exploitable quantity of groundwater, and regional water balance when comprehensively dispatching surface water and groundwater resources within the river basins (Chen *et al.* 2019b). The desert oases of the four headwaters in northern Tarim Basin were typical oases, in which natural water cycling was greatly influenced by climate change and human activities (Chen *et al.* 2019b). In recent decades, with a significant increasing population, expanding irrigated

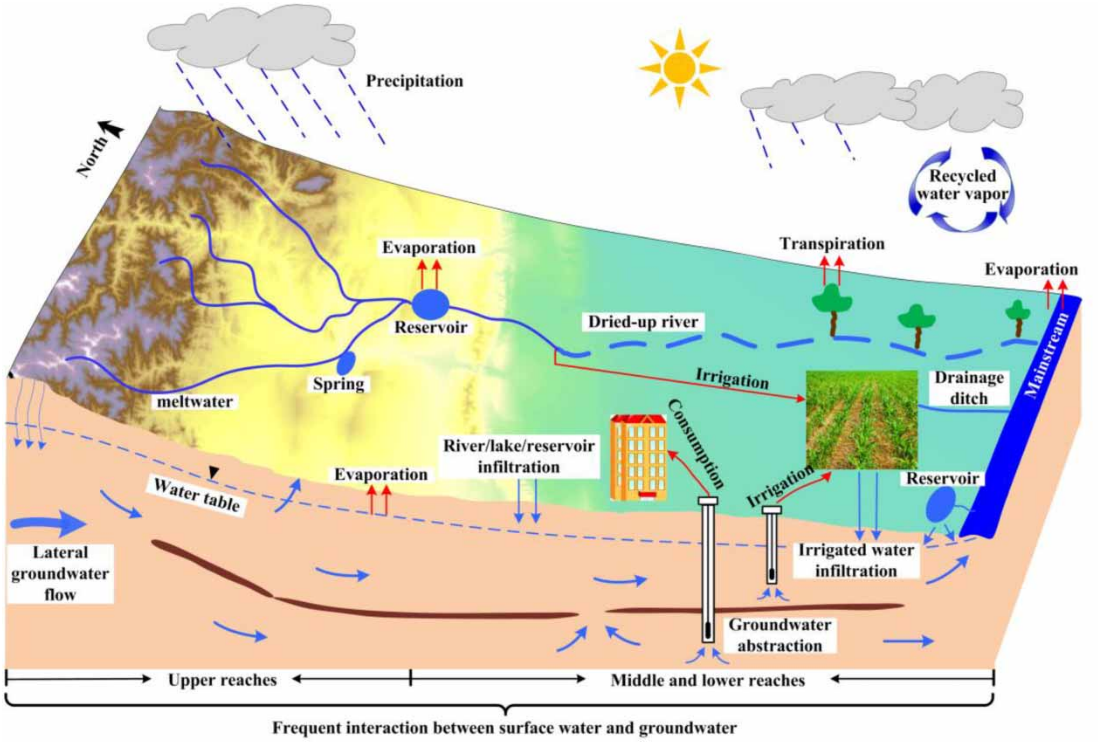


Figure 7 | Conceptual diagram of groundwater-surface water interaction in the dried-up river basin of northern Tarim Basin.

farmland, and increasing framing activity, the increasing agricultural water demands in the region exceeded the amount of surface water available, leading to the exploitation of more groundwater to supply the increasing agricultural demands, thus in turn resulting in over-pumping of groundwater and the depletion of groundwater recharge (Zhang *et al.* 2014a; Chen *et al.* 2019b; Guo *et al.* 2019a). This in turn resulted in a significant drop of groundwater levels, the cutoff of river channels, and the degradation of fragile desert ecosystems in the desert oasis areas of northern Tarim Basin, mainly due to the excessively high proportion of agricultural water use (Chen & Xu 2004; Chen *et al.* 2019b). Therefore, it is urgent to pay more attention to groundwater trends and recharge in the region to better uniformly regulate groundwater extraction and river water utilization across the whole basin, which would benefit the sustainable utilization of water resources, restoration of groundwater and ecological environment, and maintenance of ecological security and sustainable development in the desert oases in the future (Chen *et al.* 2019c; Wang *et al.* 2019).

CONCLUSIONS

Based on basin-scale surface water and groundwater samples, this study examined the spatial distributions and influence factors of groundwater stable isotopes and the sources of groundwater in the desert oases of four headwaters in the northern Tarim Basin. Our results demonstrated that the stable isotope values (δ^{18}O and δ^{2}H) of surface water and groundwater were different from each other, and varied among the sampling sites within northern Tarim Basin. Furthermore, surface water and groundwater isotopes generally became enriched towards the east throughout the study area, while surface water isotopes showed enrichment towards the upstream direction within each catchment, due to climatic conditions and human activities. Moreover, surface water in the four headwaters mainly originated from precipitation, groundwater, and meltwater, while shallow groundwater in the desert oasis areas may be derived from lateral groundwater flow, river and irrigated water infiltration, and little precipitation, implying a frequent interaction between surface water and groundwater in the oasis region. The mainstream water was directly recharged by water from the four headwaters, mainly including river water, lateral groundwater, and salt water from drainage systems. These results provide additional information on groundwater cycling in the desert oasis regions, and thus should be helpful for regional water resources management. Further research is needed to quantify the sources of groundwater and advance a deeper understanding of groundwater recharge mechanisms in the oasis areas of dried-up river basin in the Tarim Basin.

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DATA AVAILABILITY STATEMENT

The stable isotope data of water that support the findings of the current study are available from the corresponding author upon reasonable request.

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