Hydrology Research

Hydrology Research Vol 53 No 4, 532 doi: 10.2166/nh.2022.049

# Groundwater dynamic influenced by intense anthropogenic activities in a dried-up river oasis of Central Asia

Wanrui Wang[a,b], Yaning Chen[a,*], Yapeng Chen[a], Weihua Wang[a], Tianju Zhang[a,b] and Jingxiu Qin[a,b]

[a] State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China
[b] University of Chinese Academy of Sciences, Beijing 100000, China
*Corresponding author. E-mail: chenyn@ms.xjb.ac.cn

## ABSTRACT

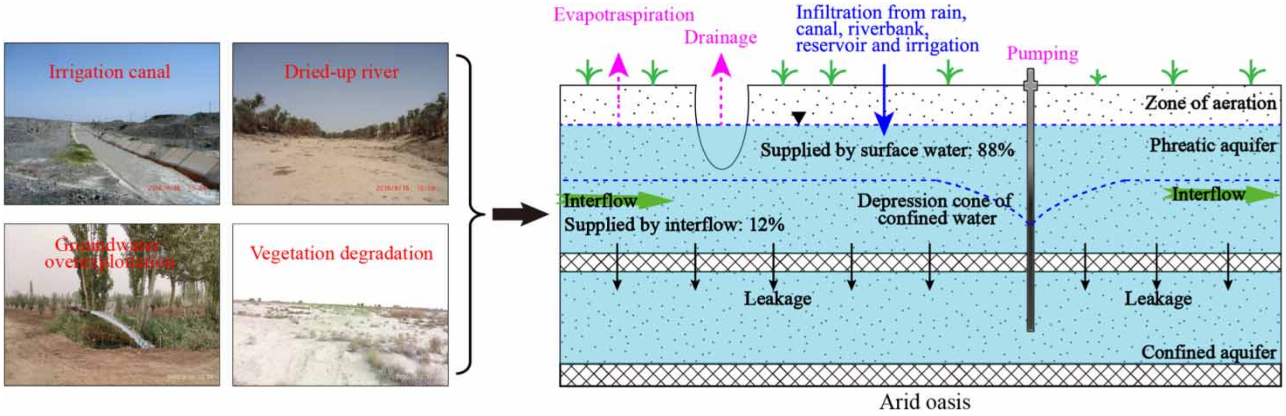
Intense anthropogenic activities in arid areas have great impacts on groundwater process by causing river dried-up and phreatic decline. Groundwater recharge and discharge have become hot spot in the dried-up river oases of arid regions, but are not well known, challenging water and ecological security. This study applied a stable isotope and end-member mixing analysis method to quantify shallow groundwater sources and interpret groundwater processes using data from 186 water samples in the Wei-Ku Oasis of central Asia. Results showed that shallow groundwater (well depth $< 20$ m) was mainly supplied by surface water and lateral groundwater flow from upstream, accounting for 88 and 12%, respectively, implying surface water was the dominant source. Stable isotopes and TDS showed obviously spatiotemporal dynamic. Shallow groundwater TDS increased from northwest to southeast, while the spatial variation trend of groundwater $\delta^{18}O$ was not obvious. Surface water and groundwater in non-flood season had higher values of stable isotopes and TDS than those in flood season. Anthropogenic activities greatly affect groundwater dynamics, where land-cover change and groundwater overexploitation are the main driving factors. The findings would be useful for further understanding groundwater sources and cycling, and help restore groundwater level and desert ecosystem in the arid region.

**Key words:** agriculture activities, dried-up river oasis, groundwater, land-cover change, recharge, stable isotope

## HIGHLIGHTS

- The sources of shallow groundwater in the dried-up river oasis of central Asia were quantified.
- Surface water was the dominant source of shallow groundwater.
- Anthropogenic activities greatly affect groundwater dynamic and cycle.

## GRAPHICAL ABSTRACT



---

## INTRODUCTION

Understanding the role of anthropogenic activities in the groundwater hydrological processes in arid region is becoming increasingly important, because intense anthropogenic activities and climate change could noticeably alter the water balance and quality of aquifer system (Han *et al.* 2017; Wang *et al.* 2021). In the past decades, groundwater storage in arid areas has decreased worldwide primarily due to a growing influence of anthropogenic activities (de Graaf *et al.* 2019; Shakya *et al.* 2019). Groundwater salinization and phreatic decline could affect hydrological processes, biogeochemical cycles, and vegetation growth (Tweed *et al.* 2011; Fuchs *et al.* 2019; Jia *et al.* 2020). Land-cover type change could affect the regional surface water and groundwater redistribution and hydrologic processes, thus influencing groundwater dynamics in arid areas (Shukla *et al.* 2018; Li *et al.* 2019a). Groundwater exploitation plays a crucial role on the dynamics and water balance of aquifer system in arid inland areas (Asoka *et al.* 2017; Hu *et al.* 2019; Mancuso *et al.* 2020). Groundwater resource sustainability is vital to the socio-economic development and ecological maintenance in arid areas due to arid climate and limited surface water resources (Gleeson *et al.* 2010; Taylor *et al.* 2013; Lezzaik *et al.* 2018), especially in arid inland oasis (Guo *et al.* 2019b; Wang *et al.* 2020). The Tarim Basin is located in the arid inland region of central Asia and the largest inland river basin in China, and is the core area of constructing the 'Silk Road Economic Belt' (Chen *et al.* 2019). In the last 30 years, groundwater overextraction has been causing river dried-up, phreatic decline, and ecological degradation in the oasis-desert areas of the Tarim Basin due to increasing population and farmland expansion (Zhang *et al.* 2014; Guo *et al.* 2019b), challenging the local water and ecological security (Chen *et al.* 2019). Consequently, it is essential to understand groundwater sources and cycle to sustainably manage water resources in the arid inland oasis of the Tarim Basin (Steward & Allen 2016; Wang *et al.* 2021).

In recent years, groundwater dynamic and its response to climate change and human activities have become hot spots in arid inland areas (de Graaf *et al.* 2019). Previous studies on the groundwater dynamics in arid inland regions, using hydrological monitoring, stable isotopic and hydrochemical data, hydrological models, and remote sensing inversion, have evaluated groundwater level and storage dynamics (Wang *et al.* 2019), groundwater salinity and hydrochemical evolution (Hasan *et al.* 2011; Liu *et al.* 2018b), groundwater recharge and circulation (Wang *et al.* 2013; Cartwright *et al.* 2019), the interaction between surface water and groundwater (Xue *et al.* 2019), and its relationship with driving factors (Liu *et al.* 2018a; Wang *et al.* 2021). Wang *et al.* (2020) reported that shallow groundwater in the oases of northern Tarim Basin may be recharged by river and irrigated water infiltration, lateral groundwater flow, and little precipitation. Wang *et al.* (2021) found that human activity was the major driving factor of groundwater level decreasing in arid oasis. However, groundwater sources and cycling mechanisms were not well understood in the oases of Tarim Basin, especially quantitative evaluation due to scarce data and intense human activities (Wang *et al.* 2020, 2021), which affects the implementation of sustainable water resource management in this arid inland region (Chen *et al.* 2019).

Stable isotopic and geochemical indicators are effective tools for investigating the groundwater cycle process and hydrochemical evolution under the influence of climate change and human activities in arid regions (Duan *et al.* 2013, 2016; Gibson *et al.* 2017; Guo *et al.* 2019b). Stable natural tracers behave conservatively and their concentrations are not affected by hydrogeochemical reactions within aquifer systems (Richards *et al.* 2018). Hence, environmental tracer methods and the end-member mixing analysis method (EMMA) have been widely used to quantitatively determine groundwater recharge sources and rates (Scanlon *et al.* 2006; Yin *et al.* 2011; Guo *et al.* 2019a), flow paths (Huang & Pang 2010), residence times (Peng *et al.* 2012), and biogeochemical cycle in arid regions (Pang *et al.* 2010; Wang *et al.* 2020; Gong *et al.* 2021). Li *et al.* (2019b) investigated the water cycle in inland regions from stable isotope tracing. Therefore, for arid inland areas with limited hydrological observation, stable isotopic and geochemical indicators are particularly useful for analyzing groundwater sources and cycle (Li *et al.* 2019b).

In this study, we attempted to combine stable isotopic indicators and EMMA to determine shallow groundwater sources and interpret groundwater processes using data from 186 water samples in the Wei-Ku Oasis, a typical dried-up river oasis of Tarim Basin in central Asia. The main objectives of our study were (1) to examine the spatiotemporal characteristics of stable isotopes and salinity in surface water and groundwater, (2) to quantify the sources of shallow groundwater, and (3) to explore groundwater recharge and discharge under the influence of anthropogenic activities (i.e. land-cover change, groundwater extraction, agricultural irrigation, and drainage activities). The results were expected to help further understand groundwater sources and cycling under intense anthropogenic activities, and improve sustainable water management in the dried-up river oasis of arid inland areas.

## STUDY AREA

Our study region is the Wei-Ku Oasis (82.09–83.47 °E, 40.90–41.85 °N), and located in the middle and lower reaches of the Weigan-Kuqa River basin, with an area of 7,104 $km^2$ (Figure 1). The Weigan-Kuqa River basin is composed of the Weigan River and the Kuqa River, and the annual streamflow is $26.6 \times 10^8$ $m^3$ and $4.6 \times 10^8$ $m^3$ (Wang *et al.* 2021), respectively, with the flood season from June to September (Figure 1). The oasis is located in the southern Tianshan Mountains and the northern Tarim Basin, which is sensitive to ecological environment changes. It was a typical and complete piedmont alluvial fan plain, whose elevation ranges from 945 to 1,147 m, and declines from north to south within the oasis. The climate of our study region is a typical temperate arid continental climate (Wang *et al.* 2021). The annual average air temperature is 11.4 °C, and the annual frost-free period is 209–226 days. The annual average precipitation is 74.6 mm, with about 76% of the total precipitation mainly occurring between May and September (Figure 1) (obtained from the Chinese National Meteorological Information Centre). The annual runoff into the Wei-Ku Oasis is about $31.2 \times 10^8$ $m^3$, and more than 90% of the total runoff is directly diverted into cultivated land for agricultural irrigation (Wang *et al.* 2021). This caused the main stream to dry up within the oasis in recent decades, and only a small amount of flood was discharged in flood season (Chen *et al.* 2019). Depth to phreatic water level ranged from 2 to 6 m across the whole oasis during 2000–2018, and phreatic water level showed a decreasing trend from northwestern (higher altitude) to southeastern (lower altitude), implying that shallow groundwater in the oasis flows from north to south, and finally into the mainstream of Tarim River (Wang *et al.* 2021).

The dominated natural plants in the Wei-Ku Oasis are *Sophora alopecuroides*, *Tamarix* spp., *Populus euphratica*, *Karelinia caspica*, *Phragmites communis*, *Halostachys caspica*, *Glycyrrhiza*, and *Alhagi pseudalhagi* (Zhao 2006). The main types of land use include cropland, grassland, and bare areas. This oasis is covered by the Quaternary sediments of different hydrogeologic units, including pebbly sandstone, fine siltstone, fine sandstone, silty fine sandstone, sandy gravel, and sandstone. The northern margin and northeastern part of the oasis are proluvial sediments, covered by pebbly sandstone and sandstone (Wang *et al.* 2021). The southeastern part of the oasis is alluvial sediment, covered by fine sandstone (40–60 m of thickness). The central part is alluvial–proluvial sediment, the sediments are from pebbly sandstone to fine siltstone. Furthermore, the main soil types include oasis soil, inland saline soil, brown desert soil, meadow soil, and aeolian sandy soil.

## MATERIALS AND METHODS

### Data collection

During the period from August 2018 to August 2019, water samples were obtained along the Weigan River and the Kuqa River, as well as within the Wei-Ku Oasis in the flood season (August) and non-flood season (April and November), including surface water samples and groundwater samples (Figure 1(c)). Surface water samples in upstream (SWU) were collected from the tributaries of Weigan River and Kuqa River (river water). Surface water samples in oasis (SWO) were obtained from the Wei-Ku Oasis, and included river water, reservoir water, and channel water, where the channel water for agricultural irrigation would be from stream water and groundwater pumping from confined aquifer. Groundwater samples were taken from regularly used boreholes (long-term observation wells) and pumped wells (industrial wells, irrigation wells, and domestic wells) within the oasis. Considering the hydrogeological characteristics in the Wei-Ku Oasis, groundwater samples were grouped into three categories: shallow groundwater (well depth $<$ 20 m), middle groundwater (20 m $<$ well depth $<$ 100 m), and deep groundwater (well depth $>$ 100 m) (Wang *et al.* 2013). Moreover, 15 shallow groundwater samples were collected from the upstream to treat as lateral groundwater flow samples for the Wei-Ku Oasis. A total of 186 water samples were obtained, including 97 surface water samples (26 in upstream and 71 in oasis) and 89 groundwater samples (67 shallow groundwater samples, 21 middle groundwater samples, and 1 deep groundwater samples). All water samples were filtered through a 0.22 μm filter, and immediately sealed in 100-mL high-density polyethylene bottles, and then stored in coolers until analysis.

Stable water isotopes ($\delta^2H$ and $\delta^{18}O$) and chemical measurements of the water samples were analyzed at the State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. $\delta^2H$ and $\delta^{18}O$ of water were determined by a liquid water isotope analyzer (LGR DLT-100), and expressed relative to the Vienna Standard Mean Ocean Water (VSMOW) in per million ($\delta$, ‰). The analytical precision for $\delta^2H$ and $\delta^{18}O$ were $\pm$0.8‰ and $\pm$0.1‰, respectively. The total dissolved solids (TDS) of water samples were measured in the fields using a multi-parameter meter (YSI ProPlus), with a TDS measurement precision of 0.01 mg/L.

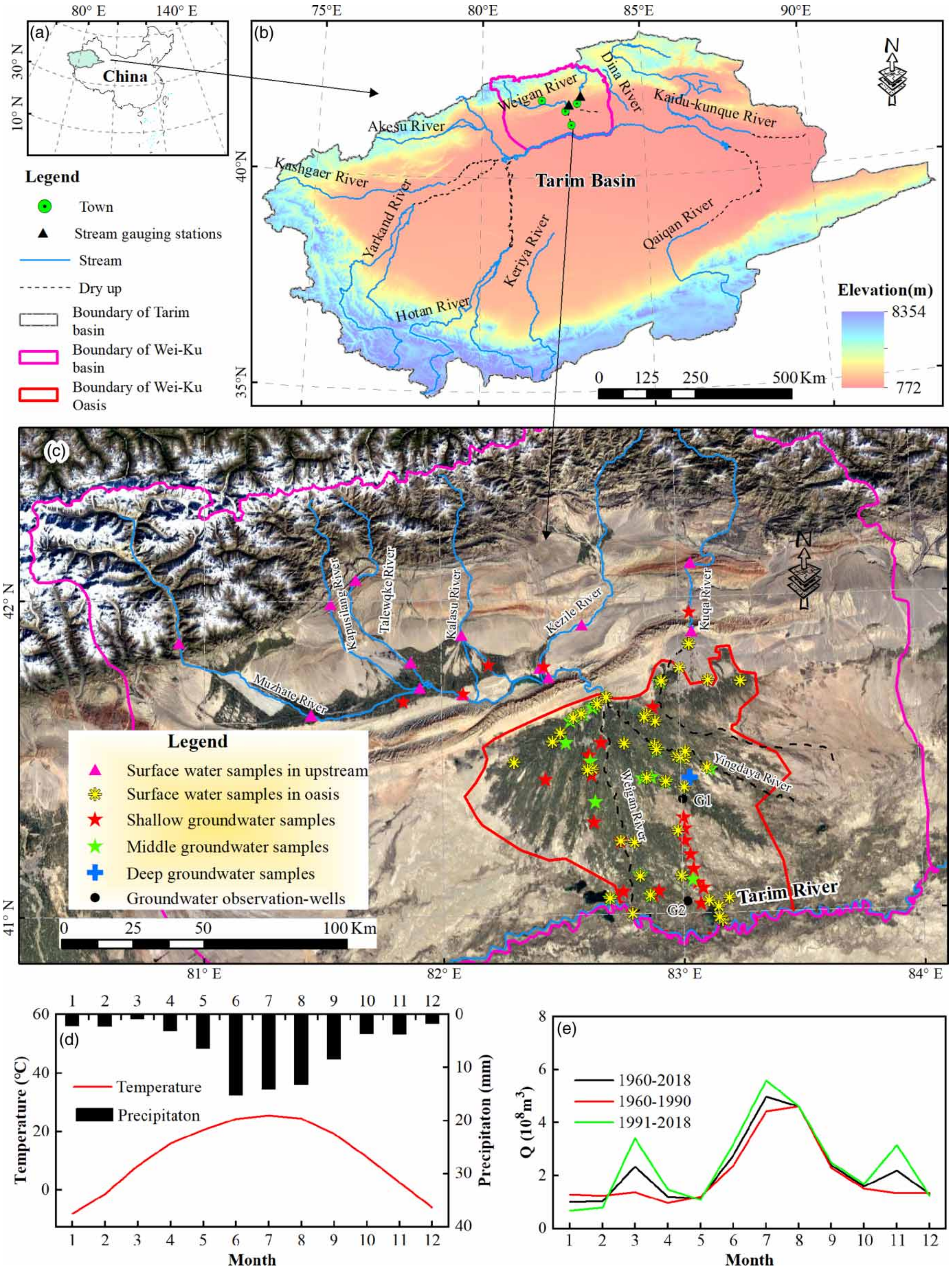


**Figure 1** | Locations of the Tarim Basin (a), Weigan-Kuqa River Basin (b), and water sampling sites (c), and the intra-annual variations of monthly average air temperature, precipitation (d), and streamflow (e) in the Wei-Ku Oasis. The map of the Tarim Basin was modified from Wang *et al.* (2021).

In this study, streamflow data at the outlets of the mountainous tributaries (Weigan River and Kuqa River) in the Weigan-Kuqa River basin from 1960 to 2018 were collected from the Weigan River Basin Authority (Figure 1(b)), which was observed daily by the hydrological observational stations (Wang *et al.* 2021). Groundwater level data of phreatic aquifer in the oasis were obtained from the Water-salt Monitoring Station of the Weigan River Basin Authority, China. Meteorological data (air temperature and precipitation) were obtained from the Chinese National Meteorological Information Centre (http://cdc.cma.gov.cn). Land-use and land-cover (LULC) data was derived from the C3S Global Land Cover products, with a 300 m resolution from 2016 to 2018 (http://cds.climate.copernicus.eu/). Moreover, data statistical analyses were conducted using the Origin (version 2021), ArcGIS (version 10.6), and MATLAB (version R2018a). The IDW (inverse distance weighting) method was applied to interpolate the data of stable isotope, TDS, and LULC into a 250 m grid data.

### End-member mixing analysis method

The EMMA based on water isotopes was used to evaluate the contributing proportions from surface water and lateral groundwater flow to groundwater in the dried-up river oasis (Sklash & Farvolden 1979), which has been widely applied to analyze potential water sources contributing to groundwater (Li *et al.* 2019b). The equations for the separation model are given as Equations (1) and (2):

$$C_{\mathrm{G}} = f_1 \cdot C_{\mathrm{SW}} + f_2 \cdot C_{\mathrm{TGF}} \tag{1}$$

$$f_1 + f_2 = 1 \tag{2}$$

where $C_{\mathrm{G}}$, $C_{\mathrm{SW}}$, and $C_{\mathrm{TGF}}$ are the stable isotopic concentration for groundwater, surface water, and lateral groundwater flow, respectively; $f_1$ is the recharge proportion of surface water; $f_2$ is the recharge proportion of lateral groundwater flow. This technique assumes that the isotopic concentration of each water component is spatial-temporally constant, any variations of isotopes are of the result of different water mixing along groundwater flow path. The formulas for $f_1$ and $f_2$ are given as Equations (3) and (4):

$$f_1 = \frac{Q_{\mathrm{SW}}}{Q_{\mathrm{G}}} = \frac{C_{\mathrm{G}} - C_{\mathrm{TGF}}}{C_{\mathrm{SW}} - C_{\mathrm{TGF}}} \tag{3}$$

$$f_2 = \frac{Q_{\mathrm{TGF}}}{Q_{\mathrm{G}}} = \frac{C_{\mathrm{SW}} - C_{\mathrm{G}}}{C_{\mathrm{G}} - C_{\mathrm{TGF}}} \tag{4}$$

where $Q_{\mathrm{G}}$, $Q_{\mathrm{SW}}$, and $Q_{\mathrm{TGF}}$ is the amount of groundwater, surface water, and lateral groundwater flow, respectively.

## RESULTS

### Stable isotopic composition

The stable isotopic compositions of surface water and groundwater are summarized in Table 1 and Figure 2. The isotopic values of various water components exhibited a large range. The stable isotopes of surface water in upstream ranged from −81.2‰ to −45.5‰ for $\delta^2$H (mean $\delta^2\mathrm{H} = -66.5‰$) and from −12.0‰ to −7.6‰ for $\delta^{18}$O (mean $\delta^{18}\mathrm{O} = -10.1‰$) were lighter than precipitation isotopes in the Hetian station ($\delta^{18}\mathrm{O} = -5.5‰$) but heavier than precipitation isotopes in the Wulumuqi station ($\delta^{18}\mathrm{O} = -10.7‰$) in Xinjiang (data from the Global Network of Isotopes in Precipitation). The $\delta^{18}$O and $\delta^2$H of surface water in the oasis (from −11.4‰ to −7.0‰ and from −75.8‰ to −42.3‰) were close to the isotopes of surface water in upstream, indicating that surface water in the oasis was mainly from river water. Additionally, the shallow groundwater data (mean $\delta^2\mathrm{H} = -69.5‰$, mean $\delta^{18}\mathrm{O} = -10.0‰$) was similar with the values of surface water in the oasis, suggesting that shallow groundwater was mainly recharged from local surface water (Wang *et al.* 2020). Furthermore, in the Wei-Ku Oasis, the isotopes of middle water ($\delta^{18}\mathrm{O} = -10.2‰$) were heavier than those of deep groundwater ($\delta^{18}\mathrm{O} = -10.8‰$), while lighter than those of shallow groundwater, but the difference of isotopes among various aquifers was small. This may indicate that the interactions between different aquifers were frequent (Wang *et al.* 2013; Zeng *et al.* 2020).

The diagrams of $\delta^{18}$O vs. $\delta^2$H for surface water and groundwater samples in the Wei-Ku Oasis illustrated that the data of surface water and groundwater were both located near the GMWL (global meteoric water line) and LMWL in northwest China (local meteoric water line; Guo *et al.* 2019a), and distributed in a relatively scattered way (Figure 2). The groundwater line (GWL) based on these groundwater data was $\delta^2\mathrm{H} = 6.71\delta^{18}\mathrm{O} - 2.58$ ($R^2 = 0.83$), and its slope and intercept were both

**Table 1** | Stable isotopes and salinity of water samples obtained in the Weigan-Kuqa River Basin

| | | **Water components** | | | | |
|---|---|---|---|---|---|---|
| | | **SWU** | **SWO** | **SG** | **MG** | **DG** |
| $\delta^2$H (‰) | Max | −45.5 | −42.3 | −52.0 | −64.1 | / |
| | Min | −81.2 | −75.8 | −83.9 | −79.9 | / |
| | Mean | −66.5 | −64.8 | −69.5 | −70.5 | −74.4 |
| $\delta^{18}$O (‰) | Max | −7.6 | −7.0 | −7.5 | −9.1 | / |
| | Min | −12.0 | −11.4 | −12.2 | −11.8 | / |
| | Mean | −10.1 | −9.7 | −10.0 | −10.2 | −10.8 |
| TDS (mg/L) | Max | 803.6 | 1,753.1 | 28,783.0 | 3,419.4 | / |
| | Min | 192.4 | 300.4 | 807.4 | 713.3 | / |
| | Mean | 427.7 | 660.5 | 9,357.1 | 1,519.8 | 373.9 |

*Note:* SWU, surface water in upstream; SWO, surface water in oasis; SG, shallow groundwater; MG, middle groundwater; DG, deep groundwater; TDS, total dissolved solids; Max, maximum value; Min, minimum value; Mean, mean value.

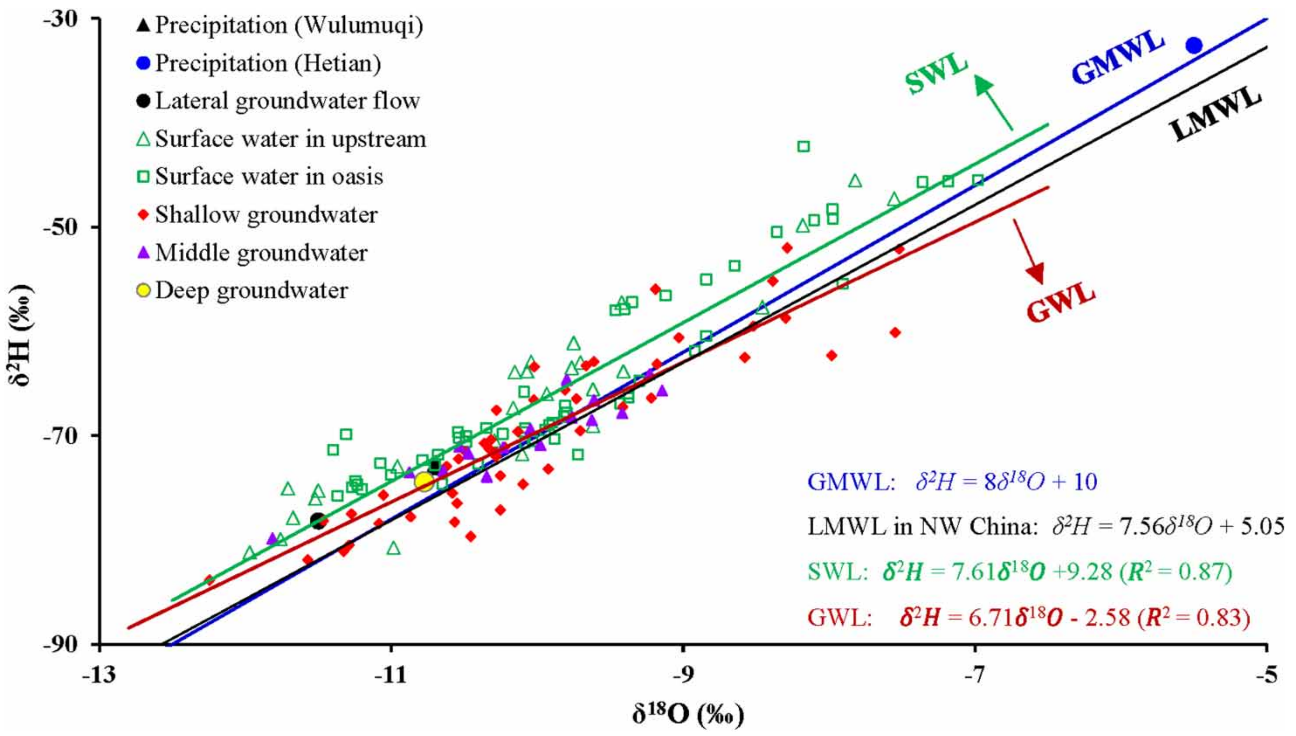


**Figure 2** | Relationship between $\delta^{18}$O and $\delta^2$H for surface water and groundwater in the Wei-Ku Oasis. GMWL, global meteoric water line; LMWL in NW China, local meteoric water line in northwest China (Guo *et al.* 2019a); SWL, surface water line in the oasis; GWL, groundwater line in the oasis. Precipitation isotopic data were from the GNIP (Global Network of Isotopes in Precipitation) for the Hetian and Wulumuqi stations.

smaller than those of GMWL ($\delta^2$H $= 8\delta^{18}$O $+ 10$) (Craig 1961) and LMWL in northwest China ($\delta^2$H $= 7.56\delta^{18}$O $+ 5.05$) (Guo *et al.* 2019a), possibly due to evaporative enrichment in the arid inland oasis (Wang *et al.* 2013). Additionally, the surface water line (SWL) based on the surface water samples in the oasis was $\delta^2$H $= 7.61\delta^{18}$O $+ 9.28$ ($R^2 = 0.87$), and the slope and intercept were smaller than those of GMWL, but greater than those of the LMWL in northwest China and the Tarim Basin ($\delta^2$H $= 7.2\delta^{18}$O $+ 3.0$) (Sun 2015). This indicated that surface water in the oasis did not experience strong evaporation, maybe due to the rapid transport of river water to irrigated fields through irrigation canals (Li *et al.* 2019b).

The spatial distribution of $\delta^{18}$O for surface water and shallow groundwater in the Wei-Ku Oasis were prepared (Figure 3). As shown in Figure 3, stable isotopic values of surface water and shallow groundwater varied among sampling sites, and

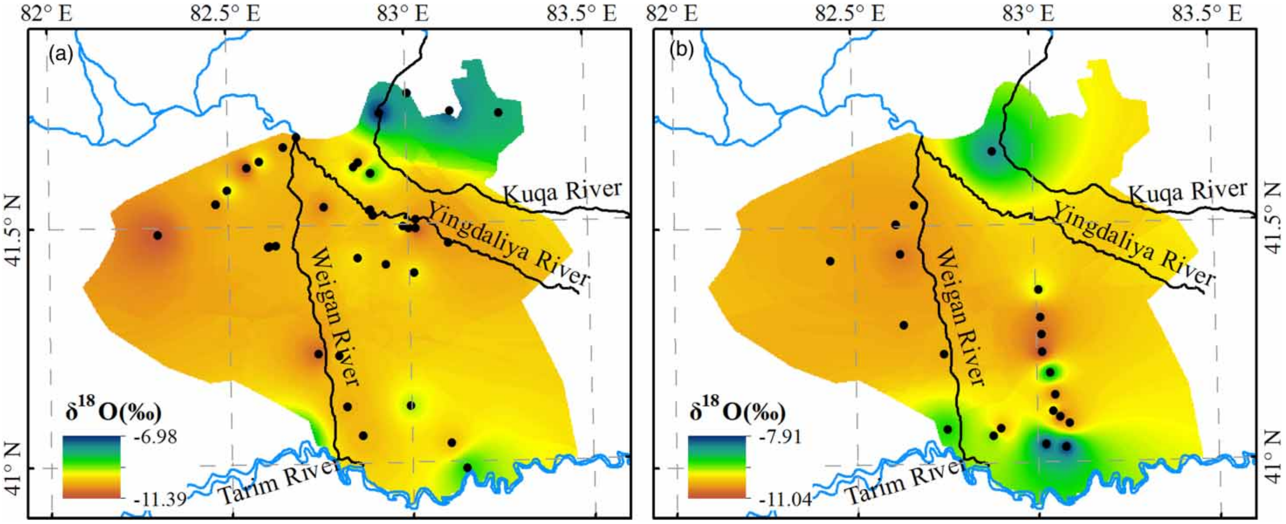


**Figure 3** | Spatial distribution of $\delta^{18}O$ for surface water and shallow groundwater in the Wei-Ku Oasis: (a) surface water and (b) shallow groundwater.

showed obviously spatial dynamic. This may be attributed to the different effects of air temperature, evaporation, and agricultural activities (well-developed irrigation canal system and agricultural drainage ditch network) by redistributing water (Wang *et al.* 2020, 2022). In general, except for the northeast corner, the $\delta^{18}O$ value of surface water in the oasis increased from northwest to southeast, while the spatial variation trend of shallow groundwater $\delta^{18}O$ in the oasis was not obvious (Figure 3). The $\delta^{18}O$ of surface water in the Wei-Ku Oasis ranged from −11.4‰ to −7.0‰, and the low value was mainly distributed in the northwestern part, while the high value was mainly distributed in the northeast and southern edge of the oasis. Additionally, shallow groundwater $\delta^{18}O$ in the Wei-Ku Oasis ranged from −12.2‰ to −7.5‰, and showed a relatively large spatial heterogeneity. The high value of shallow groundwater $\delta^{18}O$ was mainly distributed in the northern edge and southern edge of the oasis, possibly due to different sources of shallow groundwater among sampling sites. The low value of shallow groundwater $\delta^{18}O$ was distributed in several sporadic areas on the central oasis, possibly due to recharge with river water from higher elevation (Guo *et al.* 2019a).

Figure 4 shows the seasonal variations of stable isotopes for surface water and groundwater across the Wei-Ku Oasis. In the oasis, the $\delta^{18}O$ and $\delta^{2}H$ of surface water and groundwater showed obviously temporal dynamic, and varied among different aquifers, mainly due to the seasonal variations of water source, air temperature, and precipitation in the study region. Generally, the mean values of $\delta^{18}O$ and $\delta^{2}H$ in surface water and groundwater for non-flood season were both heavier than those for flood season in the oasis (Figure 4), and were contrary to the seasonal variations of rainfall and runoff (Wang *et al.* 2021), possibly due to the massive recharge from river water with lighter isotopes in flood season (Guo *et al.* 2019a). The seasonal variation of mean $\delta^{18}O$ value was the largest in surface water, followed by shallow groundwater, while the smallest in middle groundwater mainly due to the seasonal differences of recharge sources and processes among different water components

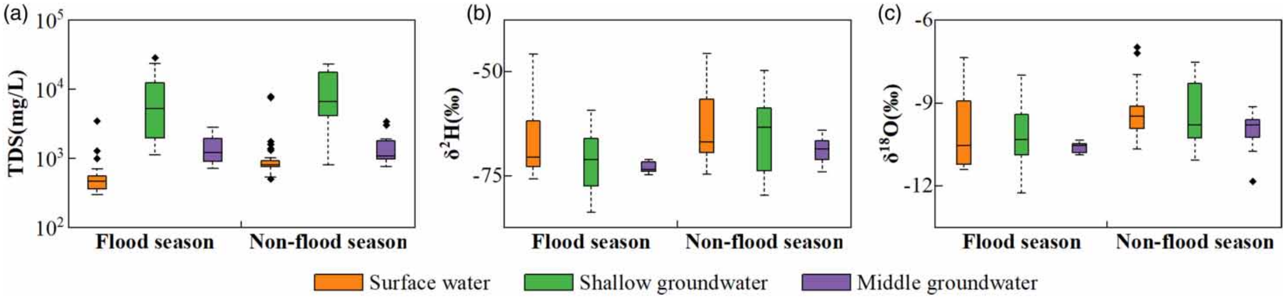


**Figure 4** | Box and whisker plots showing the variations of stable isotopes and TDS for surface water and groundwater in flood season and non-flood season across the Wei-Ku Oasis.

(Wang *et al.* 2013). However, the difference of $\delta^{18}$O seasonal variation was not obvious among various water components (Figure 4), possibly indicating the close interaction between different aquifers (Zeng *et al.* 2020). Furthermore, stable isotopes of shallow groundwater were lighter than those of surface water and heavier than those of middle groundwater both in flood season and non-flood season.

### Dissolved ions

TDS content varied significantly between different water components (Table 1). In general, the TDS content of groundwater samples in the study area was the largest, followed by surface water in the oasis, while the smallest in river water samples, mainly due to strong evaporation in such arid climate (Liu *et al.* 2018b). River water in the upstream had low salinity, and its TDS showed a small range (TDS = 428 mg/L) (Table 1). Compared with the river water samples in upstream, surface water in the oasis had slightly higher salinity (TDS = 300–1,753 mg/L), suggesting that surface water in the oasis was subjected to strong evaporation.

Furthermore, the salinity of groundwater exhibited a significant difference between various aquifers, and showed a wide range for shallow and middle groundwater samples (Table 1). Generally, the salinity of deep groundwater in the oasis was the smallest, followed by the middle groundwater, while the largest in shallow groundwater, which may be attributed to the different water sources for each groundwater components (Wang *et al.* 2013). Shallow groundwater in the oasis had high salinity (TDS = 9,357 mg/L), which was mainly because surface water provided a significant salinity contribution to groundwater in the study region (Wang *et al.* 2021). The salinity of middle groundwater samples (TDS = 1,520 mg/L) was higher than the value of deep groundwater (TDS = 373.9 mg/L), but lower than the value of shallow groundwater, which implied that phreatic water could leak downward to confined water, and in turn lead to the interaction between salt and fresh water (Zeng *et al.* 2020).

TDS concentrations of surface water and shallow groundwater in the Wei-Ku Oasis showed spatial differences among the sampling sites (Figure 5). Generally, TDS values of shallow groundwater in the oasis showed an increasing trend from northwest to southeast. TDS concentration of surface water ranged from 300 to 1,753 mg/L in the oasis. The low value of surface water TDS was mainly distributed in the west and several sporadic areas on the central and north part, while the high value was mainly distributed near the main stream of Tarim River in the south, which may be attributed to evaporative concentration effect of surface water ions along the flow path (Liu *et al.* 2018b). In addition, the TDS value of shallow groundwater in the oasis ranged from 807 to 28,783 mg/L was low in the northwest part and high in the southeast part, which may be attributed to the little recharge of groundwater from river water in the southeast desert area. Furthermore, the spatial variation trend of middle groundwater TDS was not obvious in the Wei-Ku Oasis, while the shallow groundwater TDS value showed significant horizontal zoning, which may be due to the obvious differences of water sources, hydrochemical formation mechanism, and human interference intensity between various aquifers (Wang *et al.* 2013).

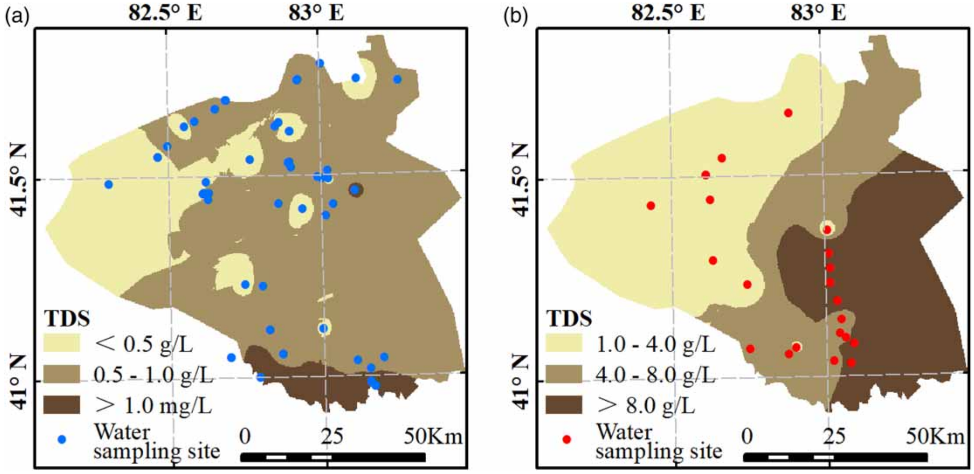


**Figure 5** | Spatial distribution of TDS for surface water and shallow groundwater in the Wei-Ku Oasis: (a) surface water and (b) shallow groundwater.

Figure 4 exhibits the seasonal variations of TDS in surface water and groundwater across the Wei-Ku Oasis. The TDS concentration of surface water and groundwater showed different fluctuation in flood season and non-flood season, and seasonal variation of TDS in the oasis was high during the sampling period. Generally, the mean TDS value of surface water and groundwater in non-flood season was higher than that in flood season in the oasis (Figure 4), possibly due to the massive recharge from river water with lower salinity in flood season (Wang *et al.* 2021). The difference of TDS value among seasons was the largest in shallow groundwater, followed by surface water, while the smallest in middle groundwater, suggesting that middle groundwater was relatively steady. The average TDS concentration of surface water in the oasis was 604 mg/L in flood season and 1,207 mg/L in non-flood season, which was contrary to the seasonal variations of rainfall and runoff. The shallow groundwater TDS value was 8,167 mg/L in flood season and 9,539 mg/L in non-flood season, while the middle groundwater TDS value was 1,467 mg/L and 1,553 mg/L in flood season and non-flood season, respectively.

### The sources of groundwater

The end-members analysis method was applied to identify water sources and to quantify the contribution proportions of each end member to shallow groundwater in the Wei-Ku Oasis. The potential water sources of shallow groundwater include surface water (leakage or infiltration from canal, riverbank, reservoir, and irrigation), lateral groundwater flow from the upstream, and confined water (leakage recharge) (Table 1 and Figure 2), in which river water and groundwater pumping from confined aquifer are used for irrigation in this area (Chen *et al.* 2019). The concentrations of $\delta^2$H and $\delta^{18}$O for surface water, lateral groundwater flow ($\delta^2\text{H} = -78.2‰$, $\delta^{18}\text{O} = -11.5‰$), confined water and shallow groundwater revealed considerable differences in the oasis (Table 1). Therefore, both $\delta^2$H and $\delta^{18}$O were selected as tracers to confirm if the three end-members exist. Shallow groundwater in the oasis was located outside the triangle spanning the three end-members (Figure 6), indicating that the three members did not exist. Confined water would recharge shallow groundwater directly or indirectly. The directly recharge of confined water to phreatic water was little and could be neglected, because groundwater level dropped continuously and caused phreatic water leakage downward to recharge confined water due to groundwater overexploitation in the Wei-Ku Oasis (Wang *et al.* 2021). Additionally, surface water samples in the oasis contain the pumping confined water used for agricultural irrigation, so the indirect recharge of confined water to shallow groundwater has been reflected in the end-member of surface water.

Hence, the two end-members analysis method (Equations (1) and (2)) was used to estimate the contribution of surface water and lateral groundwater flow to shallow groundwater in this study. The mean value of $\delta^{18}$O in lateral groundwater flow from the upstream (−11.5‰), surface water (−9.7‰) and shallow groundwater (−10.0‰) was used for this calculation (Table 1). In general, surface water and lateral groundwater flow accounted for 88 and 12% of shallow groundwater in the Wei-Ku Oasis, respectively. Obviously, shallow groundwater in the oasis mainly originated from local surface water infiltration, and lateral groundwater flow from the upstream also played an important role in shallow groundwater in the arid inland oasis.

## DISCUSSION

### Groundwater recharge

The importance of precipitation as one water source of shallow groundwater was relatively little, and was neglected during estimating the sources. Snowmelt played an important role in the runoff of mountainous areas in spring (Li *et al.* 2019b).

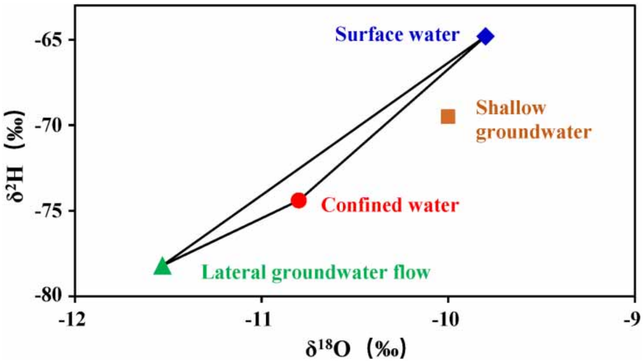


**Figure 6** | End-member mixing diagram using the mean $\delta^2$H and $\delta^{18}$O values for the shallow groundwater in the Wei-Ku Oasis.

However, the contribution of snowmelt to shallow groundwater in the oasis region was weak, because snow cover was little in the oasis and snowmelt rapidly evaporated or sublimated into the atmosphere during the melt period (Wang *et al.* 2021). In the Wei-Ku Oasis, annual average precipitation was about 74.6 mm (Figure 1), while annual potential evaporation was about 2,401 mm (Chen *et al.* 2019), resulting in relatively dry soil with large soil water holding capacity. In addition, depth to phreatic water level in the oasis was generally above 5 m, which may lead to very weak recharge from rainfall to groundwater in the arid inland oasis (Wang *et al.* 2021). Thus, precipitation can be neglected during estimating groundwater sources.

As shown before, surface water in the Wei-Ku Oasis accounted for 88% of the sources of shallow groundwater, while lateral groundwater flow from the upstream accounted for 12%, suggesting that surface water was the dominant source of shallow groundwater. The stable isotopic values of shallow groundwater were close to those of surface water rather than those of lateral groundwater flow (Figures 2 and 6), maybe due to the different water migration mechanisms between the two end-members (Wang *et al.* 2013). Furthermore, runoff into the Wei-Ku Oasis is basically consumed in this area, most of which is used for agricultural irrigation, and then migrated downward to supply groundwater (Zhang *et al.* 2014; Wang *et al.* 2021). Wang *et al.* (2021) pointed out that the intra-annual distribution of runoff exhibited three peaks due to reservoir regulation (Figure 1), corresponded to crop irrigation time (from March to April, May to August, and October to November) in the region, indicating that the recharge of groundwater from river water mainly occurred during the irrigation season. In addition, a certain degree of increase of phreatic water level from January to April confirmed the recharge of phreatic water from lateral groundwater flow (Figure 7; Wang *et al.* 2013), because there is no agricultural irrigation and almost all of river water is stored in mountain reservoir during this period (Wang *et al.* 2021). Guo *et al.* (2019a) also found that lateral groundwater flow and irrigated return water were the main sources of shallow groundwater using stable isotope data in arid oasis. Furthermore, we examined the shallow groundwater sources and its dominant contributors using one-year data in this study. More detailed long-term and continuous investigation are required to explore the groundwater source dynamics (different locations and seasons) in the arid oasis in the context of climate change and intense anthropogenic interference.

According to the above results, we analyzed groundwater recharge process in the Wei-Ku Oasis. Runoff formed in mountainous region is the dominant source of surface water and groundwater in the oasis, which is dried-up in the oasis and could not reach the Tarim River (Chen *et al.* 2019). In the flood season, rainfall infiltrates into the dry soil layer, some is consumed by soil moisture evaporation, and the other part transfers downward to supply phreatic water by gravity and capillary force. However, the recharge of groundwater from rainfall is very little due to scarce precipitation and strong evaporation in the arid oasis (Ma *et al.* 2013). At the same time, the leakage water from natural streambed, canals, reservoirs, and agricultural irrigation could infiltrate directly or indirectly to recharge shallow groundwater by gravity (accounting for 88%), as the predominant source in the oasis (Wang *et al.* 2021). In addition, lateral ground from the upstream flows into the Wei-Ku Oasis to recharge shallow groundwater by the hydraulic gradient within aquifer system (accounting for 12%), which process is continuous and slow, and affected by the magnitude and direction of hydraulic gradient (Ma *et al.* 2013; Wang *et al.* 2013). Furthermore, deep confined water also is an important source of shallow groundwater within the arid oasis (Guo *et al.* 2019b). The irrigation water from pumping deep groundwater could infiltrate into phreatic aquifer (Chen *et al.* 2019).

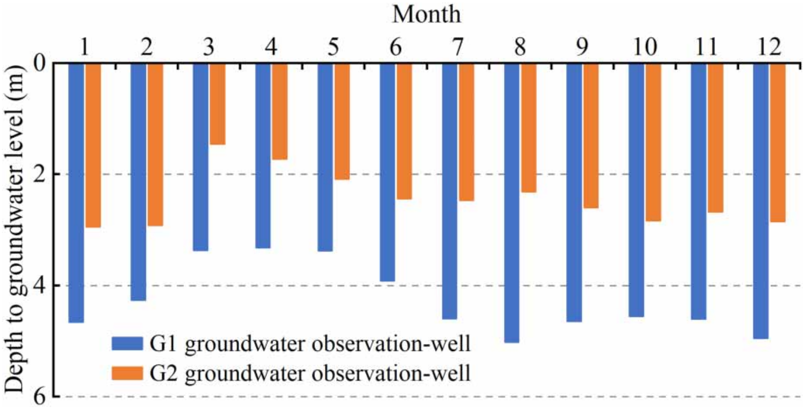


**Figure 7** | Intra-annual variation of monthly average groundwater level depth in phreatic aquifer for G1 and G2 groundwater observation wells in the Wei-Ku Oasis in 2019.

Confined water could leak upward to recharge shallow groundwater, but it is limited due to groundwater level decline caused by groundwater overexploitation (Zeng *et al.* 2020). This indicates that human activities play an important role on the groundwater recharge in the arid inland oasis (Castellano *et al.* 2019; Li *et al.* 2019a). Zeng *et al.* (2020) noted little difference of stable isotopes among phreatic water, shallow confined water, and deep confined water, and pointed out that groundwater mixing occurred among different aquifers in arid inland basin.

## Groundwater discharge

According to the spatiotemporal characteristics of groundwater TDS and isotopes, the front range of the Wei-Ku Oasis is recharge area of groundwater, and the Tarim River is discharge area. Accordingly, four main routes of the oasis groundwater discharge are possible: phreatic water evapotranspiration, groundwater extraction, agricultural drainage, and lateral flow into the Tarim River by hydraulic gradient (Wang *et al.* 2021). Under natural conditions, evapotranspiration in the shallow phreatic aquifer is an important route of groundwater discharge, and mainly occurs in the southwest part of the oasis, because phreatic water evaporation is closely related to groundwater level depth, the lithology of the unsaturated zone and vegetation coverage in the region (Wang *et al.* 2013; Guo *et al.* 2019b). As the groundwater level decreases, the area of effective phreatic evaporation decreases in the arid oasis, thus leads to the decreasing of phreatic evaporation amount (Eamus *et al.* 2015). In the past 20 years, groundwater evapotranspiration showed a decreasing trend in the Wei-Ku Oasis (Table 2), which was mainly attributed to phreatic decline during 2000–2018 in the context of land-cover change and human activities (Chen *et al.* 2019).

In addition, groundwater exploitation for industry, domestic, and agricultural use is an important route of groundwater discharge in the arid inland oasis (Asoka *et al.* 2017). In recent decades, the water demand in the oasis has continued to increase due to the oasis expansion and rapid population growth, and surface water resources could not meet the water demand, thus leads to groundwater overexploitation for irrigation (Shukla *et al.* 2018; de Graaf *et al.* 2019). During 2000–2014, groundwater extraction exhibited an increasing trend due to the rapid farmland expansion, with an increasing rate of $2{,}809 \times 10^4\ \mathrm{m^3/a}$ (Table 2). However, groundwater extraction suddenly decreased and gradually stabilized after 2015 in the Wei-Ku Oasis, mainly because the 'strictest water resource management system' was implemented to effectively curb the disorderly exploitation of groundwater (Chen *et al.* 2019). Moreover, agricultural water discharge by drainage canals is one of the important ways for groundwater discharge in the Wei-Ku Oasis, which could lower the groundwater level and salinity to effectively prevent soil salinization (Castellano *et al.* 2019; Wang *et al.* 2021). Agricultural discharge showed a decreasing trend in our study area during 2000–2018, with a decreasing rate of $939 \times 10^4\ \mathrm{m^3/a}$ (Table 2), mainly due to the decrease of groundwater level and the widespread promotion of efficient water saving irrigation methods (Liu *et al.* 2018a; Porhemmat *et al.* 2018). Groundwater flows from the recharge area toward the discharge area driven by hydraulic gradient, and ultimately reaches the main stream of the Tarim River (Wang *et al.* 2020).

## Influence of anthropogenic activities on groundwater dynamic

In recent decades, with the socio-economic development, anthropogenic activities have imposed intensive impacts on groundwater dynamics in the Wei-Ku Oasis (Wang *et al.* 2020). From 1990 onwards, with the decrease of river water as a

**Table 2** | The information related to climate condition, human activities, and groundwater within the Wei-Ku Oasis in 2000, 2010, and 2018

| Parameters | 2000 | 2010 | 2018 |
|---|---|---|---|
| Air temperature (°C) | 11.5 | 11.4 | 10.9 |
| Precipitation (mm) | 50.5 | 97.9 | 69.7 |
| Cropland area ($\mathrm{km^2}$) | 3,969.3 | 4,302.8 | 4,442.0 |
| Phreatic water evapotranspiration ($10^8\ \mathrm{m^3}$) | 13.1 | 3.7 | 1.6 |
| Depth to phreatic water level (m) | 2.7 | 4.0 | 5.7 |
| Total groundwater extraction ($10^8\ \mathrm{m^3}$) | 0.5 | 2.8 | 3.2 |
| Agricultural water discharge ($10^8\ \mathrm{m^3}$) | 3.1 | 2.3 | / |
| Agricultural salt discharge ($10^4$ tons) | 170.6 | 150.9 | / |

*Note:* Agricultural water discharge, agricultural water discharge by drainage canals; Agricultural salt discharge, agricultural salt discharge by drainage canals. The data of groundwater and human activities were from Wang *et al.* (2021).

result of increased agricultural irrigation in the middle and down reaches, the river channel in the oasis became dry (Chen *et al.* 2019). Thus, groundwater level in the Wei-Ku Oasis markedly dropped, due to surface hydrological process changes and groundwater extraction (Wang *et al.* 2021). Land-cover change and groundwater overexploitation were the dominant driving factors of groundwater dynamic changes in the Wei-Ku Oasis in the past decades (Chen *et al.* 2019). In the oasis, cropland was the dominant land-cover type, and its area gradually increased during 2000–2018 (55.9% in 2000, 62.5% in 2018) (Figure 8), which caused the increase of agricultural irrigation water demand. This, in turn, leads to the decrease of groundwater level and storage, mainly due to groundwater overexploitation (Berihun *et al.* 2019; Riley *et al.* 2019). In addition, groundwater overexploitation for agricultural irrigation in the Wei-Ku Oasis accelerated the decline of groundwater level and storage in the past decades (Table 2). This, in turn, affected the recharge and discharge of aquifer system, decreasing the amount of rainfall infiltration, canal leakage, irrigation water infiltration, phreatic evapotranspiration, and agricultural drainage (Wang *et al.* 2021).

Agricultural irrigation and drainage activities imposed intensive impacts on groundwater dynamic, including water quantity and quality (Porhemmat *et al.* 2018; Wang *et al.* 2021). In the past decades, large numbers of agricultural irrigation canals were constructed in the oasis due to the widespread promotion of water saving irrigation methods, which could increase canal water utilization coefficient and then affect groundwater distribution (Liu *et al.* 2018b). Thus, the leakage water from canals gradually reduced in the arid oasis, and could cause phreatic decline due to decreasing groundwater recharge from channel water (Zhang *et al.* 2014). In the Wei-Ku Oasis, the water saving irrigation area accounted for more than 50% of the total cultivated area in 2018, while the recharge of shallow aquifer from irrigation water infiltration gradually reduced from 2000 to 2018. That was because water saving irrigation methods could improve agricultural water use efficiency and save water resources, also could decrease deep percolation, and thus, reduce groundwater recharge from irrigation water infiltration (Liu *et al.* 2018a; Porhemmat *et al.* 2018). In addition, agricultural drainage activities noticeably influenced groundwater level and salinity (Table 2). Castellano *et al.* (2019) reported that the improved agricultural drainage could discharge some water and salt from irrigated area, thus leading to the decrease of groundwater level and salinity in shallow aquifer. Porhemmat *et al.* (2018) found that irrigated agriculture has a significant impact on groundwater chemistry in arid and semi-arid areas. However, we did not analyze the spatiotemporal variation of groundwater chemistry and its response to agricultural activities, and future studies on these aspects are needed. According to the above analysis and supported by the previous research, a conceptual diagram of groundwater recharge and discharge was proposed in the dried-up river oasis of arid inland basin (Figure 9).

## CONCLUSION

A combined application of stable isotopic indicators and EMMA were performed to quantify the sources of shallow groundwater and interpret the recharge and discharge of groundwater under the influence of human activities in the Wei-Ku Oasis. The stable isotopes and salinity of surface water and groundwater showed obviously spatiotemporal dynamics and seasonal differentiation. Except for the northeast corner, the $\delta^{18}$O value of surface water in the oasis was heavier from northwest to southeast, while the spatial variation trend of shallow groundwater $\delta^{18}$O was not obvious. The TDS value of shallow groundwater increased from northwest to southeast, while the spatial variation trend of middle groundwater TDS was not obvious, mainly due to evaporation, mineral leaching, and mixing. Surface water and groundwater in non-flood season had higher

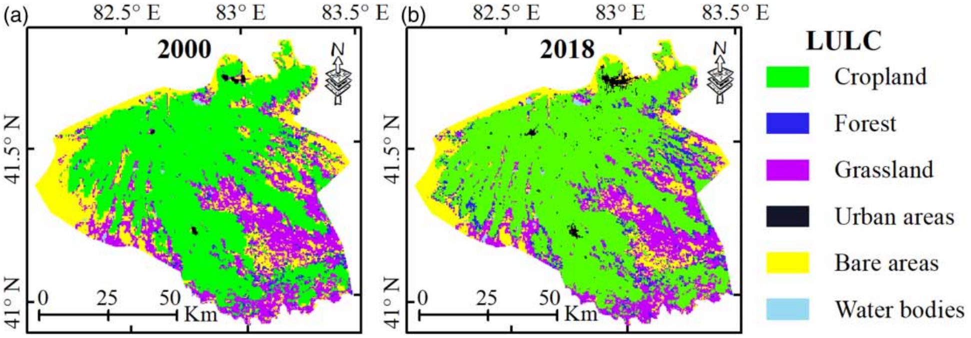


**Figure 8** | Distribution of annual averaged LULC across the Wei-Ku Oasis for 2000 and 2018. LULC, land use and land cover.

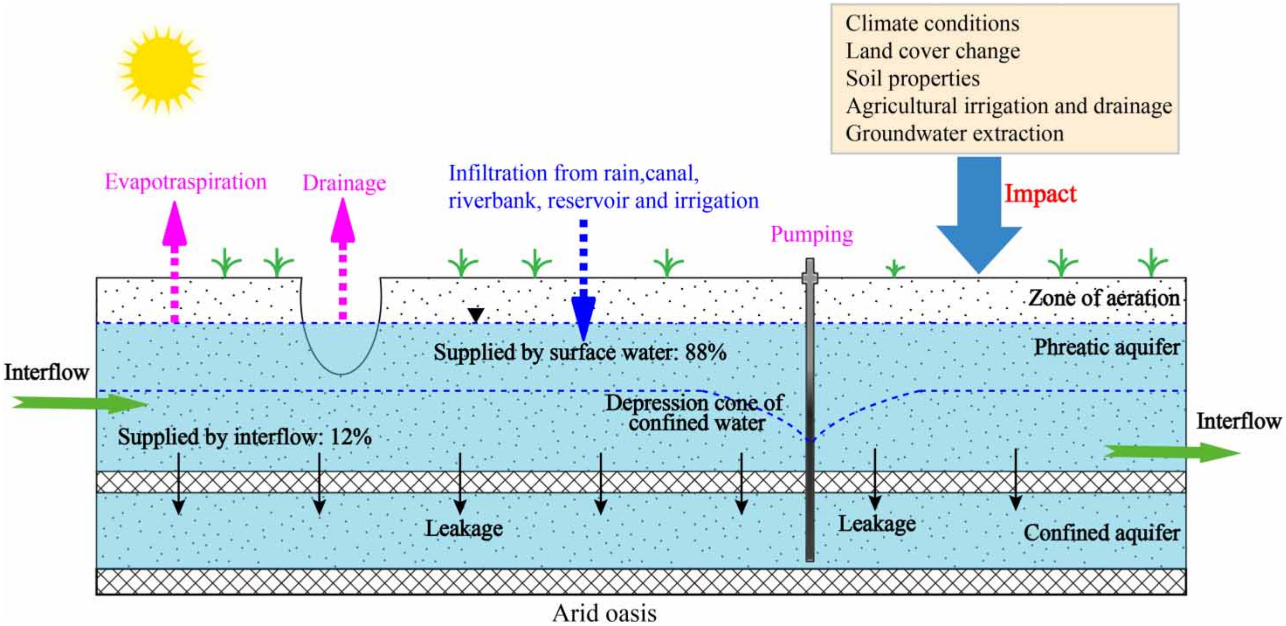


**Figure 9** | Conceptual diagram of the groundwater recharge and discharge in the dried-up river oasis of arid inland basin.

values of stable isotopes and TDS than those in flood season, possibly due to the dominant recharge from river water in flood season. The difference of $\delta^{18}O$ seasonal variation was not obvious among various water components, indicating the close interaction between different aquifers. The seasonal variation of TDS value was the largest in shallow groundwater, followed by surface water, while the smallest was in middle groundwater.

Anthropogenic activities are dramatically affecting groundwater dynamics in the Wei-Ku Oasis. Shallow groundwater in the oasis was mainly supplied by surface water and lateral groundwater flow from upstream, accounting for 88 and 12%, respectively, implying that surface water was the dominant source. The main routes of groundwater discharge include phreatic water evapotranspiration, groundwater extraction, agricultural drainage, and lateral flow into the Tarim River. Land-cover change and groundwater overexploitation are the main factors responsible for groundwater dynamic changes. Our findings could be useful for further understanding groundwater sources and cycling, and highlight the importance of anthropogenic activities on groundwater dynamic in arid inland oasis regions.

## FUNDING

This research was jointly supported by the International Cooperation Program of Chinese Academy of Sciences (131965KYSB20210045), the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA20100303), and the Chinese Academy of Sciences 'Light of West China' Program (2018-XBQNXZ-B-015).

## CONFLICT OF INTEREST

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

Data cannot be made publicly available; readers should contact the corresponding author for details.

## REFERENCES

Asoka, A., Gleeson, T., Wada, Y. & Mishra, V. 2017 Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. *Nature Geoscience* **10** (2), 109–117.

Berihun, M. L., Tsunekawa, A., Haregeweyn, N., Meshesha, D. T., Adgo, E., Tsubo, M., Masunaga, T., Fenta, A. A., Sultan, D., Yibeltal, M. & Ebabu, K. 2019 Hydrological responses to land use/land cover change and climate variability in contrasting agro-ecological environments of the Upper Blue Nile basin, Ethiopia. *Science of The Total Environment* **689**, 347–365.

Cartwright, I., Werner, A. & Woods, J. 2019 Using geochemistry to discern the patterns and timescales of groundwater recharge and mixing on floodplains in semi-arid regions. *Journal of Hydrology* **570**, 612–622.

Castellano, M. J., Archontoulis, S. V., Helmers, M. J., Poffenbarger, H. J. & Six, J. 2019 Sustainable intensification of agricultural drainage. *Nature Sustainability* **2** (10), 914–921.

Chen, Y. N., Hao, X. M., Chen, Y. P. & Zhu, C. G. 2019 Study on water system connectivity and ecological protection countermeasures of Tarim River Basin in Xinjiang. *Bulletin of Chinese Academy of Sciences* **34**, 1156–1164 (in Chinese).

Craig, H. 1961 Isotopic variations in meteoric waters. *Science* **133** (3465), 1702–1703.

de Graaf, I. E. M., Gleeson, T., van Beek, L. P. H., Sutanudjaja, E. H. & Bierkens, M. F. P. 2019 Environmental flow limits to global groundwater pumping. *Nature* **574**, 90–94.

Duan, W., Takara, K., He, B., Luo, P., Nover, D. & Yamashiki, Y. 2013 Spatial and temporal trends in estimates of nutrient and suspended sediment loads in the Ishikari River, Japan, 1985 to 2010. *Science of The Total Environment* **461**, 499–508.

Duan, W., He, B., Nover, D., Yang, G., Chen, W., Meng, H., Zou, S. & Liu, C. 2016 Water quality assessment and pollution source identification of the eastern Poyang Lake Basin using multivariate statistical methods. *Sustainability* **8** (2), 133.

Eamus, D., Zolfaghar, S., Villalobos-Vega, R., Cleverly, J. & Huete, A. 2015 Groundwater-dependent ecosystems: recent insights from satellite and field-based studies. *Hydrology and Earth System Sciences* **19** (10), 4229–4256.

Fuchs, E. H., King, J. P. & Carroll, K. C. 2019 Quantifying disconnection of groundwater from managed-ephemeral surface water during drought and conjunctive agricultural use. *Water Resource Research* **55**, 5871–5890.

Gibson, J. J., Birks, S. J. & Jeffries, D. Y. Y. 2017 Regional trends in evaporation loss and water yield based on stable isotope mass balance of lakes The Ontario Precambrian Shield surveys. *Journal of Hydrology* **544**, 500–510.

Gleeson, T., Van der Steen, J., Sophocleous, M. A., Taniguchi, M., Alley, W. M., Allen, D. M. & Zhou, Y. X. 2010 Groundwater sustainability strategies. *Nature Geoscience* **3**, 378–379.

Gong, Y., Liu, X., Ma, B., Qi, P. & Li, Y. 2021 Using geochemistry and environmental tracers to study shallow unconfined aquifer recharge and mineralization processes in the Yinchuan Plain, arid Northwest China. *Hydrology Research* **52** (3), 658–675.

Guo, X. Y., Feng, Q., Si, J. H., Wei, Y. P. & Li, Z. X. 2019a Identifying the origin of groundwater for water resources sustainable management in an arid oasis, China. *Hydrological Sciences Journal* **64** (10), 1253–1264.

Guo, X. Y., Feng, Q., Si, J. H., Xi, H. Y., Zhao, Y. & Deo, R. C. 2019b Partitioning groundwater recharge sources in multiple aquifers system within a desert oasis environment: implications for water resources management in endorheic basins. *Journal of Hydrology* **579**, 124212.

Han, D., Currell, M. J., Cao, G. & Hall, B. 2017 Alterations to groundwater recharge due to anthropogenic landscape change. *Journal of Hydrology* **554**, 545–557.

Hasan, T., Tiyip, T., Gazat, M. & Mamat, M. 2011 Spatial and temporal dynamic distribution of groundwater depth and mineralization in Weigan River irrigation district. *Scientia Geographica Sinica* **31**, 1131–1137.

Hu, K. X., Awange, J. L., Kuhn, M. & Saleem, A. 2019 Spatio-temporal groundwater variations associated with climatic and anthropogenic impacts in South-West Western Australia. *Science of The Total Environment* **696**, 133599.

Huang, T. M. & Pang, Z. H. 2010 Changes in groundwater induced by water diversion in the Lower Tarim River, Xinjiang Uygur, NW China: evidence from environmental isotopes and water chemistry. *Journal of Hydrology* **387** (3–4), 188–201.

Jia, H., Qian, H., Zheng, L., Feng, W. W., Wang, H. K. & Gao, Y. Y. 2020 Alterations to groundwater chemistry due to modern water transfer for irrigation over decades. *Science of The Total Environment* **717**, 137170.

Lezzaik, K., Milewski, A. & Mullen, J. 2018 The groundwater risk index: development and application in the Middle East and North Africa region. *Science of The Total Environment* **628**, 1149–1164.

Li, Z., Yang, Q., Yang, Y., Ma, H., Wang, H., Luo, J., Bian, J. & Martin, J. D. 2019a Isotopic and geochemical interpretation of groundwater under the influences of anthropogenic activities. *Journal of Hydrology* **576**, 685–697.

Li, Z., Gui, J., Wang, X., Feng, Q., Zhao, T., Ouyang, C., Guo, X., Zhang, B. & Shi, Y. 2019b Water resources in inland regions of Central Asia: evidence from stable isotope tracing. *Journal of Hydrology* **570**, 1–16.

Liu, M., Jiang, Y., Xu, X., Huang, Q., Huo, Z. & Huang, G. 2018a Long-term groundwater dynamics affected by intense agricultural activities in oasis areas of arid inland river basins, Northwest China. *Agricultural Water Management* **203**, 37–52.

Liu, Y. L., Jin, M. G. & Wang, J. J. 2018b Insights into groundwater salinization from hydrogeochemical and isotopic evidence in an arid inland basin. *Hydrological Processes* **32** (20), 3108–3127.

Ma, J., He, J., Qi, S., Zhu, G., Zhao, W., Edmunds, W. M. & Zhao, Y. 2013 Groundwater recharge and evolution in the Dunhuang Basin, northwestern China. *Applied Geochemistry* **28**, 19–31.

Mancuso, M., Santucci, L. & Carol, E. 2020 Effects of intensive aquifers exploitation on groundwater salinity in coastal wetlands. *Hydrological Processes* **34** (11), 2313–2323.

Pang, Z., Huang, T. & Chen, Y. 2010 Diminished groundwater recharge and circulation relative to degrading riparian vegetation in the middle Tarim River, Xinjiang Uygur, Western China. *Hydrological Processes* **24** (2), 147–159.

Peng, T. R., Huang, C. C., Wang, C. H., Liu, T. K., Lu, W. C. & Chen, K. Y. 2012 Using oxygen, hydrogen, and tritium isotopes to assess pond water's contribution to groundwater and local precipitation in the pediment tableland areas of northwestern Taiwan. *Journal of Hydrology* **450–451**, 105–116.

Porhemmat, J., Nakhaei, M., Dadgar, M. A. & Biswas, A. 2018 Investigating the effects of irrigation methods on potential groundwater recharge: a case study of semiarid regions in Iran. *Journal of Hydrology* **565**, 455–466.

Richards, L. A., Magnone, D., Boyce, A. J., Casanueva-Marenco, M. J., van Dongen, B. E., Ballentine, C. J. & Polya, D. A. 2018 Delineating sources of groundwater recharge in an arsenic affected Holocene aquifer in Cambodia using stable isotope based mixing models. *Journal of Hydrology* **557**, 321–333.

Riley, D., Mieno, T., Schoengold, K. & Brozović, N. 2019 The impact of land cover on groundwater recharge in the High Plains: an application to the Conservation Reserve Program. *Science of The Total Environment* **696**, 133871.

Scanlon, B. R., Keese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, W. M. & Simmers, I. 2006 Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes* **20** (15), 3335–3370.

Shakya, B. M., Nakamura, T., Shrestha, S. D. & Nishida, K. 2019 Identifying the deep groundwater recharge processes in an intermountain basin using the hydrogeochemical and water isotope characteristics. *Hydrology Research* **50** (5), 1216–1229.

Shukla, A. K., Ojha, C. S. P., Mijic, A., Buytaert, W., Pathak, S., Garg, R. D. & Shukla, S. 2018 Population growth, land use and land cover transformations, and water quality nexus in the Upper Ganga River basin. *Hydrology and Earth System Sciences* **22** (9), 4745–4770.

Sklash, M. G. & Farvolden, R. N. 1979 The role of groundwater in storm runoff. *Journal of Hydrology* **43** (1–4), 45–65.

Steward, D. R. & Allen, A. J. 2016 Peak groundwater depletion in the High Plains Aquifer, projections from 1930 to 2110. *Agricultural Water Management* **170**, 36–48.

Sun, C. J. 2015 *Characteristics of Streamflow Composition and Precipitation Vapor Sources in the Mountains of the Tarim River Basin*. Xinjing Institute of Ecology and Geography, Chinese Academy of Sciences.

Taylor, R. G., Scanlon, B., Doll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., Konikow, L., Green, T. R., Chen, J. Y., Taniguchi, M., Bierkens, M. F. P., MacDonald, A., Fan, Y., Maxwell, R. M., Yechieli, Y., Gurdak, J. J., Allen, D. M., Shamsudduha, M., Hiscock, K., Yeh, P. J. F., Holman, I. & Treidel, H. 2013 Ground water and climate change. *Nature Climate Change* **3** (4), 322–329.

Tweed, S., Leblanc, M., Cartwright, I., Favreau, G. & Leduc, C. 2011 Arid zone groundwater recharge and salinisation processes; an example from the Lake Eyre Basin, Australia. *Journal of Hydrology* **408** (3–4), 257–275.

Wang, P., Yu, J. J., Zhang, Y. C. & Liu, C. M. 2013 Groundwater recharge and hydrogeochemical evolution in the Ejina Basin, northwest China. *Journal of Hydrology* **476**, 72–86.

Wang, T. Y., Wang, P., Zhang, Y. C., Yu, J. J., Du, C. Y. & Fang, Y. H. 2019 Contrasting groundwater depletion patterns induced by anthropogenic and climate-driven factors on Alxa Plateau, northwestern China. *Journal of Hydrology* **576**, 262–272.

Wang, W. H., Chen, Y. N. & Wang, W. R. 2020 Groundwater recharge in the oasis-desert areas of northern Tarim Basin, northwest China. *Hydrology Research* **51**, 1506–1520.

Wang, W. R., Chen, Y. N., Wang, W. H., Jiang, J. X., Cai, M. & Xu, Y. J. 2021 Evolution characteristics of groundwater and its response to climate and land-cover changes in the oasis of dried-up river in Tarim Basin. *Journal of Hydrology* **594**, 125644.

Wang, W. R., Chen, Y. P., Wang, W. H., Yang, Y. H., Hou, Y. F., Zhang, S. & Zhu, Z. Y. 2022 Assessing the influences of land use change on groundwater hydrochemistry in an oasis-desert region of Central Asia. *Water* **14**, 651.

Xue, L. Q., Wei, Q. & Wei, G. H. 2019 Coupled simulation of surface water and groundwater in the main stream of Tarim River. *Journal of Hohai University (Natural Sciences)* **47** (3), 195–201 (in Chinese).

Yin, L., Hu, G., Huang, J., Wen, D., Dong, J., Wang, X. & Li, H. 2011 Groundwater-recharge estimation in the Ordos Plateau, China: comparison of methods. *Hydrogeology Journal* **19** (8), 1563–1575.

Zeng, Y. Y., Zhou, J. L., Nai, W. H., Li, L. & Tan, P. F. 2020 Hydrogeochemical processes of groundwater formation in the Kashgar River Basin, Xinjiang. *Arid Zone Research* **37**, 541–550 (in Chinese).

Zhang, X., Zhang, L., He, C., Li, J., Jiang, Y. & Ma, L. 2014 Quantifying the impacts of land use/land cover change on groundwater depletion in Northwestern China–a case study of the Dunhuang oasis. *Agricultural Water Management* **146**, 270–279.

Zhao, Z. Y. 2006 *Landscape Pattern Changes and its Ecological Response in Delta Oasis of Weigan River*. University of Chinese Academy of Sciences, China.

First received 14 April 2021; accepted in revised form 1 April 2022. Available online 12 April 2022