Hydrochemical characteristics and evolution of groundwater in the dried-up river oasis of the Tarim Basin, Central Asia postprint

Authors: WANG Wanrui, CHEN Yaning, WANG Weihua, XIA Zhenhua, Xiaoyang Li, Patient M KAYUMBA, CHEN Yaning

Date: 2021-11-10T00:00:00+00:00

Abstract

Intense human activities in arid areas have great impacts on groundwater hydrochemical cycling by causing groundwater salinization. The spatiotemporal distributions of groundwater hydrochemistry are crucial for studying groundwater salt migration, and also vital to understand hydrological and hydrogeochemical processes of groundwater in arid inland oasis areas. However, due to constraints posed by the paucity of observation data and intense human activities, these processes are not well known in the dried-up river oases of arid areas. Here, we examined spatiotemporal variations and evolution of groundwater hydrochemistry using data from 199 water samples collected in the Wei-Ku Oasis, a typical arid inland oasis in Tarim Basin of Central Asia. As findings, groundwater hydrochemistry showed a spatiotemporal dynamic, while its spatial distribution was complex. TDS and $ $18O of river water in the upstream increased from west to east, whereas ion concentrations of shallow groundwater increased from northwest to southeast. Higher TDS was detected in spring for shallow groundwater and in summer for middle groundwater. Pronounced spatiotemporal heterogeneity demonstrated the impacts of geogenic, climatic, and anthropogenic conditions. For that, hydrochemical evolution of phreatic groundwater was primarily controlled by rock dominance and evaporation-crystallization process. Agricultural irrigation and drainage, land cover change, and groundwater extraction reshaped the spatiotemporal patterns of groundwater hydrochemistry. Groundwater overexploitation altered the leaking direction between the aquifers, causing the interaction between saltwater and freshwater and the deterioration of groundwater environment. These findings could provide an insight into groundwater salt migration under human activities, and hence be significant in groundwater quality management in arid inland oasis areas.

Full Text

Preamble

Hydrochemical characteristics and evolution of groundwater in the dried-up river oasis of the Tarim Basin, Central Asia

WANG Wanrui[1,2], CHEN Yaning[1*], WANG Weihua[1], XIA Zhenhua[1], LI Xiaoyang[1,2], Patient M KAYUMBA[1,2]

[1]State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China

[2]University of Chinese Academy of Sciences, Beijing 100000, China

Abstract: Intense human activities in arid areas have great impacts on groundwater hydrochemical cycling by causing groundwater salinization. The spatiotemporal distributions of groundwater hydrochemistry are crucial for studying groundwater salt migration and vital to understanding hydrological and hydrogeochemical processes in arid inland oasis areas. However, due to constraints posed by the paucity of observation data and intense human activities, these processes are not well known in the dried-up river oases of arid areas. Here, we examined spatiotemporal variations and evolution of groundwater hydrochemistry using data from 199 water samples collected in the Wei-Ku Oasis, a typical arid inland oasis in the Tarim Basin of Central Asia. Our findings revealed that groundwater hydrochemistry showed spatiotemporal dynamics, while its spatial distribution was complex. TDS and $\delta^{18}O$ of river water in the upstream increased from west to east, whereas ion concentrations of shallow groundwater increased from northwest to southeast. Higher TDS was detected in spring for shallow groundwater and in summer for middle groundwater. Pronounced spatiotemporal heterogeneity demonstrated the impacts of geogenic, climatic, and anthropogenic conditions. Hydrochemical evolution of phreatic groundwater was primarily controlled by rock dominance and evaporation-crystallization processes. Agricultural irrigation and drainage, land cover change, and groundwater extraction reshaped the spatiotemporal patterns of groundwater hydrochemistry. Groundwater overexploitation altered the leaking direction between aquifers, causing interaction between saltwater and freshwater and deterioration of the groundwater environment. These findings provide insight into groundwater salt migration under human activities and are significant for groundwater quality management in arid inland oasis areas.

Keywords: spatiotemporal variations; groundwater hydrochemistry; hydrochemical evolution; human activities; dried-up river oasis; Tarim Basin

1 Introduction

Groundwater plays a critical role in socio-economic development and eco-environmental protection in arid areas due to scarce precipitation and deficient surface water (Lezzaik et al., 2018; Erler et al., 2019; Jasechko et al., 2021), especially in arid inland oasis areas (Wang et al., 2021). In recent decades, groundwater depletion and salinization in arid areas have led to a series of hydrological and ecological havocs owing to climatic variations and human activities that challenge local water and ecological security (Zhang et al., 2014; Asoka et al., 2017; de Graaf et al., 2019; Chen et al., 2020; Kulmatov et al., 2020; Zhao et al., 2021). Groundwater salinization can affect public health, soil fertility, vegetation growth, and renewable groundwater resources (Tweed et al., 2011; Fuchs et al., 2019; Jia et al., 2020). Groundwater hydrochemistry is very important in biogeochemical cycling as it may influence freshwater utilization and ecological functioning of surface water and groundwater in arid areas (Cary et al., 2015; Obeidat et al., 2021). Additionally, the spatial distributions of dissolved ion concentrations in groundwater could provide insight into the origin, migration pathways, and evolution of groundwater salt (Liu et al., 2018; Wang et al., 2018), which are helpful for understanding hydrological and hydrogeochemical cycling in arid areas (Fuchs et al., 2019; Wu et al., 2020; Shen et al., 2021). Therefore, there is a need to improve our understanding of hydrochemical characteristics and evolution of groundwater influenced by intense human activities in arid inland oasis areas.

The Tarim River Basin, the largest inland river basin in Xinjiang Uygur Autonomous Region of China, is located in the arid inland area of Central Asia and represents the core area for constructing the "Silk Road Economic Belt" (Chen et al., 2019; Wang et al., 2021). In the last 30 years, continuous intensification of farmland expansion and population growth, groundwater overexploitation, and increased surface water diversion from the river for irrigation have caused the river to dry up, phreatic decline, groundwater environment deterioration, ecological degradation, and desertification in the oasis-desert regions of the Tarim Basin (Wang et al., 2013; Xiao et al., 2015; Wang et al., 2020). Accordingly, deterioration of the groundwater environment in arid oases has influenced hydrogeochemical and ecological processes, plant communities, and soil salinization (Liu et al., 2018; Jia et al., 2020; Noshadi et al., 2020). Thus, ecological restoration of arid inland oasis areas should be based on improvement of the groundwater environment, focusing on spatiotemporal characteristics and evolution mechanisms of groundwater hydrochemistry (Wang et al., 2013). Nevertheless, due to observation data scarcity and complex interaction between surface water and groundwater following intense human activities, hydrochemical evolution and migration mechanisms of groundwater remain poorly understood in the Tarim River Basin. These gaps may affect implementation of sustainable groundwater resources management and ecological restoration (Chen et al., 2019; Zeng et al., 2020).

Based on hydrochemical and isotopic techniques, remote sensing inversion, and hydrological models, previous studies in arid inland oasis areas mainly focused on the origin and age (Ma et al., 2013), spatial distribution and temporal variation (Gates et al., 2008; Hasan et al., 2011; Pant et al., 2018), and evolution mechanism and migration (Wang et al., 2013; Huang et al., 2017) of hydrochemical components for phreatic groundwater and confined water. Additionally, the fresh-salt water interaction between phreatic groundwater and confined water has been analyzed (Liu et al., 2018; Zeng et al., 2020). The impacts of climate change and human activities on groundwater hydrochemistry in arid inland areas have also been studied (Xiao et al., 2015; Wang et al., 2021). Several mechanisms could control groundwater hydrochemistry, including flushing, evaporation-condensation, dissolution and leaching, cation exchange-adsorption, and mixing (Xiao et al., 2015; Wang et al., 2018; Li et al., 2019; Zeng et al., 2020). Groundwater hydrochemistry in arid inland areas may be affected by climatic and hydrogeological conditions, groundwater recharge, land cover types, groundwater exploitation, and agricultural activities among others (Scanlon et al., 2006; Kaur et al., 2019; Riley et al., 2019; Jia et al., 2020). Yet, the spatiotemporal heterogeneity and dominant factors of groundwater hydrochemistry have not been thoroughly investigated in the dried-up river oasis of the Tarim Basin, particularly the impact of intense human activities.

Here, we analyzed spatiotemporal variations and evolution of groundwater hydrochemistry using data from 199 water samples collected from August 2018 to August 2019 in the Wei-Ku Oasis, a typical dried-up river oasis of the Tarim Basin in Central Asia. The specific objectives of this study are to: (1) examine spatiotemporal variations of groundwater hydrochemistry; (2) analyze dominant factors influencing groundwater hydrochemistry evolution; and (3) explore groundwater salt migration under human influence. The results are expected not only to enhance understanding of groundwater salt migration under intense human activities but also to help improve groundwater management in the Tarim Basin, thereby preventing groundwater environment deterioration.

2.1 Study Area

The Tarim River Basin (73°24 -93°39 E, 34°48 -43°21 N), surrounded by the Tianshan Mountains and the Kunlun Mountains in Xinjiang Uygur Autonomous Region, covers an area of 1.02×10^{6} km^2 and is the largest inland river basin in Northwest China [Figure 1: see original paper]. The Wei-Ku Oasis (82°05 -83°28 E, 40°54 -41°51 N), located in the middle and lower reaches of the Weigan-Kuqa River Basin in the northern Tarim Basin, covers an area of 7.10×10^{3} km^2, with elevation ranging from 945 to 1147 m above sea level. It mainly includes the Weigan River and Kuqa River; the Weigan River is composed of the Kizil River, Muzhate River, Televichuk River, Kapusilang River, and Karasu River. The study region is characterized by a temperate arid continental climate. The annual mean air temperature and mean annual precipitation values are 11.4°C and 74.6 mm, respectively (data from the Chinese National Meteorological Center; http://data.cma.cn/). The highest air temperature is generally recorded in July or August, and the lowest in January [Figure 2: see original paper]. Precipitation mainly occurs from May to September, accounting for more than 76% of total annual precipitation, with peak rainfall in June or July. The annual runoff flowing into the Wei-Ku Oasis is about 31.2×10^{8} m^3 (more than 90% used for irrigation); it has three peaks due to reservoir regulation, occurring in March, July, and November. The groundwater level depth of the oasis ranges from 2 to 6 m, and groundwater level generally declines from northwest to southeast (Wang et al., 2021).

The Wei-Ku Oasis is a plain region with unconsolidated Quaternary sediments, comprising interstratified pebbly sandstone, fine sandstone, sandy gravel, silty fine sandstone, sandstone, and fine siltstone, forming porous aquifers and aquitards [Figure 1c: see original paper] (Wang et al., 2021). Within the oasis, from the northern piedmont plain to the southern alluvial plain, rock particle size ranges from coarse to fine, the aquifer system gradually transitions from single structure to multi-layer structure, and groundwater level depth declines gradually. The aquifer sediments are pebbly sandstone and sandy gravel in the piedmont plain. The pebbly sandstone transitions to silty fine sandstone in the middle alluvial-diluvial plain and fine sandstone in the alluvial plain [FIGURE:1c; Wang et al., 2021]. The dominant natural plant species are *Sophora alopecuroides*, *Tamarix* spp., *Populus euphratica*, *Karelinia caspica*, *Phragmites communis*, *Halostachys caspica*, *Glycyrrhiza* sp., and *Alhagi pseudalhagi*. Land cover types within the Wei-Ku Oasis were dominated by cropland (62.5%), grassland (17.9%), and bare land (13.0%) in 2018. Cereal crops mainly included wheat and corn, while dominant economic crops were cotton, sugar beet, and rapeseed (Chen et al., 2019).

2.2 Data and Methods

Surface water and groundwater samples were collected from August 2018 to August 2019 along the Weigan River and Kuqa River, as well as within the Wei-Ku Oasis [Figure 1b: see original paper], covering three seasons (spring, summer, and autumn). During the sampling period, precipitation samples were also collected after each day of precipitation (rainfall and snowfall) from two sites in the upper reaches of the Weigan-Kuqa River Basin [Figure 1b: see original paper]. River water samples were collected from the upstream of Weigan River and Kuqa River, along with 6 reservoir water samples obtained from the oasis. Groundwater was sampled from pumped wells (domestic, irrigation, and industrial wells) and regularly used boreholes within the Wei-Ku Oasis. We grouped groundwater samples into three classes based on hydrogeological conditions (Wang et al., 2013): shallow groundwater (well depth <20 m), middle groundwater (well depth 20–100 m), and deep groundwater (well depth >100 m).

A total of 199 water samples were collected for hydrochemical and stable isotope analyses, including 23 precipitation samples, 101 surface water samples (95 river water and 6 reservoir samples), and 75 groundwater samples (53 shallow, 21 middle, and 1 deep). All samples were first filtered through a 0.22- m filter, then immediately stored in 100 mL polyethylene bottles, wrapped with parafilm to avoid evaporation fractionation, and refrigerated at 4°C until laboratory analysis. All hydrochemical components and stable isotopes were measured at the State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. Major cations and anions (chloride, sulfate, sodium, potassium, magnesium, and calcium) were determined by ion chromatograph (Dionex ICS-5000, Thermo Fisher Scientific, Massachusetts, USA), while HCO_3^- and CO_3^{2-} were analyzed using titration methods. Analytical precision of major ions was below 1%, with detection limit of 0.1 mg/L. Ionic charge balance errors for all samples were within $±$10%. Electrical conductivity (EC) and temperature were measured in the field using a conductivity meter (YSI ProPlus, Yellow Springs Instrument Inc., Ohio, USA), with EC measurement precision of 0.01 S/cm (Wang et al., 2020). The δ^{18}O and δ^2H of water samples were measured using a liquid water isotope analyzer (LGR DLT-100, Los Gatos Research Inc., California, USA) and reported relative to Vienna Standard Mean Ocean Water (VSMOW) in delta per million (δ, ‰). Measurement precisions for δ^2H and δ^{18}O were $±$0.8‰ and $±$0.1‰, respectively.

Meteorological data (air temperature and precipitation) were obtained from the Chinese National Meteorological Information Centre (http://cdc.cma.gov.cn), and runoff data for mountainous tributary outlets were collected from the Weigan River Basin Authority, Xinjiang, China. Statistical analyses were conducted using SPSS (version 22.0), ArcGIS (version 10.5), MATLAB (version R2018a), and Origin (version 2017). The inverse distance weighting method interpolated hydrogeochemical and meteorological data into 250 m grid data. Piper (1944) and Gibbs (1970) plots were used to further elaborate findings.

3.1 General Characterization of Hydrochemistry

Stable isotope values (δ^2H and δ^{18}O) for precipitation, surface water, and groundwater are shown in Figure 3 [Figure 3: see original paper]. The δ^2H and δ^{18}O values of different water components presented a large range and differed significantly among water components. Generally, stable isotope values became progressively more depleted from reservoir water to precipitation, river water, and groundwater, which may be attributed to differences in evaporation and water sources (Wang et al., 2020). Both δ^{18}O and δ^2H values of precipitation exhibited a relatively wide range, varying from -15.8‰ to 0.1‰ and from -116.3‰ to 11.5‰, respectively. Mean isotopic values of precipitation (δ^{18}O = -7.6‰ and δ^2H = -48.0‰) in our study area were higher than those at the Urumqi station in northern Xinjiang (δ^{18}O = -10.7‰ and δ^2H = -72.8‰, from the Global Network of Isotopes in Precipitation (GNIP)), but lower than those at the Hotan station in southern Xinjiang (δ^{18}O = -5.5‰ and δ^2H = -32.6‰, from GNIP), indicating complex water vapor sources and local recycling processes (Chen et al., 2019).

Surface water data were located near the global meteoric water line (GMWL; $\delta^2H = 8\delta^{18}O + 10$; Craig, 1961), while most groundwater samples were located above the GMWL [Figure 3: see original paper]. Stable isotope values of river water (mean δ^2H = -53.6‰ and mean δ^{18}O = -8.9‰) during the sampling period were lower than precipitation values, likely due to recharge from glacier/snow meltwater and groundwater in the upstream (Chen et al., 2019). Isotope values of reservoir water ranged from -9.3‰ to -5.2‰ for $\delta^{18}O$ (mean $\delta^{18}O$ = -6.5‰) and from -57.9‰ to -35.3‰ for $\delta^{2}H$ (mean $\delta^{2}H$ = -42.6‰), which were higher than river water values due to strong evaporation fractionation in this arid region (Wang et al., 2013). Furthermore, mean values of $\delta^{18}O$ and $\delta^{2}H$ for shallow groundwater (from -12.2‰ to -7.5‰ and from -83.9‰ to -49.7‰, respectively) were similar to those of middle groundwater ($\delta^{18}O$ ranging from -10.3‰ to -8.4‰ and $\delta^{2}H$ ranging from -73.9‰ to -59.3‰) and deep groundwater ($\delta^{18}O$ = -9.5‰ and $\delta^{2}H$ = -61.2‰) in the Wei-Ku Oasis.

Table 1 presents hydrochemical results for precipitation, surface water, and groundwater. Generally, main dissolved ion concentrations in groundwater were significantly higher than in surface water, whereas ion concentrations in precipitation were lower compared to surface water (Cl^-, SO_4^{2-}, Na^+, K^+, Mg^{2+}, and Ca^{2+}; Table 1), mainly due to strong evaporative concentration, mineral dissolution, and leaching (Jia et al., 2020). Precipitation samples had low ion concentrations and salinity (Cl^- = 4.5 mg/L and TDS = 91.7 mg/L), with HCO_3-Ca hydrochemical type [Figure 4a: see original paper]. River water samples were slightly alkaline (mean pH = 7.95) and freshwater (TDS = 379.4 mg/L). Cl^- concentration ranged from 1.6 to 146.5 mg/L, and EC varied from 208 to 1206 S/cm, with SO_4-HCO_3-Ca chemistry. Compared to river water, reservoir water in the oasis had slightly higher ion concentrations and salinity (EC 665-1361 S/cm and Cl^- 67.7-173.3 mg/L), with identical HCO_3-SO_4-Ca chemistry, indicating direct river water origin but strong evaporation.

Middle groundwater samples were intermediate between shallow and deep groundwater samples [Figure 4b: see original paper], providing further evidence for close water relationships among aquifers in this oasis. Groundwater pH generally ranged from 7.48 to 8.42, indicating slightly alkaline character resulting from extremely arid conditions and slow groundwater flow (Wang et al., 2013). Groundwater samples exhibited high hydrochemical variability, with TDS ranging from 314.0 to 24,156.4 mg/L (varying from freshwater to saline water), suggesting great variation in groundwater quality. Vertically, highly saline groundwater was observed in the shallow aquifer, whereas low-salinity groundwater was mostly found in the deep aquifer (Table 1). Most shallow groundwater had relatively high salinity and ion concentrations (mean TDS = 7560.3 mg/L and mean Cl^- = 2875.2 mg/L), with Cl-SO_4-Na-Mg hydrochemical type. Middle groundwater had similar hydrochemical type (Cl-SO_4-Na-Mg-Ca) compared to shallow groundwater, with average TDS of 1279.5 mg/L, implying direct recharge from the overlying shallow aquifer (Zeng et al., 2020). Deep groundwater was dominated by Na and Ca cations and HCO_3 and SO_4 anions, with lower ion concentrations and salinity (TDS = 314.0 mg/L) and HCO_3-SO_4-Cl-Na-Ca chemistry (Table 1; [Figure 4b: see original paper]). The large difference in ion concentrations among shallow, middle, and deep groundwater samples reveals that saline shallow groundwater could leak downward to confined water and undergo mixing between salt and fresh water (Liu et al., 2018).

3.2 Spatial Variations of Hydrochemistry

Salinity of river water and shallow groundwater generally increased along flow paths from recharge to discharge areas in our study region [FIGURES:5 and 6], connoting evaporation occurrence (Wang et al., 2013; Liu et al., 2018). Figure 5 [Figure 5: see original paper] shows spatial distributions of TDS and $\delta^{18}O$ for river water in the upstream of the Weigan-Kuqa River Basin. TDS and $\delta^{18}O$ values of river water presented obvious spatial heterogeneity. The $\delta^{18}O$ of river water in the upstream ranged from -10.9‰ to -6.4‰, with values much lower in the western part than in the eastern part, most probably due to larger snow area in the west, resulting in relatively low isotopes from snow meltwater recharge (Wang et al., 2020). Similarly, TDS values ranged from 133.7 to 680.9 mg/L and were lower in the west (Muzhate River) than in the east (Kuqa River). Overall, TDS concentration of river water in the upstream increased from west to east.

As shown in Figures 6 and 7, hydrochemical components of shallow and middle groundwater across the Wei-Ku Oasis varied among sampling sites, exhibiting spatial heterogeneity probably due to lithology, underlying surface conditions, and human activities [FIGURE:1c; Wang et al., 2021]. Generally, concentrations of hydrochemical components (TDS, Cl^-, $SO_4{}^{2-}$, Na^+, K^+, Ca^{2+}, and Mg^{2+}) in shallow groundwater showed horizontal zoning and increased along the regional flow direction from northwest to southeast [Figure 6: see original paper]. TDS of shallow groundwater samples ranged from 1021.9 to 24,134.6 mg/L. High dissolved ion concentrations for shallow groundwater were observed in several sporadic areas in the southeastern and central parts, whereas low values were distributed in the northwestern part. Overall, the spatial distribution pattern of dissolved ion concentrations in shallow groundwater was consistent across the oasis but lower in the northwest than in the southeast [Figure 6: see original paper], which could be explained by groundwater depth, mineral dissolution, agricultural irrigation, and drainage in this region (Pant et al., 2018).

Figure 7 [Figure 7: see original paper] shows that spatial variation trends of middle groundwater hydrochemistry were not obvious in the oasis, and distribution patterns differed among ions, probably due to spatial heterogeneity of lithology and groundwater exploitation [Figure 1c: see original paper] (Wang et al., 2013). TDS of middle groundwater ranged from 561.0 to 2934.8 mg/L. Spatial distribution patterns of TDS, Cl^-, and $SO_4{}^{2-}$ of middle groundwater were consistent and much higher in the central part than in surrounding areas [Figure 7: see original paper]. However, cation concentrations (Na^+, K^+, Mg^{2+}, and Ca^{2+}) of middle groundwater did not exhibit obvious spatial variation trends. For middle groundwater within the oasis, recording sites with highest and/or lowest values varied significantly among ions. Among major cations, Ca^{2+} concentration of middle groundwater was higher in the western part than in the eastern part, with maximum values observed near Xinhe County. Mg^{2+} concentration was much higher in the central and western parts, while Na^+ and K^+ concentrations were relatively high in the central and southwestern parts.

3.3 Seasonal Variations of Hydrochemistry

Figure 8 [Figure 8: see original paper] exhibits seasonal variations of hydrochemical components (TDS, Cl^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, and Mg^{2+}) for surface water and groundwater. Dissolved ion concentrations fluctuated during the sampling period, showing significant seasonal variations [Figure 8: see original paper]. Except for K^+, seasonal variation patterns of major dissolved ion concentrations (Ca^{2+}, Mg^{2+}, Na^+, Cl^-, and SO_4^{2-}) for river water in the upstream were consistent. The lowest values of Cl^-, SO_4^{2-}, Na^+, Mg^{2+}, and Ca^{2+} concentrations were observed in summer (26.7, 75.5, 23.9, 15.7, and 72.2 mg/L, respectively), whereas highest values were detected in spring (67.4, 162.7, 42.2, 25.0, and 87.0 mg/L, respectively). Nonetheless, highest and lowest K^+ concentrations were observed in autumn and spring, respectively [Figure 8e: see original paper]. In contrast, seasonal differences of Cl^-, SO_4^{2-}, Na^+, and Mg^{2+} concentrations of river water were significant, while K^+ and Ca^{2+} concentrations varied slightly among seasons.

As shown in Figure 8, ion concentrations of middle groundwater were much lower than those of shallow groundwater across the Wei-Ku Oasis in each season. Hydrochemical components of shallow and middle groundwater varied significantly among seasons, revealing seasonal variations that may be related to water sources and water-salt interaction between aquifers (Zeng et al., 2020). Except for Na^+ and Mg^{2+}, seasonal variation patterns of major dissolved ions (Cl^-, SO_4^{2-}, K^+, and Ca^{2+}) of middle groundwater were consistent. However, seasonal variations of different ion concentrations of shallow groundwater differed [Figure 8: see original paper]. For middle groundwater, Cl^- and Ca^{2+} concentrations were slightly higher in spring (Cl^- = 280.9 mg/L and Ca^{2+} = 160.4 mg/L) than in summer (Cl^- = 258.7 mg/L and Ca^{2+} = 140.4 mg/L), whereas Na^+ and Mg^{2+} concentrations were lower in spring (Na^+ = 175.6 mg/L and Mg^{2+} = 80.7 mg/L) than in summer (Na^+ = 232.6 mg/L and Mg^{2+} = 88.2 mg/L). For shallow groundwater, highest and lowest values of Cl^-, SO_4^{2-}, and Na^+ concentrations were observed in spring and summer, respectively. Meanwhile, K^+ and Ca^{2+} concentrations were highest in autumn (Ca^{2+} = 514.1 mg/L and K^+ = 28.9 mg/L) and lowest in summer (Ca^{2+} = 397.5 mg/L and K^+ = 18.1 mg/L), and Mg^{2+} concentration was highest in spring (358.3 mg/L) but lowest in autumn (309.0 mg/L) [Figure 8: see original paper].

4.1 Spatiotemporal Variation Characteristics of Hydrochemistry

Mean ion concentrations (Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-}) of river water in our study area were much higher than the global average (Meybeck, 2003) but lower than those in the Tarim River (Table 2), probably reflecting lower precipitation and stronger evaporation in the Tarim River Basin (Pant et al., 2018). Similarly, Ca^{2+}, Cl^-, and SO_4^{2-} concentrations of river water in the Wei-Ku Oasis were higher than those in the Shule River, Heihe River, and Shiyang River, while

Mg^{2+} concentration was higher than in the Shule River but lower than in the Heihe River and Shiyang River (Table 2). Such findings may be attributed to different water sources and evaporation (Wang et al., 2013; Liu et al., 2018). Dissolved ion concentrations of groundwater samples displayed wide ranges, indicating groundwater had undergone different hydrogeochemical processes within the aquifer system (Liu et al., 2018). Another reason may be water exchange between confined water and higher-salinity phreatic water in the oasis (Zeng et al., 2020). In recent decades, farmland expansion and population increase have resulted in sharply increased water consumption. Due to limited surface water resources, agricultural irrigation water consumption increased and groundwater level decreased, which in turn caused phreatic water leakage downward into the confined aquifer (Wang et al., 2021). Moreover, ion concentrations of water samples varied significantly among different water components and were much higher in shallow groundwater than in river water and deep groundwater (Table 1). Higher dissolved ion concentrations in shallow groundwater may be attributed to high temperature and surface water infiltration promoting erosion, dissolution, and leaching of soluble minerals within the soil profile, causing large amounts of soluble salts to migrate to shallow aquifers (Tweed et al., 2011; Ma et al., 2013; Huang et al., 2017). Additionally, large amounts of liquid and solid wastes from nearby cropland, settlements, and factories were directly or indirectly discharged into aquifers, critically affecting groundwater hydrochemical components in the oasis (Sharma et al., 2012; Pant et al., 2018).

Spatial heterogeneity of groundwater hydrochemical components was evident in the oasis [FIGURES:6 and 7], probably overlapping with soluble minerals, groundwater depth, and cropland [FIGURES:1 and 9] (Pant et al., 2018). Most major ion concentrations of shallow groundwater within the Wei-Ku Oasis followed the same increasing trend along the flow direction from northwest to southeast [Figure 6: see original paper]. Higher shallow groundwater hydrochemistry concentrations in the southeast were found mainly in desert regions with relatively low groundwater depth [Figure 9: see original paper], representing areas most affected by strong evaporation (Huang et al., 2017). In contrast, lower shallow groundwater hydrochemistry concentrations in the northwestern oasis were considered outcomes of irrigation and drainage processes as well as groundwater extraction (Thomas et al., 2015), due to stronger dilution by agricultural irrigation water and greater salt discharge by agricultural drainage canals (Wang et al., 2018; Wang et al., 2021). Moreover, higher TDS values of middle groundwater were found in the central part of the Wei-Ku Oasis [Figure 7: see original paper], which may be related to land use types and groundwater overexploitation. Cultivated area expansion has caused groundwater overexploitation in arid oases (Huang et al., 2017; Wang et al., 2021). Groundwater overexploitation could alter leaking direction between aquifers and redistribute soluble salt within aquifers (Zeng et al., 2020; Wang et al., 2021).

Concentrations of most major ions in groundwater varied significantly among seasons in the arid oasis [Figure 8: see original paper], closely related to air temperature, runoff, groundwater depth, and agricultural activities (Wang et al., 2013), suggesting that seasonal variation characteristics of groundwater salt concentration can reflect temporal variations of recharge sources and methods, as well as hydrological and hydrogeochemical processes (Beal et al., 2019; Wang et al., 2021). Hydrochemical values of river water in the upstream were lower in summer and higher in spring, contradicting seasonal variations of rainfall and runoff. Heavy runoff [Figure 2: see original paper] generated from coupled effects of intense glacier/snow melting and high rainfall during the wet season was responsible for mildly low concentrations of hydrochemical components in surface water (stronger dilution effect) (Zhou, 2015; Liu et al., 2018). Additionally, TDS values of shallow groundwater were higher in spring than in summer and autumn, which may be ascribed to infiltration from agricultural irrigation water following application of chemical fertilizers and pesticides, mineral dissolution and soil salinity, and dumping of post-harvest residues (flood irrigation in winter and spring) (Sharma et al., 2012; Wang et al., 2021). Furthermore, higher TDS values of middle groundwater were observed in summer [Figure 8: see original paper], closely related to cropland area and groundwater level depth in summer [Figure 9: see original paper], suggesting accumulated influences of human activities (agricultural irrigation and groundwater extraction) (Pant et al., 2018; Castellano et al., 2019).

4.2 Dominant Factors of Groundwater Hydrochemistry Evolution

The diagram of weight ratios between TDS and $Na^+/(Na^++Ca^{2+})$ or $Cl^-/(Cl^-+HCO_3^-)$ exhibited major mechanisms controlling hydrochemistry of natural water bodies (Gibbs, 1970), including rock dominance, precipitation dominance, and evaporation-crystallization processes (Wang et al., 2013) [Figure 10: see original paper]. The weight ratio $Na^+/(Na^++Ca^{2+})$ of river water in the upstream of the Wei-Ku Oasis was lower than 0.5, with low salinity, indicating that hydrochemical compositions of river water are primarily controlled by rock dominance. Regarding natural mechanisms controlling groundwater hydrochemistry, obvious differences existed among aquifers in the Wei-Ku Oasis. Hydrochemical compositions of phreatic water were mainly controlled by rock dominance and evaporation-crystallization processes, similar to deep groundwater hydrochemistry primarily influenced by rock dominance. However, the weight ratio $Na^+/(Na^++Ca^{2+})$ of some middle groundwater samples was higher than 0.6 [Figure 10: see original paper], suggesting additional mechanisms contribute to middle groundwater hydrochemical compositions in the arid oasis (e.g., human activities) (Zeng et al., 2020). Major cations and TDS of deep groundwater in the oasis were similar to those of confined groundwater in the upstream, again reflecting deep groundwater hydrochemistry being majorly controlled by rock dominance mechanisms (such as water-rock interactions) (Ma et al., 2013; Pant et al., 2018).

Dissolved species and their relations could reveal solute origin and hydrogeochemical processes (Fisher and Mullican, 1997; Wang et al., 2013). River water samples were mainly located near the Ca end-member and HCO_3+CO_3 end-member, indicating that major ionic compositions were mainly derived from carbonate dissolution (Xiao et al., 2015). Generally, hydrochemical compositions of deep groundwater samples were mainly derived from carbonate dissolution and evaporite, while those of middle groundwater came from carbonate dissolution, and those of shallow groundwater from evaporite dissolution in the Wei-Ku Oasis (Pant et al., 2018; Zeng et al., 2020). Additionally, several geochemical processes such as evaporation-condensation, dissolution and precipitation, cation exchange/adsorption, and mixing would be responsible for different groundwater types (Wang et al., 2013; Li et al., 2019). Phreatic groundwater salinization in the arid oasis may result from increasing ionic concentrations due to evaporation-condensation of recharge water (infiltration from riverbank, canal, reservoir, and irrigation), as well as rock-water interactions, eventually leading to mineral deposition and formation of saturated zones (Wang et al., 2021). Furthermore, the Na^+/Ca^{2+} ratio of groundwater samples increased along the flow path, implying Ca^{2+} loss due to carbonate precipitation and additional Na^+ increase through cation exchange (Tweed et al., 2011; Liu et al., 2018). The mixing process between groundwater and environmental flows within the aquifer system could also play an important role in groundwater hydrochemistry, especially for shallow and middle groundwater, including mixing between groundwater and weakly mineralized surface water, as well as between confined water and high-mineralized phreatic water in some areas (Su et al., 2009; Zeng et al., 2020).

Human activities such as land use changes, groundwater extraction, agricultural irrigation, and drainage have significantly affected hydrochemistry of phreatic and confined water in the Wei-Ku Oasis in recent decades (Xiao et al., 2015; Li et al., 2019). In the Tarim River Basin, evapotranspiration results in evaporite accumulation in the upper soil profile, and inappropriate irrigation regimes can exacerbate soil salinization, leading to widespread soil salinization (Liu et al., 2018; Chen et al., 2019). Wang et al. (2021) reported that soil salinization in irrigated districts was notable due to intense evaporation, long-term irrigation, and relatively shallow groundwater in the Wei-Ku Oasis; they observed soil salt content of 3.98 g/kg in the 0–100 cm depth in 2017. Our findings revealed that cropland area in the oasis depends on river water and groundwater extraction for irrigation and has expanded over decades [Figure 9: see original paper]. Consequently, these activities resulted in irrigation return flow as a dominant recharge source for shallow groundwater.

Vertical infiltration from irrigation water could promote dissolution and leaching of soil salt and soluble minerals by agricultural activities, thus transferring soluble salt into shallow groundwater and increasing ion concentrations (Han et al., 2011). Previous studies observed significant linear correlation between groundwater salinity and soil salinity in agricultural and saline-alkaline land in arid inland oasis areas (Wang et al., 2021), indicating that irrigated cultivation could easily affect groundwater salinity due to intensive irrigation and inefficient drainage. Improved agricultural drainage channels also significantly affected groundwater hydrochemistry, discharging shallow groundwater with high salinity near cultivated land through drainage canals (Table 3), thus decreasing groundwater level and salinity (Wang et al., 2021). A large amount of salt was discharged by drainage canals in the irrigation district, reaching 94.5×10^{4} t in 2015 (Table 3). Furthermore, due to river water deficiency, groundwater (especially confined water) was overexploited for agricultural irrigation during growing seasons over decades, causing groundwater level reduction (Table 3). Therefore, groundwater exploitation intensifies groundwater salinization to some extent (Wang et al., 2013), leading to downward leakage of phreatic groundwater into confined water with declining groundwater levels. This process also promotes mixing and interaction of fresh and saline water among aquifers (Zeng et al., 2020; Wang et al., 2021). Relevant research has shown that shallow groundwater depth and intense evaporation are primary factors influencing spatial distribution of phreatic groundwater hydrochemistry (Wang et al., 2021).

4.3 Implications for Groundwater Salt Migration Under Human Influence

As mentioned above, spatiotemporal distributions of groundwater hydrochemistry within aquifer systems in arid inland oasis areas provide insight into groundwater salt sources and migration mechanisms under human influence (Wang et al., 2021). Groundwater salt migration is influenced by many factors in arid dried-up river oases, including climate conditions (precipitation and temperature), runoff, hydrogeological conditions, land cover types, groundwater extraction, agricultural irrigation, and drainage (Pant et al., 2018; Porhemmat et al., 2018; Castellano et al., 2019). In the upstream of the Weigan-Kuqa River Basin, salt ions in river water migrate downstream primarily controlled by rock dominance. In the oasis, river water flows into fields for agricultural irrigation through canals and experiences strong evapotranspiration before infiltration, but salt ions can also transfer downward into the soil layer (Chen et al., 2019). Within the vadose zone, soil moisture supplied by infiltration of rain, riverbank, canal, reservoir, and irrigation water could migrate downward to recharge phreatic groundwater by gravity gradient, while soluble ions also migrate downward and accumulate in the phreatic aquifer due to evaporation, surface water dilution, soil salt dissolution, leaching, and cation exchange (Xiao et al., 2015). Soil moisture and salt patterns in irrigated districts were reshaped by long-term irrigated agriculture (Yin et al., 2021). Within the aquifer, phreatic groundwater supplied by surface water infiltration and lateral groundwater flow could leak downward to confined aquifer under water potential gradient due to groundwater overexploitation. Meanwhile, high concentrations of dissolved ions in phreatic groundwater also transfer downward into the confined aquifer, leading to confined water quality deterioration due to interaction of saline and fresh water mainly controlled by evaporation-crystallization processes, rock dominance (strong water-rock interaction), and mixing mechanisms. Thus, large-scale land reclamation and groundwater extraction have dramatically altered groundwater

water-salt migration processes in this region.

5 Conclusions

Spatiotemporal variations and evolution of groundwater hydrochemistry were investigated using data from 199 water samples collected in the Wei-Ku Oasis of the Tarim Basin. Results showed that mean ion concentrations of river water in the Wei-Ku Oasis were much larger than the global average but lower than the Tarim River. Groundwater hydrochemistry showed spatiotemporal dynamics and seasonal differentiation, with complex spatial distribution. Vertically, groundwater ion concentrations decreased with depth. Generally, TDS and $\delta^{18}O$ values of river water in the upstream increased from west to east, while shallow groundwater ion concentrations increased from northwest to southeast. Higher TDS values were found in spring for shallow groundwater and in summer for middle groundwater.

Pronounced spatiotemporal heterogeneity demonstrated impacts of geogenic, climatic, and anthropogenic conditions. Agricultural irrigation and drainage, land cover change, and groundwater extraction reshaped spatiotemporal patterns of groundwater hydrochemistry. Groundwater overexploitation altered leaking direction between phreatic and confined aquifers, causing salt-fresh water interaction and groundwater environment deterioration.

Acknowledgements

This research was funded by the Natural Science Foundation of Xinjiang Uygur Autonomous Region, China (2021D01D01). We thank the Water-salt Monitoring Station of the Weigan River Basin Authority, Xinjiang Uygur Autonomous Region, China. We also appreciate the editors and anonymous reviewers for their time and constructive comments.

References

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

Beal L K, Wong C I, Bautista K K, et al. 2019. Isotopic and geochemical assessment of the sensitivity of groundwater resources of Guam, Mariana Islands, to intra- and inter-annual variations in hydroclimate. *Journal of Hydrology*, 568: 174–183.

Cary L, Petelet-Giraud E, Bertrand G, et al. 2015. Origins and processes of groundwater salinization in the urban coastal aquifers of Recife (Pernambuco, Brazil): A multi-isotope approach. *Science of the Total Environment*, 530: 411–429.

Castellano M J, Archontoulis S V, Helmers M J, et al. 2019. Sustainable intensification of agricultural drainage. *Nature Sustainability*, 2(10): 914–921.

Chen H Y, Chen Y N, Li W H, et al. 2019. Quantifying the contributions of snow/glacier meltwater to river runoff in the Tianshan Mountains, Central Asia. *Global and Planetary Change*, 174: 47–57.

Chen Y N, Hao X M, Chen Y P, et al. 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)

Chen Y N, Zhang X Q, Fang G H, et al. 2020. Potential risks and challenges of climate change in the arid region of northwestern China. *Regional Sustainability*, 1(1): 20–30.

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 R, et al. 2019. Environmental flow limits to global groundwater pumping. *Nature*, 574(7776): 90–94.

Erler A R, Frey S K, Khader O, et al. 2019. Evaluating climate change impacts on soil moisture and groundwater resources within a lake-affected region. *Water Resources Research*, 55(10): 8142–8163.

Feng Q, Liu W, Su Y H, et al. 2004. Distribution and evolution of water chemistry in Heihe River basin. *Environmental Geology*, 45(7): 947–956.

Fisher R S, Mullican III W F. 1997. Hydrochemical evolution of sodium-sulfate and sodium-chloride groundwater beneath the Northern Chihuahuan Desert, Trans-Pecos, Texas, USA. *Hydrogeology Journal*, 5(2): 4–16.

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 Resources Research*, 55(7): 5871–5890.

Gao Y X, Wang G L, Liu H T, et al. 2006. Analysis the interaction between the unconfined groundwater and surface water based on the chemical information along the Shiyang River, northwestern China. *Journal of Arid Land Resources and Environment*, 20(6): 84–88. (in Chinese)

Gates J B, Edmunds W M, Darling W G, et al. 2008. Conceptual model of recharge to southeastern Badain Jaran Desert groundwater and lakes from environmental tracers. *Applied Geochemistry*, 23(12): 3519–3534.

Gibbs R J. 1970. Mechanisms controlling world water chemistry. *Science*, 170: 1088–1090.

Han D M, Song X F, Currell M, et al. 2011. A survey of groundwater levels and hydrogeochemistry in irrigated fields in the Karamay Agricultural Development Area, northwest China: Implications for soil and groundwater salinity resulting from surface water transfer for irrigation. *Journal of Hydrology*, 405: 217–234.

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

Huang T M, Pang Z H, Liu J L, et al. 2017. Groundwater recharge in an arid grassland as indicated by soil chloride profile and multiple tracers. *Hydrological Processes*, 31(5): 1047–1057.

Jasechko S, Seybold H, Perrone D, et al. 2021. Widespread potential loss of streamflow into underlying aquifers across the USA. *Nature*, 591(7850): 391–395.

Jia H, Qian H, Zheng L, et al. 2020. Alterations to groundwater chemistry due to modern water transfer for irrigation over decades. *Science of the Total Environment*, 717: 13717, doi: 10.1016/j.scitotenv.2020.137170.

Kaur L, Rishi M S, Sharma S, et al. 2019. Hydrogeochemical characterization of groundwater in alluvial plains of River Yamuna in Northern India: an insight of controlling processes. *Journal of King Saud University-Science*, 31(4): 1245–1253.

Kulmatov R, Mirzaev J, Abuduwaili J, et al. 2020. Challenges for the sustainable use of water and land resources under a changing climate and increasing salinization in the Jizzakh irrigation zone of Uzbekistan. *Journal of Arid Land*, 12(1): 90–103.

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 J, Yang Q C, Yang Y S, et al. 2019. Isotopic and geochemical interpretation of groundwater under the influences of anthropogenic activities. *Journal of Hydrology*, 576: 685–697.

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

Ma J, He J, Qi S, et al. 2013. Groundwater recharge and evolution in the Dunhuang Basin, northwestern China. *Applied Geochemistry*, 28: 19–31.

Meybeck M. 2003. Global occurrence of major elements in rivers. *Treatise on Geochemistry*, 5(1): 207–223.

Nie Z L, Chen Z X, Cheng X X, et al. 2005. The chemical information of the interaction of unconfined groundwater and surface water along the Heihe River, Northwestern China. *Journal of Jilin University (Earth Science Edition)*, 35(1): 48–53. (in Chinese)

Noshadi M, Fahandej-Saadi S, Sepaskhah A R. 2020. Application of SALTMED and HYDRUS-1D models for simulations of soil water content and soil salinity in controlled groundwater depth. *Journal of Arid Land*, 12: 447–461.

Obeidat M, Awawdeh M, Al-Kharabsheh N, et al. 2021. Source identification of nitrate in the upper aquifer system of the Wadi Shueib catchment area in Jordan based on stable isotope composition. *Journal of Arid Land*, 13(4): 350-374.

Pant R R, Zhang F, Rehman F U, et al. 2018. Spatiotemporal variations of hydrogeochemistry and its controlling factors in the Gandaki River Basin, Central Himalaya Nepal. *Science of the Total Environment*, 622-623: 770-782.

Piper A M. 1944. A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions, American Geophysical Union*, 25(6): 914-928.

Porhemmat J, Nakhaei M, Dadgar M A, et al. 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.

Riley D, Mieno T, Schoengold K, et al. 2019. The impact of land cover on groundwater recharge in the High Plains: An application of the Conservation Reserve Program. *Science of the Total Environment*, 696: 133871, doi: 10.1016/j.scitotenv.2019.133871.

Scanlon B R, Keese K E, Flint A L, et al. 2006. Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes*, 20(15): 3335-3370.

Sharma A, Singh A K, Kumar K. 2012. Environmental geochemistry and quality assessment of surface and subsurface water of Mahi River basin, western India. *Environmental Earth Sciences*, 65(4): 1231-1250.

Shen B B, Wu J L, Zhan S, et al. 2021. Spatial variations and controls on the hydrochemistry of surface waters across the Ili-Balkhash Basin, arid Central Asia. *Journal of Hydrology*, 600: 126565, doi: 10.1016/j.jhydrol.2021.126565.

Su Y H, Zhu G F, Feng Q, et al. 2009. Environmental isotopic and hydrochemical study of groundwater in the Ejina Basin, northwest China. *Environmental Geology*, 58(3): 601-614.

Thomas J, Joseph S, Thrivikramji K P. 2015. Hydrochemical variations of a tropical mountain river system in a rain shadow region of the southern Western Ghats, Kerala, India. *Applied Geochemistry*, 63: 456-471.

Tweed S, Leblanc M, Cartwright I, et al. 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 D D, Zhao C Y, Zheng J Q, et al. 2021. Evolution of soil salinity and the critical ratio of drainage to irrigation (CRDI) in the Weigan Oasis in the Tarim Basin. *Catena*, 201: 105210, doi: 10.1016/j.catena.2021.105210.

Wang J, Han H D, Zhao Q D, et al. 2013. Study on hydrochemical components of river water in the Tarim River Basin, Xinjiang, China. *Arid Zone Research*, 30(1): 10-15. (in Chinese)

Wang P, Yu J J, Zhang Y C, et al. 2013. Groundwater recharge and hydrogeochemical evolution in the Ejina Basin, northwest China. *Journal of Hydrology*, 476: 72-86.

Wang W H, Wu T H, Zhao L, et al. 2018. Hydrochemical characteristics of ground ice in permafrost regions of the Qinghai-Tibet Plateau. *Science of the Total Environment*, 626: 366-376.

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, et al. 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, doi: 10.1016/j.jhydrol.2020.125644.

Wu H W, Wu J L, Li J, et al. 2020. Spatial variations of hydrochemistry and stable isotopes in mountainous river water from the Central Asian headwaters of the Tajikistan Pamirs. *CATENA*, 193: 104639, doi: 10.1016/j.catena.2020.104639.

Xiao J, Jin Z D, Wang J, et al. 2015. Hydrochemical characteristics, controlling factors and solute sources of groundwater within the Tarim River Basin in the extreme arid region, NW Tibetan Plateau. *Quaternary International*, 380: 237-246.

Yin X W, Feng Q, Zheng X J, et al. 2021. Assessing the impacts of irrigated agriculture on hydrological regimes in an oasis-desert system. *Journal of Hydrology*, 594: 125976, doi: 10.1016/j.jhydrol.2021.125976.

Zeng Y Y, Zhou J L, Nai W H, et al., 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, et al. 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 M, Geruo A, Zhang J, et al. 2021. Ecological restoration impact on total terrestrial water storage. *Nature Sustainability*, 4(1): 56-62.

Zhou J X. 2015. Hydrograph separation in the headwater area of Shule River Basin: combining water chemistry and stable isotopes. MSc Thesis. Beijing: University of Chinese Academy of Sciences. (in Chinese)

Note: Figure translations are in progress. See original paper for figures.