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PAPER

Investigating the mysteries of groundwater in the Badain Jaran Desert, China

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Abstract

The Badain Jaran Desert (BJD) in China is a desert with impressive sand dunes and a groundwater situation that has attracted numerous researchers. This paper gives an overview of the mysteries of groundwater in the BJD that are exhibited as five key problems identified in previous studies. These problems relate to the origin of the groundwater, the hydrological connection between the BJD and the Heihe River Basin (HRB), the infiltration recharge, the lake–groundwater interactions, and the features of stable isotope analyses. The existing controversial analyses and hypotheses have caused debate and have hindered effective water resources management in the region. In recent years, these problems have been partly addressed by additional surveys. It has been revealed that the Quaternary sandy sediments and Neogene-Cretaceous sandstones form a thick aquifer system in the BJD. Groundwater flow at the regional scale is dominated by a significant difference in water levels between the surrounding mountains and lowlands at the western and northern edges. Discharge of groundwater from the BJD to the downstream HRB occurs according to the regional flow. Seasonal fluctuations of the water level in lakes are less than 0.5 m due to the quasi-steady groundwater discharge. The magnitude of infiltration recharge is still highly uncertain because significant limitations existed in previous studies. The evaporation effect may be the key to interpreting the anomalous negative deuterium-excess in the BJD groundwater. Further investigations are expected to reveal the hydrogeological conditions in more detail.

Keywords Groundwater recharge/water budget · Groundwater/surface-water relations · Stable isotopes · Unsaturated zone · China

Introduction

Groundwater is an essential source of drinking water and plays an important role in terrestrial ecological systems, especially in arid and semiarid regions. In Northwest China, both natural ecological systems and the economy are highly dependent on groundwater. In this region, the mean annual precipitation is less than 400 mm, whereas the mean annual potential evapotranspiration is higher than 800 mm. Despite the importance of groundwater, the properties and behavior of groundwater in most of the region are poorly understood, partly due to the absence of sufficient data. This shortfall in knowledge is particularly evident with regard to the widespread deserts, some of which are included in the list of the world's largest deserts, e.g., the Taklamakan Desert in Xinjiang Province is the world's second largest shifting sand desert (Sun and Liu 2006). In-depth investigations of the hydrogeological conditions in several deserts have been carried out in recent years but these require a long period to extract and integrate the useful information into a new conceptual model of the groundwater system.

The Badain Jaran Desert (BJD) in the Alxa Plateau, Inner Mongolia (Northwest China), is an enigmatic desert that has attracted researchers worldwide for three decades because it is home to the tallest sand dunes on Earth and ~100 groundwater-fed lakes. Surveys in geography and geology at the regional scale in the Alxa Plateau have been carried out by Chinese scientists since 1957 (Sun et al. 1961; Wang 1990; Dong et al. 1995, 2013; Li et al. 2010). A number of non-Chinese scientists have been coming to China since the 1980s

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to contribute their experience to studies on the BJD. During 1988–1995, a team from Germany undertook expeditions in and around the BJD with the cooperation of Chinese officials and scientists to investigate the origin and development of the sand dunes (Jäkel 1996; Hofmann 1996; Geyh et al. 1996). In the 2000s, the palaeoclimatic changes in the area of BJD interested researchers from several different countries (Yang 2000; Yang and Williams 2003; Ma et al. 2004; Ma and Edmunds 2006; Gates et al. 2008b). Chloride mass balance (CMB) techniques for unsaturated zone profiles were introduced to the research portfolio and the groundwater recharge rate was estimated to be less than 5 mm/year (Ma and Edmunds 2006; Gates et al. 2008b). This recharge seemed tiny in comparison with the evaporation loss through lakes and it raised questions as to the origin of water in the BJD. Chen et al. (2004) speculated on the possibility of long-distance transportation of water from the Qilian Mountain (~500 km from the BJD) to the desert lakes. It led to debate in the Chinese scientific community regarding the region's hydrogeology and geography. There were at least four hypotheses accounting for the primary source of water in the BJD, as summarized by Dong et al. (2013): direct precipitation recharge, near-source recharge, remote-source recharge, and paleo-source recharge. None of these theories have been widely accepted due to lack of evidence.

In the 2010s, more intensive investigations were undertaken in the BJD using modern monitoring devices, setting up observation stations and extracting information from remote sensing data. Experiments on the diurnal variations of soil moisture were reported and analyzed (Zeng et al. 2009, 2011; Wen et al. 2014). Ground penetrating radar (GPR) and gravimetric analyses were used to probe bedrock landforms beneath the sand dune surfaces by Yang et al. (2011). They argued that the subsurface landforms characterized by hilly bedrock landscapes should be of great significance in forming the mega dunes, which is an extension of the previous perspective that the mega dunes were attributed mainly by the wind regime rather than the pre-existing surface relief (Dong et al. 2009). Bai et al. (2011) also used GPR to probe the layered sandy sediments in the BJD and determined the age of palaeo-lacustrine deposits using an optically stimulated luminescence dating technique. A team from the Lanzhou University built observation stations on sand dunes in the BJD (Ma et al. 2014). They did not find any evidence of groundwater recharge from rainfall infiltration. However, they found evidence of the occurrence of very high lake-levels during 8.6–6.3 ka cal. BP from additional field investigations (Wang et al. 2016). A different conclusion about the rainfall infiltration was obtained by Zhao et al. (2017) who found evidence of surface runoff and effective infiltration that passes through the dunes or bypasses the low permeability interbeds. A group in the China University of Geosciences, Beijing (CUGb), started a long-term hydrogeological survey in the BJD in 2012, and have built up an observation system for a saline lake to monitor the meteorological factors, lake water, soil water and groundwater level (Wang et al. 2014). This work provided new results related to the regional groundwater flow (Wang et al. 2014; Zhang et al. 2015b), the basin-scale aquifer system (Zhang et al. 2015c), the structure of the sand dunes (Qian and Liu 2016), and the dynamics of the lakes (Jin et al. 2014; Gong et al. 2016) and soil water (Hou et al. 2016), as well as a new interpretation on isotopes measured in water samples (Wu et al. 2017). During 2012–2016, groundwater–lake interactions were investigated by different research groups with multiple methods for several typical lakes in the BJD (Liu et al. 2015; Chen et al. 2015; Luo et al. 2016, 2017; Zhang et al. 2017). In recent years, different remote sensing data have been applied to identify the variations in lakes (Jin et al. 2014; Zhang et al. 2015a) and regional groundwater storage (Jiao et al. 2015).

It has been clearly shown in the previous studies that groundwater is the key to solving many different problems in the BJD. The issue is to improve knowledge on the key factors for a better understanding on the history and the current status and future of the desert environment, which is a concern for the local people who have to face a changing world. The objective of this presentation is to provide an overview of the controversial questions relevant to groundwater in the BJD. The paper also highlights several up-to-date results that can address or partially solve some of the problems. An overview of the issues and recent advances is expected to be of benefit for further scientific investigations in the desert or other regions with similar conditions.

Background to the Badain Jaran Desert

The BJD (39°20′ N to 41°50′ N; 99°50′ E to 103°50′ E) is located in the Alxa Plateau in Northwest China, as shown in Fig. 1a. It covers an area of ~49,000 km^2 by which it is ranked as the second largest desert in China (Wang 1990). The region of the BJD is bounded by several mountains—elevations up to 1,960 m above sea level (a.s.l.)—to the south and east, with lowland intervals along the west and north edges of the Yabulai Mountains. To the west and north, it is bounded by plains of Gurinai and Guaizihu (elevation ranges between 950 and 1,000 m a.s.l.) with wetlands and grasslands. The area of Gurinai lies in the downstream area of the Heihe River Baisn (HRB). The Heihe River has been significantly influenced by human activities (Cheng et al. 2014). The BJD itself is characterized by sand with mega dunes that are generally 100–300 m tall (elevation ranges between 1,100 and 1,400 m a.s.l.). A few of the dune peaks are higher than 400 m above the nearby lakes and considered as the highest sand hills on Earth (Dong et al. 2013).

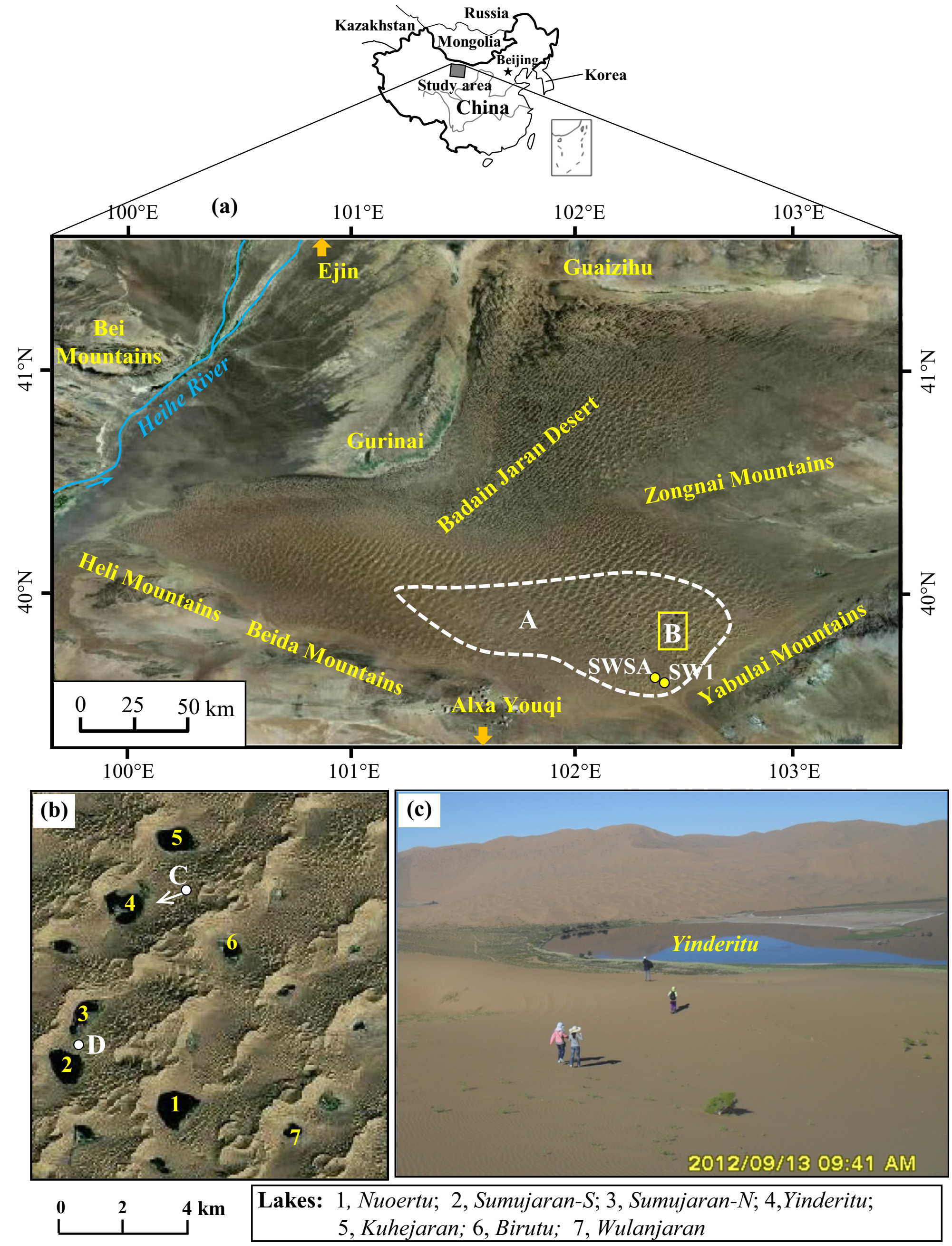

Fig. 1 The study area: **a** location and satellite image of the Badain Jaran Desert with ~100 lakes distributed in zone A; **b** satellite image of groups of lakes in zone B; **c** a picture taken at the site C, facing toward Lake Yinderitu. The satellite images were provided by the Cloud Service Platform of ZY-3 Satellite Image, China (SASMAC 2017)

Most of the groundwater-fed lakes are in the southwestern part of the desert, within zone A shown in Fig. 1a, which has an area of ~5,700 km^2. The number of lakes was reported to be 144 in the 1970s (Wang 1990). During 1990–2010, the number of lakes identified from remote sensing ranged between 78 and 109 with seasonal variations (Zhu et al. 2011; Jin et al. 2014). The distribution pattern of lakes can be observed in Fig. 1b for a relatively small zone (zone B in Fig. 1a) in which the largest lake (Lake Nuoertu, 1.65 km^2) in the BJD is located. A few of the lakes are larger than 1.0 km^2 in area and have a maximum water depth of more than 10 m. Small grasslands, shrub patches or even trees can be found surrounding some lakes, whereas the vegetation coverage is extremely low on sand dunes (Fig. 1c).

The climate in the BJD is cold desert arid (type: BWk) according to the Köppen-Geiger climate classification (Peel et al. 2007). The meteorological conditions in the center of the desert have not been well monitored before 2010 but could be roughly determined from standard weather stations installed in the Alxa Plateau cities of Youqi and Ejin (Fig. 1a), which are near to the south and north edges of the BJD, respectively. In the southern part of the BJD where the lakes are located, the mean annual precipitation would be 80–100 mm as interpolated from the two weather stations. More than 80% of the annual precipitation is contributed by rains from June to September under the impact of the East Asian monsoon.

The characteristics in chemistry of groundwater and lakes in the BJD have been reported by numerous researchers (Wang 1990; Hofmann 1996, 1999; Yang and Williams 2003; Ma and Yang 2008; Chen et al. 2012a, b; Gong et al. 2016). A summary of the chemistry data is presented in Table 1. Shallow groundwater exposed in wells and springs around the lakes in zone A (Fig. 1a) generally has very low salinity (total dissolved solids (TDS) <1.0 g/L) and is of Na(Ca)-CO_3(SO_4-Cl) type with a pH value between 7.7 and 8.4. High salinity groundwater is mainly found in the area between the edge of the desert and the mountains. In contrast to the low salinity in shallow groundwater in zone A, the salinity of water in most of the lakes in the northern district (Hofmann 1999) is very high (TDS >35 g/L, up to 483 g/L) and is of Na-Cl(SO_4) type, indicating a long history in a closed environment. In the southeastern district of zone A, both sub-saline and hypersaline lakes exist and the distance between a saline lake and a sub-saline lake could be less than 2 km. Water in some of the sub-saline lakes is close to fresh (TDS = 1–2 g/L) and of Na(Mg)-Cl(SO_4-CO_3) type; thus, the lakes in the southeastern district show more complex evolutionary environments.

Does groundwater mostly come from a distance via faults?

Fault system models

Where does groundwater come from to maintain so many lakes in the BJD? This became a controversial point when Chen et al. (2004) published their model. This model was one of the four hypotheses that were summarized by Dong et al. (2013), which attributed groundwater in the BJD to remote-source recharge; however, the most surprising point of the model is not the distance – at least 400 km between the source and the desert according to Chen et al. (2006) – but the way the water moves through faults. The main fault system described by Chen et al. (2006) is plotted in Fig. 2 and renumbered as F1, F2 and F3 for this study. F3 is a deeply hidden fault which is required for the BJD to receive water from F2 at an estimated rate of 5×10^8 m^3/year (Chen et al. 2004). As further estimated by Chen et al. (2006), the total flow in F2 is about 20×10^8 m^3/year, which not only contributes water to the BJD but also supplies the Tengger Desert and the other downstream regions. Chen et al. (2012a) provided more isotopic and chemical data of water samples to try and support their hypothesis.

Table 1 Chemistry content of groundwater and lakes in the BJD according to Yang and Williams (2003) and Gong et al. (2016)

Components	Groundwater	Lakes
pH	7.7–8.4	7.2–11.0
TDS (g/L)	< 1.9	1.2–483.0
Na (g/L)	< 0.6	0.2–220.0
Ca + Mg (g/L)	< 0.2	0.0–4.0
K (g/L)	< 0.1	0.0–19.2
Cl (g/L)	< 0.6	0.3–247.0
CO_3 (g/L)	< 0.1	0.0–102.2
HCO_3 (g/L)	< 0.5	0.2–33.4
SO_4 (g/L)	< 0.6	0.2–84.0

There are alternative models of faults system for the hypotheses of remote-source recharge. Ding and Wang (2007) suggested that groundwater in the southern part of BJD could have originated from the Heihe River, via the Altyn Fault. In Fig. 2, the proposed Altyn Fault is denoted as F4, which is connected with a group of faulting branches that are oriented toward the lakes. It receives water from the leaking channel of Heihe River. The flow rate in the F4 fault was estimated to be 2.86×10^8 m^3/year on average (Ding and Wang 2007). A different choice of faults was suggested by Wu et al. (2010) who attributed the leakage loss to a hidden fault shown as F6 in Fig. 2. The fault was speculated within the EH4 electrical conductivity survey by Wu et al. (2004) and they estimated the flow rate would be $\sim 1.76 \times 10^8$ m^3/year. Wu et al. (2010) believed that a part of the flow in fault F6 can disperse in the south toward the lake group in the BJD.

Analysis and discussion

The fault system models provided a possibility of water origin in BJD, which refers the source of groundwater to surface water outside of the BJD area. However, the weakness of the models is the difficulty in explaining the huge flow rate in the hidden faults without any visible signs along the route. The physical basis of hydrogeology is described by Darcy law, in which the flow rate of groundwater, Q [L^3T^{-1}], across a section can be estimated by

$$Q = KJA = KJWD \qquad (1)$$

where K is the hydraulic conductivity [LT^{-1}] of fractured rocks in the faults for the special problem in this section, J is the hydraulic gradient [−] and A is the area of the cross section [L^2] which could be approximately estimated as the width, W [L], multiplied by the thickness, D [L], of a rectangular-shape section. K should be less than 10 m/day for the fractured rocks under normal conditions and J would be no more than 0.003

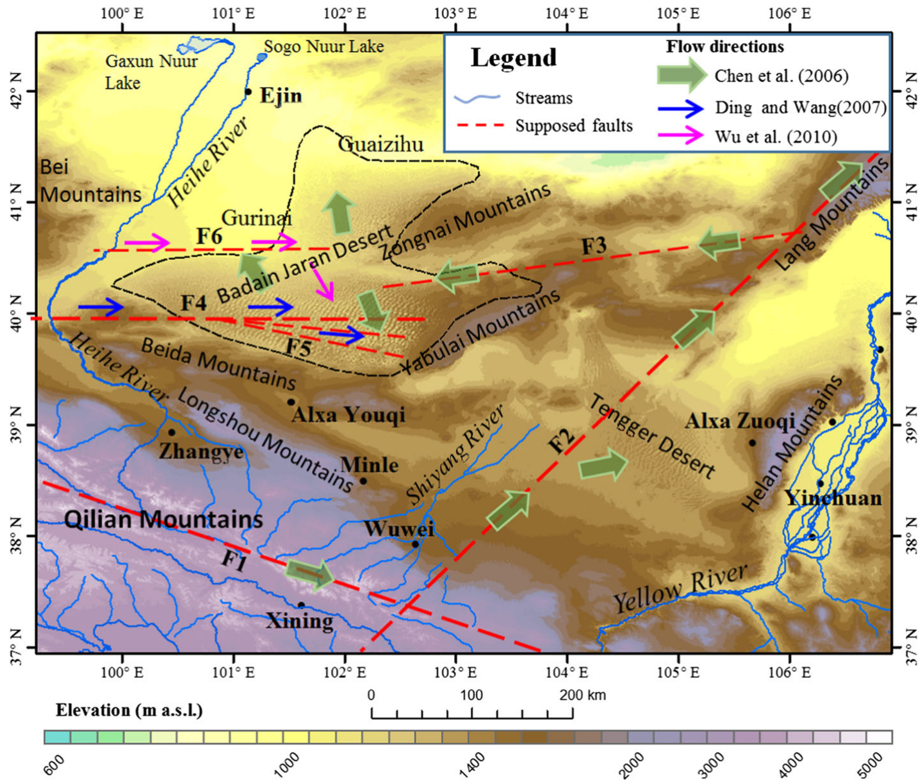

Fig. 2 Different groundwater transport routes along faults supposed in previous studies. F1 to F5 are the faults reported in the literature and renumbered in this study

according to the maximum difference in water level at the ends of a fault. If one applies a maximum penetrating depth of $D = 2{,}000$ m for the faults without decrease in permeability, the W value has to be larger than 4,500 m to yield a Q value that is higher than 1.0×10^8 m^3/year. The F2 fault (Fig. 2) should be wider than 90 km for the flow rate 20×10^8 m^3/year proposed by Chen et al. (2006). A fault of such a width should behave like the Great Rift Valley but why is it silently hidden underground without any impacts on the earth's surface? Thus, F2 could not be as wide and powerful as to carry so much water. If F2 exists and behaves like the famous San Andreas Fault in which a 200-m-wide damage zone was found (Morrow et al. 2014), the maximum flow rate would be only 0.044×10^8 m^3/year, i.e., less than 1% of the expected flow rate in F3 for the BJD. In the concept proposed by Wu et al. (2010), the fault F6 has formed a paleo-river valley in the Quaternary sediments with a width of ~4 km. It yields $W \approx 4{,}000$ m in calculating the flow rate but the thickness of Quaternary sediments is limited to $D < 400$ m, and then the Q value should be less than 0.18×10^8 m^3/year. This flow rate is less than 10.3% of that proposed by Wu et al. (2010).

Accordingly, the possibility is very low that groundwater in the southern BJD is mostly transported by those faults from surface water located hundreds of kilometers away. The isotopic and chemical data of water samples used in this type of hypothesis should be carefully considered because they do not provide direct evidence and could be adopted to support other explanations (Zhang and Ming 2006; Liu 2010; Zhao et al. 2012).

How is the BJD linked with the Heihe River Basin by groundwater?

Background to the problem

The downstream area of the HRB, which includes the Gurinai Grasslands and the city of Ejin (Fig. 2), has long been a region of concern in northwestern China because its hydrological and ecological environments have been significantly influenced by water use in the midstream area. During 2000–2012, this area received 5.29×10^8 m^3 runoff per year on average from the Langxinshan section of Heihe River (Cheng et al. 2014), but only ~11.7% of this flow arrived at the Sogo Nuur Lake shown in Fig. 2 because of significant leakage. The BJD was not included in the HRB in the conventional division map of watersheds in China (Li et al. 2010, 2014) even though no terrain divides exist between them. This is partly because of the unclear hydrological connection between them. In a few of the recent studies, the BJD was introduced as a part of the HRB (Yao et al. 2015).

The potential exchange of water between the BJD and HRB has been investigated in the hypothetical models of the fault systems (Chen et al. 2004, 2006; Ding and Wang 2007; Wu et al. 2010). As suggested in Fig. 2, if a large amount of surface water in Qilian Mountains is transported in faults F1, F2 and F3 to the BJD, groundwater in the BJD could be driven by this flow (5×10^8 m^3/year) and partly move to the downstream area of the HRB. The models of the other faults, F4 or F5, suggest an opposite flow direction. As estimated, the potential contribution of flow rate from the Heihe River to the BJD would be about 2.86×10^8 m^3/year (Ding and Wang 2007) or 1.76×10^8 m^3/year (Wu et al. 2010).

Faults are not necessarily the only means of inter-basin exchange of groundwater. Connected aquifers and non-zero difference in hydraulic heads on both sides of a boundary can create flow across the boundary. The difficulty in this area is the unclear situation of the aquifers and groundwater level due to lack of data.

Recent advances from surveys on hydrogeological conditions

In the past decade, with the increasing number of geophysical surveys in the Alxa Plateau for finding petroleum resources, the structures of tectonic basins in the study area have become clearer. It has been revealed that the BJD is the southern part of the Yingen-Ejinaqi basin that is bounded by magmatic rock mountains with thick sedimentary formations (Yan et al. 2011). Seven gravity-magnetoelectric inversion profiles were established (Liu et al. 2011) and three of them extended across the BJD. According to the profiles, the BJD and the Gurinai-Ejin areas are controlled by different sub-basins with a hidden tectonic uplift between them but the sedimentary formations are basically joined as a whole. Among the formations, the Cretaceous sandstones can be considered as a porous-fractured aquifer with a thickness that normally ranges between 1,000 and 3,000 m, up to 4,000 m (Wang et al. 2014; Zhang et al. 2015c). The overlying Neogene (absence of Paleogene system) semi-consolidated sandstones are the porous aquifers of 10–400 m thickness. On the top are the Quaternary sediments with fine to coarse sands. The thickness of the saturated zone in the Quaternary system is generally larger than 200 m in the BJD. These sedimentary formations form a huge basin-type aquifer system, as shown schematically in Fig. 3.

The structure of the aquifer system has been preliminarily verified by several boreholes drilled in recent years in the BJD, shown as K1 to K4 and WEDP02 in Fig. 4. A profile map of the boreholes is presented in Zhang et al. (2015c). K1 and K2 are close to the Zongnai Mountains, and revealed Cretaceous and Neogene sandstones underlain by granites at depths that are less than 60 m, exhibiting the boundary conditions of the BJD aquifer system. K3 and K4 are located on inter-dune lowlands in the middle of the BJD with maximum depths of 68 and 84 m, and without observation of bedrocks. These findings confirm the reports of Guo et al. (2014) from borehole WEDP02 (on the bank of a brine lake) drilled 310 m deep into the aquifer (Fig. 4). At the bottom of WEDP02, the Neogene sandstones were revealed. As reported by Guo et al. (2014), the majority of sediments observed in WEDP02 are fine-to-coarse sands, whereby no silty or clayey media were found. Thus, the Quaternary sands provide a huge space for groundwater to be stored and to freely flow in the BJD.

Fissures and fractures are frequently found in the granite rocks in the mountains area, with groundwater in the weathered zone and fracture networks that can be observed emerging as springs. Wells in the mountains show higher water tables in such a fractured aquifer compared with wells in the porous aquifer in the BJD. Using the observed data from wells and boreholes, Zhang et al. (2015c) estimated the hydraulic gradients for shallow groundwater flow which should be driven by the significant difference in water table height between the mountains and the BJD. The data are reorganized in this presentation to draw a contour map of groundwater level, as shown in Fig. 4. This groundwater level distribution indicates the groundwater flow directions: from the mountains to the BJD and then to lower plains in the west and north; therefore, the BJD is one of the source areas of water for the HRB. This concept of hydrological connection was adopted by Yao et al. (2015) when they performed numerical modeling of groundwater flow in the whole HRB.

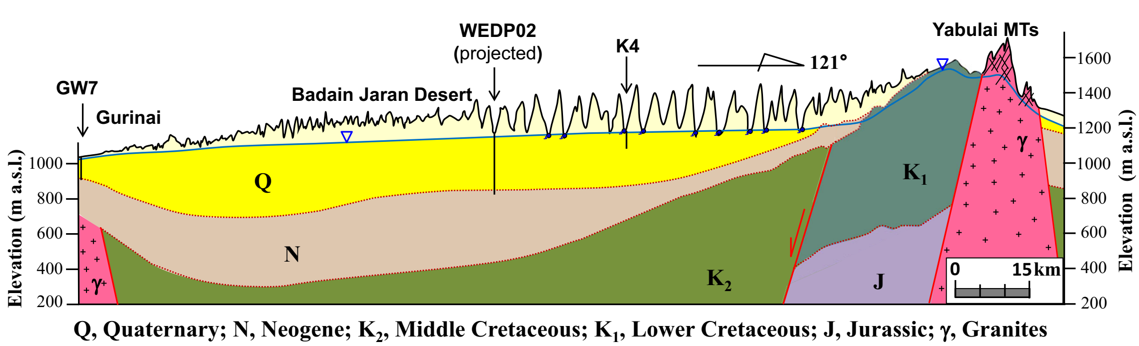

Fig. 3 Schematic geological profile across the BJD from the Gurinai to the Yabulai Mountains. The locations of boreholes (GW7, WEDP02 and K4) are shown in Fig. 4

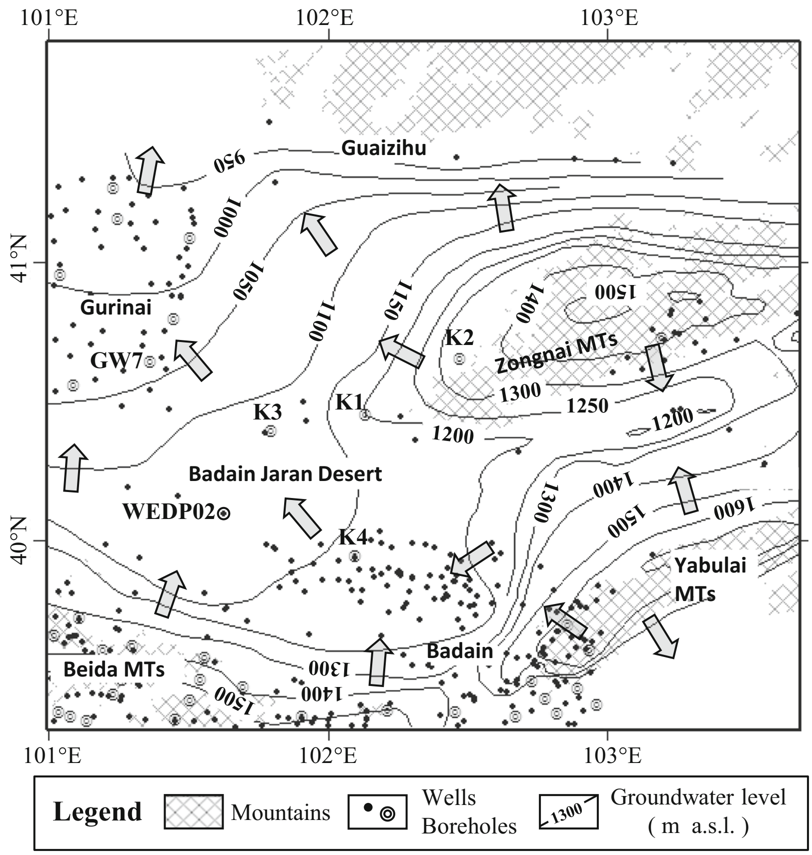

Fig. 4 Distribution of groundwater level in the BJD and surrounding areas. The arrows denote the general flow directions of groundwater

Discussions on the hydrological significance

Even though the recent geological and hydrogeological surveys revealed the continuity of the Quaternary aquifer along the BJD-HRB boundary and the BJD-to-HRB flow direction, the amount of groundwater discharge is still poorly understood. The flow rate from the BJD to the downstream area of the HRB was determined to be (0.2–0.7) × 10^8 m^3/year in Wang et al. (2014), as the result of a rough water balance in the BJD. A slightly higher result, (0.33–1.06) × 10^8 m^3/year, was estimated by Zhang et al. (2015b) where the Darcy law was applied with given hydraulic conductivities and hydraulic gradients along the boundary. These estimations included a lot of uncertainties such as the total evaporation loss of water in the BJD, and the variable hydraulic conductivities of different aquifers at different depths. Further investigations are expected to provide clearer parameter values for water balance models or boundary flow models.

Another unresolved problem is how to extend the eastern boundary of the HRB into the BJD. One option is to include the whole BJD. However, this would not be suitable because most of the BJD groundwater flow across the northern boundary is contributed to the Guaizihu area (Fig. 4) which does not belong to the HRB. In Yao et al. (2015), only the west part of the BJD was included in the hydrological model of the HRB with a presumed no-flow condition across the boundary. The divide line should be more carefully determined based on the characteristics of the regional groundwater flow in the BJD and surrounding areas.

Could precipitation provide sufficient groundwater recharge via infiltration through the thick unsaturated zone?

Groundwater in a particular location could be directly recharged by local precipitation as long as the precipitation could infiltrate into the subsurface media with a smaller evapotranspiration loss and without interception across the vertical infiltration path. In the BJD, this infiltration recharge seems to be difficult because the potential evaporation is ~10 times that of the precipitation and the unsaturated zone is generally thicker than 100 m in most of the dune area near the lakes. Is the infiltration recharge in the BJD sufficient or insufficient to drive groundwater circulation or even impossible due to the strong evapotranspiration? Researchers have different perspectives on this matter.

Existing assessments of potential infiltration recharge

In some of the early investigations (Sun et al. 1961; Sheng et al. 1981; Gao et al. 1981), the infiltration recharge seemed to be at least 10% of the precipitation (~100 mm/year) in the southern part of the BJD. More optimistic assessments (up to 50 mm/year) were presented in several later studies (Wang 1990; Hofmann 1999). These investigations presumed that the infiltration recharge in a limited area would be sufficient to balance the evaporation loss in lakes.

Significantly smaller results of infiltration recharge were obtained by using the CMB method on unsaturated zone profiles (Ma et al. 2004; Ma and Edmunds 2006; Gates et al. 2008b). Data of moisture content and Cl on typical profiles in Ma and Edmunds (2006) and Gates et al. (2008b) are shown in Fig. 5. When using the CMB method, a piston-like downward flow in the unsaturated zone with a constant input rate of Cl in mass is assumed (Allison and Hughes 1978; Edmunds et al. 1988). As a result, the estimated infiltration recharge at SW1 (Fig. 1a) was less than 3 mm/year over the past 1,200 years (Fig. 5a,b) with a mean value of 0.95 mm/year (Ma and Edmunds 2006). At the site SWSA (Fig. 1a), the estimated infiltration recharge with respect to the profile SWSA05–16 (Fig. 5c) was 1.12 mm/year on average (Gates et al. 2008b). More results for the past 2,000 years were reported for the unsaturated zone in the BJD (Ma and Edmunds 2006; Gates et al. 2008b; Stone and Edmunds 2016); however, none of them yielded a recharge rate that is higher than 4.0 mm/year.

Physical-based modeling of the unsaturated-zone flow is another way to estimate the infiltration recharge, in comparison to the CMB method. Hou et al. (2016) performed such modeling, based on a long-term monitoring system of soil moisture and temperature at the site D (Fig. 1b) near the lake Sumujaran-S, which was established in 2012 (Wang et al. 2014). The daily observation data at the depths of 20, 50 and 100 cm indicated that the fluctuations of the soil moisture decrease significantly with depth, similar to that of the soil temperature. At 1-m depth, the volumetric moisture content showed a persistent increase for 5 months in response to the summer rains though the total increment is small. Such a delayed but persistent response may indicate an effective infiltration of water to the deep zone in the BJD. The numerical model was built up with HYDRUS-1D (Šimunek et al. 2013) for a 3-m unsaturated zone with a free-drainage boundary at the bottom to capture the observed variations in the soil moisture and temperature. Then, the model was applied to simulate a 30-year fluctuation of the bottom flux (groundwater recharge) resulting in an annual groundwater recharge between 11 and 33 mm with a mean value of 17 mm, which was ~14% of the mean annual precipitation. A further investigation on the unsaturated flow in the sand dunes was undertaken by Zhou and Wang (2017). The volumetric moisture content (θ) data for a special zone below a depth of 3 m from ground surface, and above 3 m height from the water table (to eliminate effects of the evaporation near surface and the capillary rise near the water table), were retrieved from previous studies (Ma and Edmunds 2006; Zhou 2010; Ma et al. 2011; Zhao et al. 2011). The θ values randomly fall into a range between 0.0 and 15.0%, following a non-Gaussian distribution. Zhou and Wang (2017) assumed that the non-Gaussian θ-distribution in this special zone is a result of quasi-steady-state unsaturated flow in the sands with stochastic hydraulic parameters. By using the technique developed in Carsel and Parrish (1988), a Monte-Carlo simulation was performed. According to the results, a downward flow rate is highly possible varying

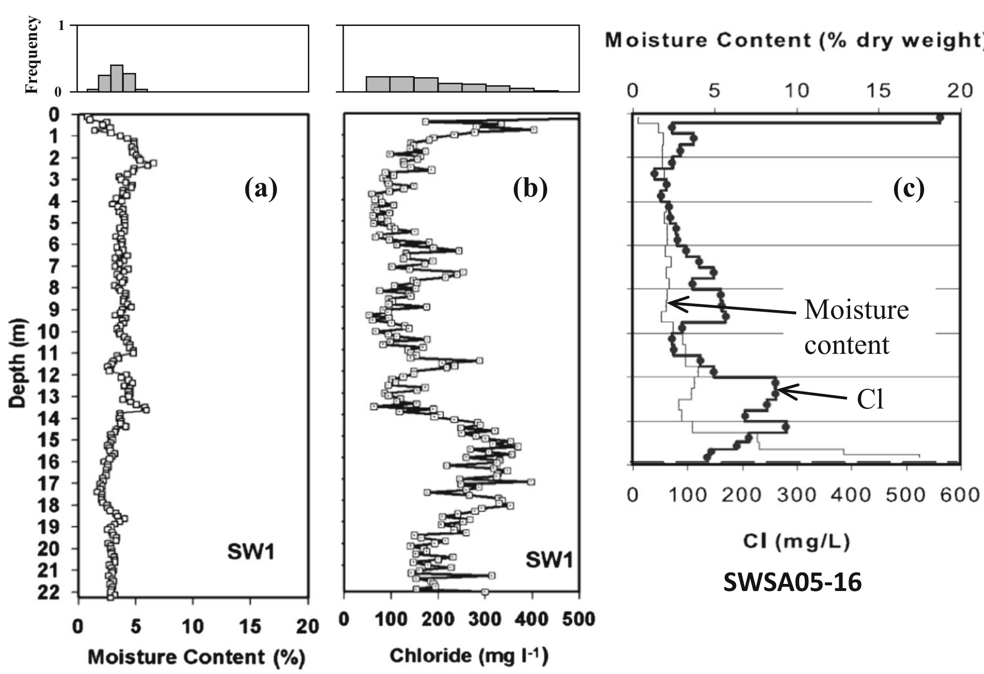

Fig. 5 Profiles of **a** soil moisture content and **b** chloride in the BJD using data of a 22.5-m profile (SW1), from Ma and Edmunds (2006), with the histograms plotted. **c** Shows data of a 16-m profile (SWSA05–16) from Gates et al. (2008b)

between 29 and 41 mm/year, which should not be less than 10 mm/year or higher than 50 mm/year according to sensitivity analysis on the other uncertainties. This work provides a new insight on groundwater recharge in the BJD.

Observations on the infiltration process after rains

Several researchers made efforts in directly observing the infiltration process after rains in the BJD to check the consideration of local precipitation-induced recharge. Zeng et al. (2009) reported a 22-day experiment of soil-water dynamics in a 50-cm profile undertaken in June 2008. They captured a 6.6-mm rainfall event which was followed by a rapid rising and slow falling of the soil moisture content at the depth 10 cm. Numerical modeling of unsaturated flow according to the observations showed that this rainfall would never penetrate into the zone deeper than 1 m. Wen et al. (2014) reported another similar experiment in a longer period of 2 months in 2008. They captured three rainfall events (23.9, 14.7 and 11.4 mm) from July to August and found a wet zone (θ = 15–20%) at depth 20–60 cm was developed after the rains. The near-surface dry sands seemed to significantly increase the resistance to evaporation so that the wet zone can exist for at least 7 days. They also found a negative latent heat flux in the night according to eddy covariance turbulent flux measurements, which may indicate a transformation of vapor in the atmosphere to the pore water in sands by condensation. This observation encouraged Wen et al. (2014) to consider the local water circulation in a lake basin; however, Ma et al. (2014) had drawn a different conclusion from a long-term monitoring of soil moisture near Lake Sumujaran-S. They found that the soil moisture content at 65-cm depth stayed almost constant in July even though five rainfall events were recorded. Again, eddy covariance turbulent flux measurements were used to determine the actual evaporation but Ma et al. (2014) found that the accumulative evaporation (they did not mentioned the negative latent heat flux in the night) after a heavy rainfall event will finally equal the accumulative precipitation, even for an extreme rainstorm of 43 mm/day. Thus, they concluded that the precipitation in the BJD is insufficient to produce effective infiltration recharge. Dong et al. (2016) repeated this conclusion with an artificial rainfall experiment in which a 30-mm rainfall over 30 min seemed to only penetrate to a depth of 42 cm within 17 h.

Discussion on hydrogeological processes

It is still a big challenge to account for the possibility and magnitude of infiltration recharge in the BJD from precipitation in the present or in the past. There were significant limitations in the previous studies. These limitations should be considered in further investigations to improve the accuracy of analyses.

First of all, one should be cautious in drawing a negative conclusion when the wetting front in the soils after a rain event seems unable to penetrate to depth (Ma et al. 2014; Dong et al. 2016). That is because soil water in unsaturated zones can move not only in the form of piston flow but also in the form of diffuse flow (Šimunek et al. 2013; Stone and Edmunds 2016) or even multi-phase flow (Zeng et al. 2009, 2011). A downward hydraulic gradient could produce downward flow without the wetting front. In addition, the fluctuation amplitude of soil moisture decreases with depth due to the storage effect (buffering effect) which has been proved in theory (Bakker and Nieber 2009) and exhibited in long-term monitoring at different depths (Hou et al. 2016). Thus, it is not strange that the moisture content in a deep zone seems unresponsive to rainstorms, but the downward infiltration is going on.

The challenge of the CMB method is the uncertainty in specifying the input of Cl from precipitation (Edmunds and Tyler 2002; Stone and Edmunds 2016) because Cl is not only brought by rains but also comes from dry deposition, especially in the BJD with local sources of salts (Yang et al. 2010). However, it is difficult to present a quantitative assessment on the dry deposition in the BJD due to lack of observation data. When the CMB method was applied on a profile, a steady-state ground surface for ~1,000 years without the eolian sedimentation and erosion was assumed. This assumption is false for moving dunes in the BJD where the micro-topography changes rapidly. A 10 mm/year vertical shift of the ground surface on average could produce or destroy a 10-m-thick unsaturated zone within 1,000 years. Such a significant change in the topography has to be accounted for before using the CMB method and other methods that are built up on the basis of profile information.

It is difficult to provide an accurate assessment of evaporation loss from the land surface even though in situ measurements have been carried out. Both Wen et al. (2014) and Ma et al. (2014) observed the eddy covariance turbulent flux on dunes in the BJD but they calculated the soil water balance in different ways. Ma et al. (2014) estimated the accumulated evapotranspiration through the latent heat flux data in the daytime and found it was almost equal to the accumulated precipitation, so that infiltration recharge seemed to be impossible. However, Wen et al. (2014) found that almost half of the positive latent heat flux in the daytime could be counteracted by the negative latent heat flux in the night. Accordingly, the net evapotranspiration loss on dunes may be significantly lower in comparison with the precipitation, which is positive for the infiltration recharge but more evidence with higher accuracy observations are required to verify the conclusion. Overestimation of evaporation from lakes exists in previous studies, e.g., 2,600 mm/year was used in Gates et al. (2008a), which led to a debate on how much infiltration recharge is sufficient to balance the groundwater discharge to lakes. Yang et al. (2010) provided a model on how a tiny infiltration recharge can drive hydrological circulation in the lakes area. They argued that a recharge rate of 5 mm/year would be enough if the annual evaporation of lakes is corrected to 940–1,150 mm. This problem should be checked by reasonable measurements on the actual evaporation rate from lakes, covering different seasons.

What is the relationship between groundwater and lakes?

Different models for groundwater discharge to lakes

How groundwater discharges into lakes is related to the stability of hydrogeological conditions in the desert lakes area. This process involves the structural properties of the aquifers under the sand dunes and lakes so that a model of the regional aquifer system is required. The existing groundwater discharge models, taking existing descriptions of the groundwater–lake relationship in the BJD, are summarized in Fig. 6. In the early investigations, Sheng et al. (1981) suggested a layer-by-layer structure of the Quaternary aquifer-aquitard system (Fig. 6a), in which the aquitards are discontinuous in some places where groundwater in the confined aquifers can flow upward directly into the lakes or through ascending springs. This kind of groundwater–lake relationship was adopted in Wang (1990) and Gates et al. (2008a). The model of Chen et al. (2004) can be schematically represented by Fig. 6b where bedrocks are overlain by sands dunes and opened by a fault in which groundwater flows upward to a peak of the bedrock and then flows downward to a nearby lake along the bedrock surface. Ding et al. (2015) mixed the two previous models as shown in Fig. 6c. Instead of considering infiltration recharge, the model supposed an upward vapor flow in the unsaturated zone of the dunes above water table. It is interesting that these three models can feasibly show how ascending and descending springs have developed in or beside a lake.

Springs developed on islands in some saline lakes exhibit a special kind of ascending spring that has been investigated by Arp et al. (1998). The islands are formed by tufa with a larger body in the lake than that shown above water level (Fig. 6d). Fractures and seeps can be seen on the tufa surface, with upwelling groundwater. The limestone-like sediments in the spring mounds were also noticed by Chen et al. (2004) and referred to deposits of carbonate-rich groundwater coming from carbonate rocks. This speculation was unreasonable because the spring water is not rich in carbonate. In fact, the

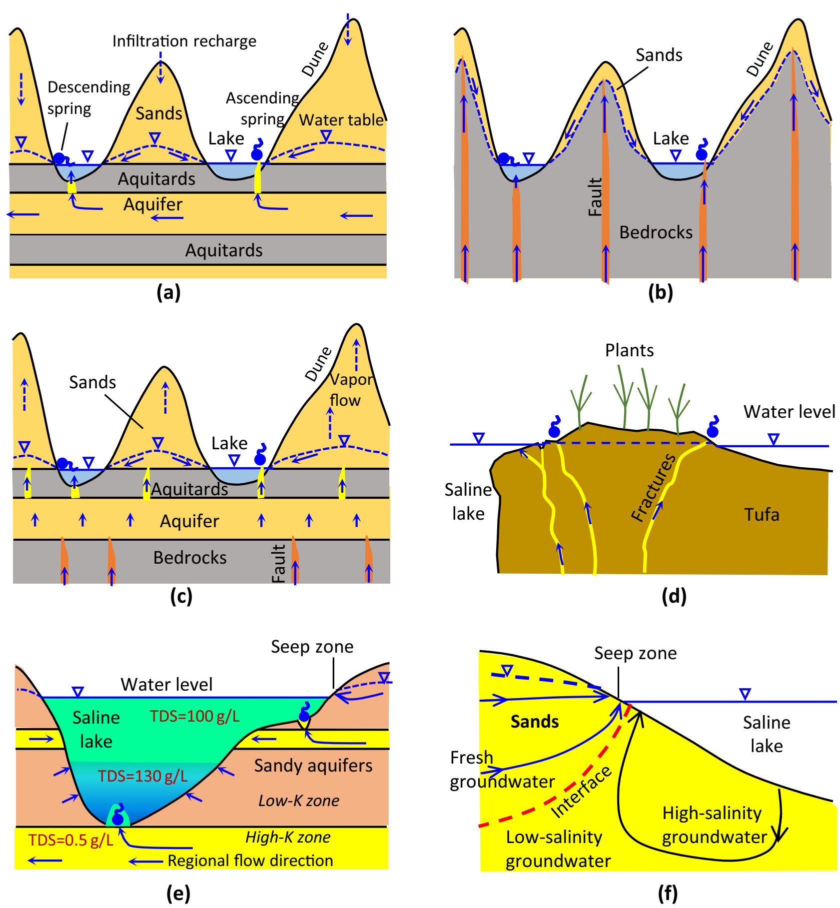

Fig. 6 Schematic diagrams (not to scale) of groundwater discharge to the lakes according to different conceptual models described in the literature. **a** Sheng et al. (1981); **b** Chen et al. (2004); **c** Ding et al. (2015); **d** Arp et al. (1998); **e** Chen et al. (2015); Gong et al. (2016) and **f** Luo et al. (2016)

predominant ions in groundwater near the lakes are Na and Cl-SO_4, not Ca-Mg and HCO_3-CO_3. Arp et al. (1998) found that the tufa was developed from a hydro-chemically forced calcification of microbial mats at sublacustrine springs. Such sublacustrine springs were also identified in lakes without islands, for example in lakes Sumujaran-S and Sumujaran-E (Fig. 1b), as reported by Chen et al. (2015) and Gong et al. (2016). These sublacustrine springs indicate the heterogeneity of the aquifer media beneath the lakes which lead to a groundwater discharge model shown in Fig. 6e. This is a refinement of the model in Fig. 6a, including both layered high-*K* (more permeable) and low-*K* (less permeable) zones that were penetrated by the lakes. Seep zones of small wetlands and ponds on lowlands inclining toward a lake are commonly found so that they are also included in the model; however, the model should be further improved for the part near the lake shoreline if density driven flow is significant. Luo et al. (2016) investigated the spatial variations of groundwater chemistry along a section of Lake Sumujaran-S. According to the salinity profile, an interface of freshwater and saline water exists and inclines toward the sand dune. The salinity difference in groundwater may imply a density-driven flow beneath the lake, which is schematically represented in Fig. 6f and looks like a model of submarine groundwater discharge (SGD) in which the seepage circulation of seawater driven by density differences in the aquifers should be taken into account (Burnett et al. 2003).

The mixed distribution of sub-saline and hypersaline lakes in the southeastern district (Hofmann 1999) triggers a new problem for the groundwater–lake relationship: how can a sub-saline lake keep low salinity in the vicinity of a hypersaline lake with similar groundwater discharge conditions? A typical example is the area of the Badain lakes (Figs. 5 and 7a) where the sub-saline Lake Badain-E (TDS < 2 g/L) is separated from the hypersaline Lake Badain-W (TDS > 300 g/L) by a sand dune. If Lake Badain-E has been there for thousands of years, an outflow is necessary to export salts in the lake that were brought in from the groundwater-fed process. Liu et al. (2015) used the distributed temperature sensing (DTS) technique in an experiment to identify groundwater discharge to the Badain-E. Groundwater discharge in this lake was also investigated using the information of stable ^{18}O and ^{2}H isotopes and temporal ^{222}Rn distributions (Luo et al. 2016, 2017). These investigations resulted in different models of groundwater flow between the two lakes. The model in Fig. 7b suggests that the lake water in Badain-E would leak to Lake Badain-W across the inter-lake dune (Luo et al. 2017); however, the model in Fig. 7c considers a water table in the dune that is higher than water levels in both of the lakes (Liu et al. 2015). To allow export of salts from Lake Badain-E (otherwise it should be a saline lake), Liu et al. (2015) suggested an outflow along the northern lakeshore (Fig. 7d). Which model agrees with the reality? This is a problem for future studies.

Temporal variation patterns of lakes and groundwater

Water levels in the lakes and boreholes have been observed in recent years but long-term monitoring was only undertaken at the sites of Lake Sumujaran-S (Wang et al. 2014; Gong et al. 2016) and Lake Nuoertu (Wu et al. 2014). Wu et al. (2014) reported the observation results of water level change in the Nuoertu and in a nearby spring pond for the period between 2011 and 2012. It was showed that the water levels decrease in the summer and increase in the winter but the seasonal fluctuation was limited to ±30 cm for the lake and ±10 cm for the spring water level. Similar observation results were reported and analyzed in Wang et al. (2014) and Gong et al. (2016) for the Sumujaran-S. The monitoring system at the site of Sumujaran-S was established in 2012, including (1) an automated meteorological station on a platform in the lake which is about 50 m away from the shoreline, (2) an evaporation pan (60 cm in diameter) installed near the platform to measure the evaporation rate of the lake water, (3) water pressure and temperature sensors installed near the bottom of the lake, and (4) a 16-m-deep borehole, W7, drilled at a location 200 m away from the lakeshore to monitor the groundwater (Wang et al.

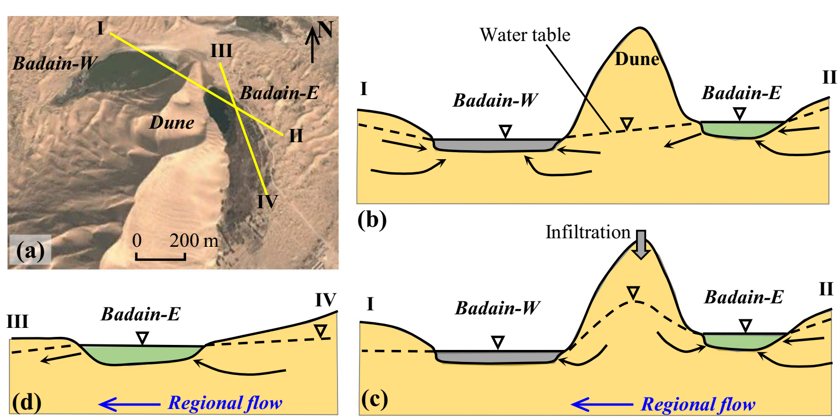

Fig. 7 Conceptual models of the groundwater–lake relationship in the Badain lakes area: **a** location of lakes; **b** profile I-II according to the model described in Luo et al. (2017); **c** profile I-II and **d** profile III-IV according to the model described in Liu et al. (2015). Arrows denote the groundwater flow directions

2014). The monthly data of precipitation, evaporation, groundwater level and lake water level in the period 2012–2014 are shown in Fig. 8. It can be seen that from May to October the monthly evaporation rate was higher than 100 mm (Fig. 8a), causing decrease in both the groundwater (Fig. 8b) and lake water levels (Fig. 8c), at a rate of 30–50 mm/month, significantly smaller than the evaporation rate. The seasonal fluctuation of the water level in the lake was about ±15 cm. A 1-month delayed response was exhibited in groundwater level in W7. Gong et al. (2016) built a linear dynamic model to capture the seasonal variation of water balance in the lake. The seasonal groundwater discharge rate was estimated as 85.4 (±4.0%) mm/month, covering the area of the lake (1.27×10^6 m^3/year), which is highly stable in comparison to the precipitation and evaporation. In summary, the quasi-steady groundwater discharge in the lakes is the key to the significantly small seasonal fluctuation of water level in the lakes against the strong evaporation loss in the summer.

At the regional scale, the dynamic behavior of the lakes was mainly analyzed through remote sensing data (Jin et al. 2014; Zhang et al. 2015a; Jiao et al. 2015). In particular, Jiao et al. (2015) introduced the NASA ice, cloud and land elevation satellite (ICESat) data to identify the inter-annual change in lake water levels. They found a decreasing trend during 2003–2009 for most of the analyzed lakes. The changes in groundwater storage at regional scale on 1° × 1° grids were retrieved with satellite source data of gravity (GRACE), which also showed a declining trend during 2003–2011. Zhang et al. (2015a) quantified the change in the area of 50 lakes in the BJD using 30-m-resolution remote-sensing images. They obtained a different result in which the total area of the 50 lakes increased from ~15 km^2 in 2000 to ~18 km^2 in 2010. Uncertainties in analyzing the remote-sensing data should be taken into account in further study on the inter-annual variations in the desert lakes.

Discussion on the groundwater/surface-water relations

The relationship between groundwater and lakes at the regional scale is controlled by flow paths in the aquifer system and the penetrating depth of the lakes in the aquifers, as shown in Fig. 6a–c. Only Fig. 6a,c includes normal aquifers and aquitards, which basically agrees with the geological structure in the BJD shown in Fig. 3. However, the aquitards beneath the lakes are formed by materials that are not very different from the aquifers; these materials are also Quaternary sandy sediments, but just with a bit lower permeability (low-*K* zone in Fig. 6e). Accordingly, the lakes are actually lying on an aquifer with isotropic and heterogeneous porous media. The depth and surface area of water in a lake are generally less than 20 m and 2.0 km^2, respectively, significantly smaller than the size of the Quaternary aquifer. Therefore, a lake in the BJD analogically roles as a partially penetrating well with a pumping rate that is proportional to the evaporation rate, which raises the problem of how three-dimensional (3D) groundwater flow at the regional scale is affected by the lakes with variable "pumping rate". A following question refers to

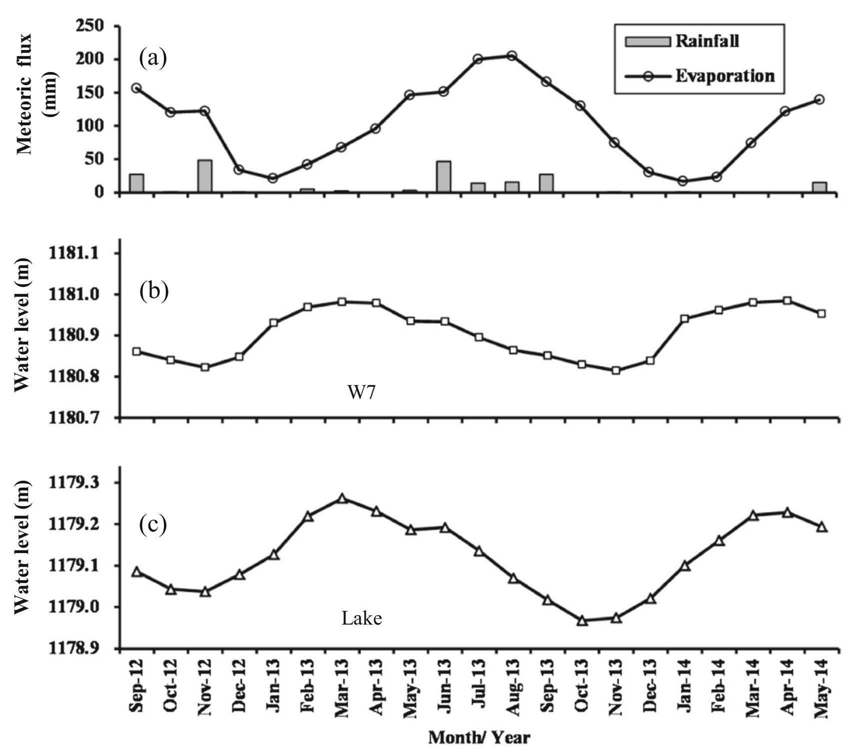

Fig. 8 Observed data at the site of Lake Sumujaran-S: **a** monthly rainfall and evaporation; **b** monthly average groundwater level in borehole W7, which is 200 m away from the lakeshore; **c** monthly average water level in the lake

how the lakes influence each other through groundwater hydraulics. Wang et al. (2014) addressed the problem but only discussed the two-dimensional (2D) hierarchical flow systems beneath the lakes in the steady state along a profile. The 3D patterns and unsteady behaviors of the coupling between groundwater and lakes are worthy of further investigation with multiple remote-sensing data sources and modeling techniques. Saline water intrusion in the aquifer beneath a lake driven by variable density flow (Fig. 6f) should be taken into account at the scale of a depression. It is still not known how deep the saline water penetrates into the fresh groundwater body.

Why is the deuterium excess in groundwater abnormally negative?

Deuterium excess data and previous analyses

The relationship between δD and $\delta^{18}O$ in rains is characterized by the global meteoric water line (GMWL)

$$\delta D = 8\delta^{18}O + 10‰ \quad (2)$$

Equation (2) can be rewritten to define the deuterium excess (Dansgaard 1964) for any water sample, as follows:

$$D\text{-excess} = \delta D - 8\delta^{18}O \quad (3)$$

The D-excess would be close to 10‰ if groundwater in a region originated from precipitation without any isotope fractionation processes.

The first published report on the anomalous negative D-excess in groundwater in the BJD was presented by Geyh et al. (1998). They collected samples from groundwater at different sites in the Alxa Plateau (Ejin, Gurinai, BJD and surrounding areas) and surface water from the Heihe River. Samples of the precipitation collected in different seasons in 1988 were also used to build up a local meteoric water line (LMWL). They found that the groundwater samples in the BJD and Gurinai exhibited a significantly low D-excess (−22‰); even the regression line of data points seemed to be parallel to the LMWL. In comparison, the D-excess values of groundwater in the other arid regions in North Africa, Saudi Arabia and India were generally positive (Geyh et al. 1998). Groundwater samples in the Ejin Oasis and other places near the Heihe River showed D-excess values between −10 and 20‰, mostly higher than 2‰.

Zhao et al. (2012) collected more samples from the BJD to investigate the D-excess of groundwater in a more detailed way, along with existing data in the literature. Unlike that shown in Geyh et al. (1998), the regression line of groundwater in the BJD is not parallel to the LMWL but extends with a smaller slope and intercepts the LMWL at $\delta^{18}O$ = −13.4‰ and $\delta^{18}D$= −90.8‰, yielding negative D-excess ranges between −17.5 and −34.5‰. The BJD seems to be a center of extremely negative D-excess groundwater in the Alxa Plateau according to the spatial distribution of data. Zhao et al. (2012) speculated that the present desert groundwater originated from paleo-recharge under a colder and wetter climate condition and has been influenced by strong evaporation. How did both the cold precipitation and strong evaporation in the past cause the negative D-excess in the present groundwater without a significant increase in salinity? This has remained a big question behind the hypothesis.

It has been well known that evaporation can result in a progressive enrichment of ^{18}O and ^{2}H in the residual liquid water. For natural open water bodies the enrichment will approximately follow a line of $\delta^{18}O$ versus δD (Gonfiantini 1986), but the slope depends on the environment. This evaporation effect can be also found in groundwater samples. The evaporation lines with respect to groundwater and lakes in the BJD were analyzed by Gates et al. (2008a) and Zhao et al. (2012). A slope of +4.7 (Gates et al. 2008a) or +4.5 (Zhao et al. 2012) was suggested for shallow groundwater samples. The regression line of lake samples seemed to be consistent with that of groundwater samples. Since the slope is smaller than that of the GMWL and LMWL, a decrease in D-excess occurs when water is undergoing evaporation. Water samples extracted from soils in the unsaturated zone using the azeotropic distillation method were also analyzed by Gates et al. (2008a), which showed a smaller slope (+2.4) of the evaporation line and a significant enrichment in ^{18}O (being close to lakes). Accordingly, Gates et al. (2008a) suggested that direct infiltration across the unsaturated zone is not a major source of groundwater recharge. Anyway, isotope fractionation in the evaporation process, with such a smaller slope, can cause more significant increase in the D-excess.

Recent experiments on the evaporation effect in the BJD were reported by Wu et al. (2017). The experiments were undertaken in the summer at the site near Lake Sumujaran-N. Two pans were used to measure evaporation from open water bodies, one pan is initially filled with groundwater from a nearby well, whereas another pan is initially filled with the lake water. Three sandboxes were used to measure the evaporation effect in the unsaturated zone. Groundwater extracted from the nearby well was uniformly dripped onto the surface of the sandboxes to reproduce infiltration. Relevant data on the evaporating groundwater are shown in Fig. 9. Details and results are reported in Wu et al. (2017). It was indicated that all the water samples collected in the experiments share an evaporation line with a slope of +4.6, which soundly falls between the suggested values in Gates et al. (2008a) and Zhao et al. (2012).

A backward analysis of the evaporation effect and related discussion

The new results in Wu et al. (2017) encouraged the authors to perform a backward analysis on the evolution of stable isotopes in subsurface water before recharging to groundwater. The conceptual model is shown in Fig. 9 with data of the Zhangye precipitation and lakes in the BJD (Zhang et al. 2011). The D-excess of fresh groundwater is about −20‰. It can be retrieved backward along the evaporation line to a point with a D-excess value between 10 and 0‰. The start point represents a presumed paleo-precipitation. The arrival of the water molecule in the saturated zone, as a component of groundwater recharge, was delayed by a long-time flow through the thick unsaturated zone. The significant increase in the D-excess was triggered by evaporation during infiltration in the near surface zone. After that, the isotopes of water in the saturated zone will continue a change (as a result of groundwater discharge to lakes or flow across a shallow water-table area) along the evaporation line, yielding a very low D-excess value (which may reach −40‰). Thus, the abnormal negative D-excess in groundwater in the BJD is a combined effect of evaporation processes during infiltration recharge and groundwater flow across the inter-dune depressions.

Further investigations are expected to confirm or improve this backward analysis. The evaporation effect on the infiltration water across the sand box described in Wu et al. (2017) seemed to be different from that reported in Gates et al. (2008a) for samples in the unsaturated zone. Chen et al. (2012a) also detected the isotopes in soil water with a maximum depth of 3 m and obtained an evaporation line with the slope of +3.88. These different slopes (from +2.4 to +4.6) of the evaporation line in soils bring uncertainties in determining the backward speculated position of the paleo-precipitation. A laboratory experiment carried out by Sun et al. (2009) indicated that the evaporation line of samples in the unsaturated sands was close to that of open water as long as they are in the same environment. Similar experiments should be performed in the in situ environment in the BJD, maybe in different seasons with different vegetation coverages, to confirm this evaporation effect on the D-excess.

Summary and prospects

The emergence of questions and debates on groundwater in the BJD in the past few decades has been an active driver, prompting scientists to increase the number of expeditions, observations and investigations in the BJD, with an open mind and with interdisciplinary cooperation. Recently, significant progress has been achieved in solving some of the problems, which can be summarized:

1. The possibility is very low that groundwater in the BJD is mostly transported by tectonic faults from remote sources. Instead, groundwater flow occurs in an aquifer system composed by thick sedimentary formations (Fig. 3) and is mainly driven by lateral recharge from surrounding mountains (Fig. 4).
2. A portion of groundwater in the BJD is flowing toward the downstream area of the HRB. The flow rate across the boundary between the BJD and HRB is still indeterminable but the range would probably be (0.2–1.1) × 10^8 m^3/year.

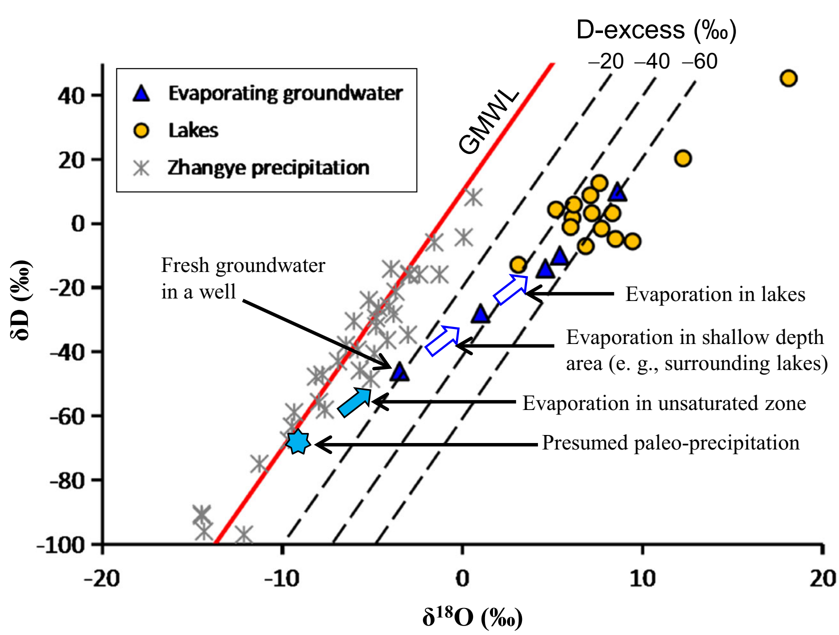

Fig. 9 Conceptual model for the change in D-excess of water in the BJD, from precipitation to groundwater and then to lakes. The evaporating groundwater data were obtained in a pan-evaporation experiment (Wu et al. 2017). The lakes data were presented in Zhang et al. (2011). The data of Zhangye precipitation (1986–2003) were obtained from the IAEA/WMO Global Network Isotopes in Precipitation (GNIP)

3. Fresh groundwater is widely distributed in the desert and discharges to the lakes with different kinds of springs, including sublacustrine springs and upwelling springs on mounds in saline lakes. Seasonal fluctuations of water level in the lakes are less than 0.5 m due to quasi-steady groundwater discharge.
4. The anomalous negative D-excess in groundwater in the BJD should be a synthetic result of the paleo-precipitation, evaporation during infiltration through the unsaturated zone, and secondary evaporation when groundwater flows across depression areas with shallow water tables.

With respect to further investigations, this paper firstly highlights the unresolved problem of infiltration recharge. The limitations that applied in previous studies should be carefully considered. Second, this paper highlights the problem of coupling behaviors between lakes and groundwater at the regional or sub-basin scales in the BJD. To reveal the coupling behaviors, multiple remote-sensing data sources and modeling techniques may be necessary. In addition, the structural and dynamic features of the flow systems beneath the lakes are not well known but are also worthy of study.

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