



Hydrologic partition and maintenance mechanism of Badain Jaran Desert lake group indicated by hydrogen and oxygen stable isotopes, northwest China

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Abstract

The study of hydrologic partition has great significance in exploring the water cycle mechanism of Badain Jaran Desert (BJD) lakes in northwest China. This study analyzes the characteristics of δD and $\delta^{18}O$ isotopes of 160 groups of water bodies in the BJD area, an isotopic buildup model is constructed to classify the hydrologic partition of the lakes by estimating the ratio between lake evaporation (E) and discharge (I), and the maintenance mechanism of the lake group indicated by E/I is discussed. The results show that the lake group primarily relies on groundwater recharge and direct recharge of a small amount of local rainwater and the local rainwater is not the main source of groundwater recharge. The mean E/I values of δD and $\delta^{18}O$ calculated for 30 lakes in the BJD ranged from 0.74 to 1.33 (mean 1.05), indicating that the lake group largely maintained total recharge and evaporation at the same level; however, lake group have a tendency for terminal lakes to evolve into desiccating lakes. The primary reasons for the constant E/I of approximately 1 and the stability of lake group are: (1) stable groundwater recharge ensures the stability of total recharge and (2) small interannual changes in temperature, relative humidity, and the salinity effect ensure the stability of the annual evaporation of salt lakes. E/I of Badandong Lake to estimate the amount of water discharged by its seasonal drainage channels in winter and spring is approximately 10,649.16 m³/a. The outflow water discharges salt, which is the main reason the lake maintains a brackish water state. This study provides a reference for future research on the water cycle mechanism of lakes in arid regions.

Keywords Badain Jaran Desert · Lake group · δD and $\delta^{18}O$ isotopes · Hydrologic partition · Evaporation fractionation

Introduction

Lakes are a critical link in the global water cycle, especially in arid and semiarid areas, and provide important barriers for maintaining fragile ecological environments (Good et al. 2015; Lyons and Sheng 2017; Wurtsbaugh et al. 2017). In arid areas, precipitation is scarce, and evaporation is high, and in this situation, it is difficult to maintain surface runoff or for the lakes to maintain stability. However, in the extremely arid Badain Jaran Desert (BJD) in northwest China, annual precipitation is only 70–120 mm, and evaporation is as high as 1200–2000 mm (Zhang 2020), but

it can maintain the existence of 110 perennial lakes. It is unclear how these lakes maintain stability. In this regard, there are currently five different theories, which are: local atmospheric precipitation or condensate recharge (Dong et al. 2004; Shao et al. 2012; Hou et al. 2016); recharge from ancient water residues in the humid period (late Pleistocene or Mid-Holocene) (Yang et al. 2010); flooding in southern mountainous areas such as Mount Yabulai or local precipitation recharge (Gates et al. 2008a); regional deep groundwater is recharge to the lakes along the altitude gradient from southeast to northwest (Wu et al. 2014; Wang et al. 2016); and groundwater from the Qinghai–Tibet Plateau and Qilian Mountains passes through the deep and large faults to recharge BJD lakes (Chen et al. 2004). However, the source of lake water recharge and the maintenance mechanism remain inconclusive.

The study of water balance is key to understanding the lake recharge sources and maintenance mechanisms. In the past 20 years, many scholars have made important

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progress in the study of water balance in BJD lakes (Wang et al. 2018; Zhang 2020), and the research mainly focused on quantifying evaporation and groundwater recharge (Chen et al. 2004; Yang et al. 2010; Gong et al. 2016; Luo et al. 2016, 2017; Zhang et al. 2017; Wang et al. 2020); the hydrologic partition of lakes has not been fully studied. δD and $\delta^{18}\text{O}$ isotopes are an effective method to study the water cycle; this method is based on the theory that during the processes of evaporation, condensation, and migration, light and heavier isotopes have different saturated vapor pressures and diffusion rates, which cause the light isotopes to easily separate from the liquid water into the air, and for the heavy isotope to be enriched in the liquid water. The isotope content in different water phases is different, which is an important method used for tracing the water cycle process and studying water balance (Gibson and Reid 2010; Xiao et al. 2017; Liao et al. 2018, 2020). Based on this theory, some scholars use the relationship between the budget terms of the δD and $\delta^{18}\text{O}$ isotopes mass balance models to convert the ratio between evaporation (E) and discharge (I) in lakes (E/I) and to quantify the hydrologic partition of lakes (Gat 1995; Gibson and Edwards 2002; Gibson et al. 2010, 2016a, b, 2017).

The lakes in the BJD lack surface runoff recharge and mainly rely on groundwater recharge and direct recharge of a small amount of rainwater (Wu et al. 2014; Wang et al. 2016). Evaporation is the main drainage pattern, and the water cycle process of BJD lakes is simple; hence, this is an ideal place to study the E/I of lakes. However, δD and $\delta^{18}\text{O}$ isotopes in the BJD are currently mainly used as other indicators, such as inferring groundwater recharge sources (Chen et al. 2004; Zhao et al. 2012; Wu et al. 2014, 2017), tracing whether or not precipitation can infiltrate and recharge groundwater (Gates et al. 2008a, b; Ma et al. 2009; Yang et al. 2010; Jin et al. 2018), and determining groundwater age (Wu et al. 2014); they are less used in the research of E/I of lakes (Luo et al. 2017). Therefore, quantitative research on lake group E/I and the lake maintenance mechanism indicated by it is still insufficient.

The objectives of this research were to: (1) analyze the δD and $\delta^{18}\text{O}$ isotope characteristics of BJD lake water, well water, spring water, and rainwater and (2) explore the lake maintenance mechanism based on the E/I of lakes indicated by δD and $\delta^{18}\text{O}$ isotopes. The aims of this study were to quantify the hydrologic partition of BJD lakes from the perspective of δD and $\delta^{18}\text{O}$ isotopes, reveal the perennial maintenance mechanism of lakes, and provide reference for regional ecological environment protection and water resources utilization.

Materials and methods

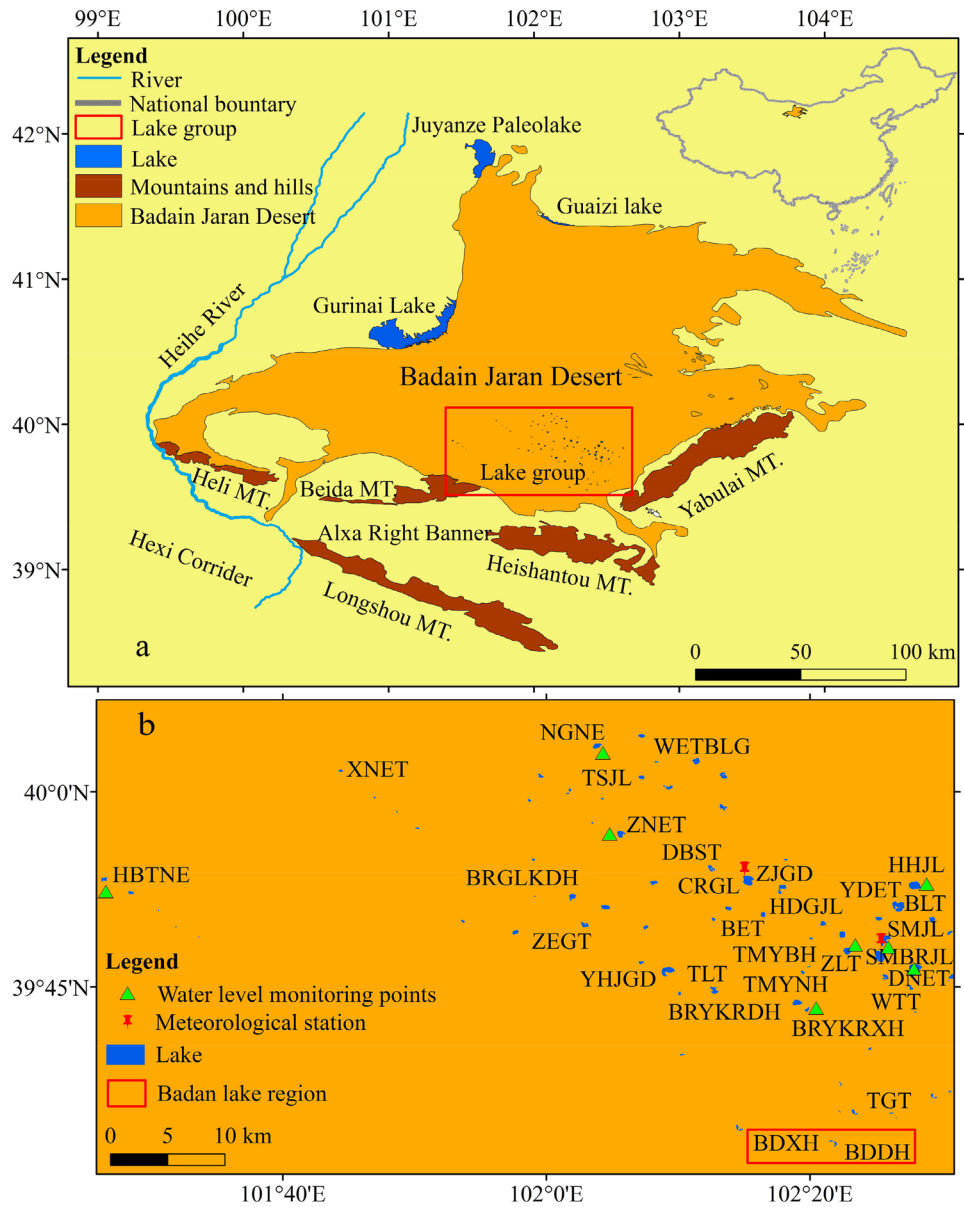
Site descriptions

The BJD is located between the western part of Alxa League and the Hexi Corridor in the Inner Mongolia Autonomous Region of northwest China (Fig. 1a). The desert is approximately 350 km wide from north to south and 420 km long from east to west, with an area of approximately $5.2 \times 10^4 \text{ km}^2$, making it the second largest desert in the China (Zhu et al. 2010). The terrain of the entire desert is low in the northwest and high in the southeast (1100–1700 m). The highest sand hills in the world have developed in this desert, generally to heights of 200–300 m, with the highest sand hill being $> 453 \text{ m}$ (Niu et al. 2021). There are 105 perennial lakes distributed in the depressions between the sandy mountains, which generally cover areas of $< 1 \text{ km}^2$; their locations are shown in Fig. 1b. The BJD is located at the edge of the confluence of Asian monsoon and Westerly wind (Wang et al. 2010), which has a typical continental climate. The annual mean precipitation is between 70 and 110 mm and is concentrated from May to September (Liang et al. 2020). The annual mean temperature is 8–8.9 °C, and the annual lake evaporation is 1200–2000 mm (Zhang 2020). Most of the lakes in the hinterland of the desert are salt lakes, with total dissolved solids (TDS) concentrations between 0.80 and 500 g/L. There are a few freshwater lakes and weak salt lakes on the edge of the desert, especially in the southeast, such as BDDH in Fig. 1b.

Field work and laboratory analyses

The team successively collected and analyzed 160 groups of lake water, well water, spring water, and rainwater samples with δD and $\delta^{18}\text{O}$ isotopes from 2009 to 2015, including 76 groups of lake water, 25 groups of well water, 39 groups of spring water, and 20 groups of rainwater; the collection time and quantities of each type of sample are shown in Table 1. The δD and $\delta^{18}\text{O}$ isotopes were measured with a high-temperature conversion elemental analyzer (TC-EA) connected with a Thermo Finnigan MAT 253 isotope ratio mass spectrometer at the Environmental Isotope Laboratory of the Geographic Sciences and Resources Institute, Chinese Academy of Sciences. When transporting samples, the positions of the standard and experimental samples were interspersed; we first inserted three standard samples, followed by ten samples, and each sample had test six times. At the end of the test, data were imported into the instrument calibration software Post Process Chem Correct, the software parameters were set (ignoring the values of the first three times), and the software automatically calibrated the data. The measurement results adopted the V-SMOW

Fig. 1 Geological and topographic settings of the Badain Jaran Desert **a** location of the Badain Jaran Desert and **b** distribution of lakes, water level monitoring points, and meteorological stations)



| Lake name and abbreviation | | |
|----------------------------|----------------------|----------------------------|
| Xinuortu: XNET | Wuertabulage: WETBLG | Zhongnuoertu: ZNET |
| Habutenuoer: HBTNE | Tamayingnanhu: TMYNH | Huhejilin: HHJL |
| Badandonghu: BDDH | Taosenjilin: TSJL | Barunyikeridonghu: BRYKRDH |
| Tonggututu: TGT | Buerte: BET | Barunyikerixihu: BRYKRXH |
| Zhunjigede: ZJGD | Dabusutu: DBST | Barungelikedonghu: BRGLKDH |
| Zhalate: ZLT | Yihejigede: YHJGD | Hudugejilin: HDGJL |
| Cherigele: CRGL | Tamayinbeihu: TMYBH | Badanxihu: BDXH |
| Yindeertu: YDET | Dongnuoertu: DNET | Taolaitu: TLT |
| Naogunnuoer: NGNE | Zhaoergetu: ZEGT | Sumujilin: SMJL |
| Bilutu: BLT | Wutongtu: WTT | Sumubarunjilin: SMBRJL |

standard, and the measurement errors of δD and $\delta^{18}O$ isotopes were $< 2\text{‰}$ and 0.3‰ , respectively.

The research team successively installed a batch of Solinst3001 self-recording water level dataloggers in 2011

to observe the groundwater level and lake water level, and a Barologger barometer exposed to the air was installed at the SMBRJL meteorological station (Fig. 1b) to measure the air pressure. The water level dataloggers record the hourly

Table 1 Details of δD and $\delta^{18}O$ isotope collection samples from lake water, well water, spring water, and rainwater in the Badain Jaran Desert from September 2009 to September 2015

| Lake water | | Well water | | Spring water | | Rainwater | |
|------------|--------|------------|--------|--------------|--------|-----------------|--------|
| Date | Number | Date | Number | Date | Number | Date | Number |
| 2009.09 | 17 | 2009.09 | 11 | 2009.09 | 7 | 2009.09 | 1 |
| 2010.09 | 14 | 2010.09 | 5 | 2010.09 | 9 | 2010.09 | 1 |
| 2011.04 | 3 | 2011.04 | 3 | 2011.04 | 3 | 2013.06–2013.09 | 6 |
| 2012.04 | 7 | 2012.04 | 1 | 2012.04 | 6 | 2015.06–2015.09 | 12 |
| 2015.07 | 35 | 2013.1 | 5 | 2013.04 | 14 | — | — |
| Total | 76 | Total | 25 | Total | 39 | Total | 20 |

“—” represents no sampling

average water level data—the data observation accuracy is 0.05% of the range, and the barometer accuracy is 0.1 cm. The groundwater water level dataloggers were mainly arranged in a shallow well of 1.5–2 m within a radius of 200 m around the lake, the lake water level dataloggers were mainly arranged within the range of 30–100 m from the lake shore, and the water level dataloggers were initially placed about 30 cm below the water surface. After collection and sorting, the observed water level pressure was subtracted from the atmospheric pressure for air pressure correction. Individual lakes were eliminated or corrected in the case of obvious errors due to excessive water level drop from the water level dataloggers, fluctuations before and after data collection, high-salinity lake water corrosion of the water level dataloggers, and lake water icing. This study selected water level datasets with longer observation time and improved accuracy from eight lakes and analyzed both lake water level and groundwater level. Specific locations are shown in Fig. 1b.

We deployed a MAWS-301 meteorological station produced by Finnish Vaisala on the edge of the SMBRJL and CRGL lakes in May and October 2010, respectively (Fig. 1b). The meteorological station was equipped with a VRQ101 rain gauge, a QMH102 temperature and humidity sensor, a WAA151 wind speed sensor, and other equipment, which were able to operate stably in the field environment of -50 to 60 °C. The meteorological station monitored meteorological factors such as precipitation, temperature, and relative humidity on the scale of 10 min and 1 h. The accuracy of meteorological factors observed by various types of sensors was $\pm 1\%$, ± 0.1 °C/2.0%, and ± 0.17 m/s, respectively. The data were calibrated by a 16-bit analog/digital converter to ensure the weather information accuracy. The monthly changes in meteorological factors of the two stations from 2011 to 2015 are shown in Fig. 2.

Methods

Under the assumption that a lake is stable and the water body is uniformly mixed, combining the lake water balance model and the δD and $\delta^{18}O$ isotopes mass balance models can trace

the lake E/I (Gibson et al. 2016a, b). BJD lakes have small annual changes (Wang et al. 2020; Yu 2020), so these lakes can be regarded as somewhat stable environments. Moreover, most of these lakes are shallow and dish-shaped lakes in arid areas, where wind propulsion can easily mix water and δD and $\delta^{18}O$ isotopes. According to the results of Wu et al. (2014) and Luo et al. (2017) who studied two deeper lakes, DNET (maximum depth 15.96 m, the deepest lake in the BJD) and SMBRJL (mean depth 8 m), both lakes exhibited uniform water mixing and no obvious physicochemical parameter differences or δD and $\delta^{18}O$ isotopes stratification. Therefore, the hypothesis of uniform isotope mixing is also valid for our study. Under the premise of satisfying the above assumptions, the lake δD and $\delta^{18}O$ isotopes mass balance models can be expressed as Eqs. 1 and 2:

$$\frac{dV}{dt} = G + P - E \quad (1)$$

$$\frac{dV(\delta_L)}{dt} = I\delta_I - E\delta_E \quad (2)$$

In Eqs. (1 and 2), V is the lake water volume; t is the time; I is the total recharge of the lake, including groundwater G and rainwater P ; and E is the lake evaporation. δ_L , δ_I , and δ_E , represent the isotope value of the corresponding water body. The isotope δ_E of lake water surface evaporation cannot be directly observed, according to its relationship with temperature and relative humidity. δ_E can be calculated by the Craig and Li (1965) model, as shown in Eq. (3):

$$\delta_E = \frac{(\delta_L - \epsilon^*)/\alpha^* - RH\delta_A - \epsilon_K}{1 - RH + 10^{-3}\epsilon_K} \quad (3)$$

In Eq. (3), α^* represents the equilibrium fractionation coefficient, and Majoube (1971) adopted the regression equation to describe the relationship between α^* and the absolute temperature of the lake surface (K) as shown in Eqs. (4 and 5):

$$10^3 \ln \alpha^*(^2H) = 24.844 \times 10^6/T^2 - 76.248 \times 10^3/T + 52.612 \quad (4)$$

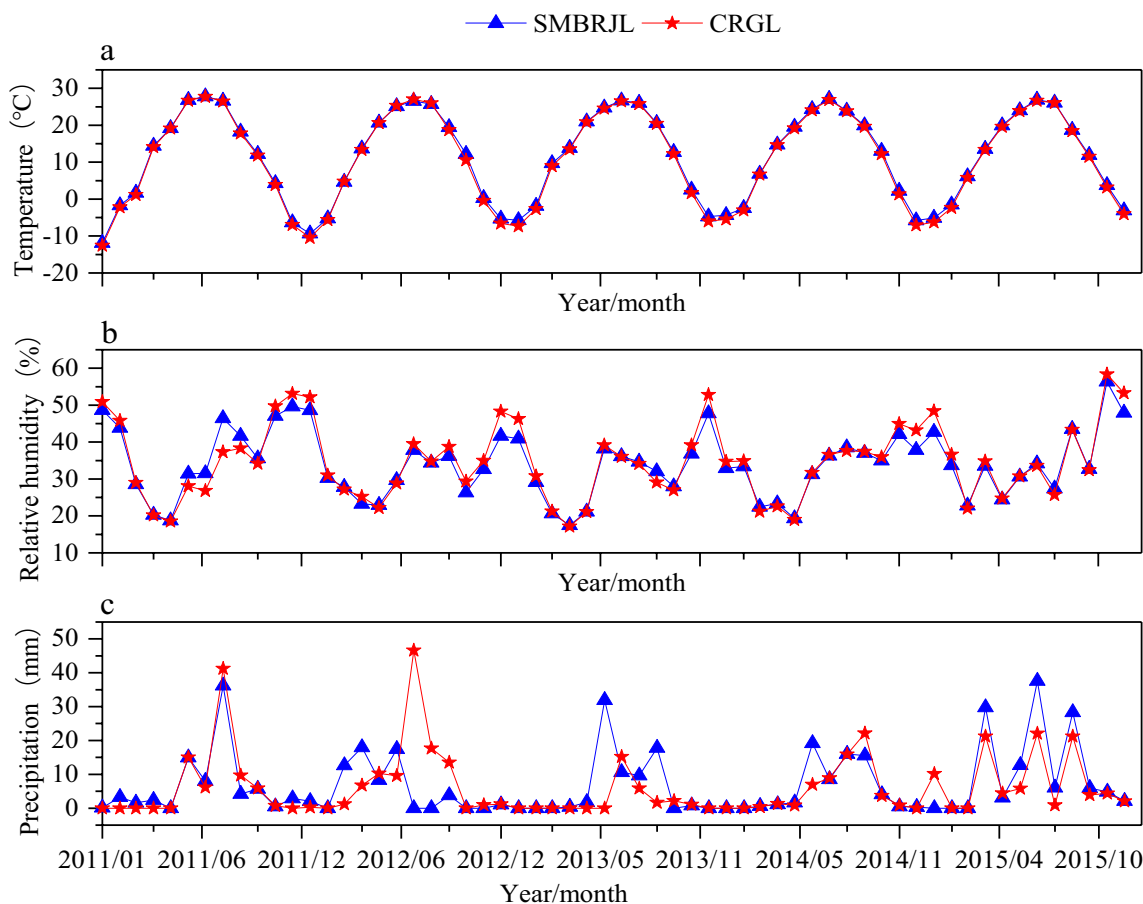


Fig. 2 Interannual variation of meteorological factors in the Badain Jaran Desert **a** temperature; **b** relative humidity; and **c**. precipitation)

$$10^3 \ln \alpha^* (^{18}O) = 1.137 \times 10^6 / T^2 - 0.4156 \times 10^3 / T - 2.0667 \quad (5)$$

ϵ^* is the equilibrium enrichment coefficient, which is converted to the equilibrium fractionation coefficient α^* , $\epsilon^* = 1000 \times (\alpha^* - 1)$; RH is the normalized relative humidity, expressed by the ratio of relative humidity h and water activity coefficient a_w ($RH = h/a_w$); a_w is affected by the salinity effect (Gat and Levy 1978; Gonfiantini 1986; Gat 1995; Horita 1990), which is calculated by the functional relationship between water density ρ (kg/m³) and a_w in the Dead Sea based on Oroud (1994), Asmar and Ergenzinger (1999) investigated results, shown in Eq. (6):

$$a_w = -30.285 + 77.650\rho - 62.712\rho^2 + 16.300\rho^3 \quad (6)$$

δ_A is the isotopic composition of the atmosphere above the water body, which can be determined by the function relationship between δD and $\delta^{18}O$ in the atmosphere and temperature t (°C) proposed by Jacob and Sonntag (1991) such as Eqs. (7–8):

$$\delta D_A = -0.11t^2 + 5.17t - 175 \quad (7)$$

$$\delta^{18}O_A = -0.014t^2 + 0.67t - 23.4 \quad (8)$$

ϵ_k is the dynamic enrichment coefficient, $\epsilon_k = C_K(1-RH)$, C_K is the kinetic constant of water molecule diffusion, and δD and $\delta^{18}O$ isotopes are 12.5‰ and 14.2‰, respectively (Gonfiantini 1986). When a lake is in a stable state, assuming $d\delta_L/dt = 0$, the above equations can be combined, and the relationship between E and I can be determined, as shown in Eq. (9) (Gibson 2002, 2016a):

$$\frac{E}{I} = \frac{\delta_I - \delta_L}{\delta_E - \delta_L} = \frac{\delta_I - \delta_L}{m(\delta^* - \delta_L)} \quad (9)$$

Here, m and δ^* are the slope and limit value of lake isotope enrichment over time, respectively, and the calculations are shown in Eqs. (10) and (11):

$$m = \frac{RH - 10^{-3} \times (\epsilon_K + \epsilon^* / \alpha^*)}{1 - RH + 10^{-3} \epsilon_K} \quad (10)$$

$$\delta^* = \frac{RH\delta_A + \epsilon_K + \epsilon^*/\alpha^*}{RH - 10^{-3} \times (\epsilon_K + \epsilon^*/\alpha^*)} \tag{11}$$

In this study, we selected 30 lakes that had δD and $\delta^{18}O$ isotopes of lake water, well water, or spring water at the same time and divided their hydrologic partition by calculating mean E/I based on δD and $\delta^{18}O$ isotopes. All lakes' T and h were taken as the mean values of 21.78 °C and 30.78% from April to September 2011–2015 at the CRGL and SMBRJL meteorological stations. For isotope values, the mean value of multiple samples of the same lake was taken as the lake water δ_L ; the total recharge δ_I was calculated by the recharge ratio of groundwater and rainwater to the lake, the recharge ratio based on the results of previous studies (Zhang et al. 2017; Zhao 2018), taken the mean values of 83.75 and 16.23%, respectively. The groundwater δD and $\delta^{18}O$ values were taken as the mean values of well water and spring water; the rainwater δD and $\delta^{18}O$ values were taken as the mean values of 20 groups of rainwater samples. The lake water density ρ was converted from

the average TDS in September 2010 and April 2011. The lake TDS was calculated according to the results of Zhang (2020), and a_w was calculated to be between 0.84 and 1.

With reference to the previous classification standards of lake hydrologic partition (Horita 1990; Gat 1995; Gibson et al. 2010, 2016a; Luo et al. 2017), $E/I < 1$ was divided into a through-flow lake, $E/I = 1$ was divided into a terminal lake, and $E/I > 1$ was divided into a desiccating lake. In reality, lakes with E/I equal to 1 are rare. Luo et al. (2017) classified lakes with $E/I \approx 1$ as terminal lake, but there is no specific fluctuation range. This study considers that there are seasonal differences in the isotopes of BJD lake water, well water, and spring water (Table 2). The collection locations of different water bodies are scattered, resulting in greater E/I fluctuations. Therefore, this study counts the 95% confidence interval of mean E/I value calculated by δD and $\delta^{18}O$ as ± 0.05 , so the division standard is adjusted; $E/I < 0.95$ is classified as a through-flow lake; $0.95 \leq E/I \leq 1.05$ is classified as a terminal lake; and $E/I > 1.05$ is classified as a desiccating lake.

Table 2 δD and $\delta^{18}O$ isotope values of lake water, well water, and spring water in the Badain Jaran Desert seasonal changes from September 2009 to July 2015 (‰)

| Lake | Samples | 2009.09 | | 2010.09 | | 2011.04 | | 2012.04 | | 2013.1 | | 2015.07 | |
|--------|--------------|------------|----------------|------------|----------------|------------|----------------|------------|----------------|------------|----------------|------------|----------------|
| | | δD | $\delta^{18}O$ | δD | $\delta^{18}O$ | δD | $\delta^{18}O$ | δD | $\delta^{18}O$ | δD | $\delta^{18}O$ | δD | $\delta^{18}O$ |
| WETBLG | Lake water | -4.81 | 8.49 | - | - | - | - | - | - | - | - | 19.00 | 10.35 |
| ZJGD | Lake water | -8.17 | 5.96 | 3.50 | 8.94 | - | - | - | - | - | - | - | - |
| HDGJL | Lake water | 20.32 | 12.25 | 15.45 | 9.73 | - | - | - | - | - | - | - | - |
| ZNET | Lake water | 10.35 | 8.43 | - | - | -2.81 | 5.42 | - | - | - | - | -0.18 | 7.95 |
| BDDH | Lake water | 5.88 | 6.18 | - | - | - | - | -33.60 | -0.49 | - | - | -43.38 | -0.44 |
| TMYNH | Lake water | 0.03 | 8.07 | - | - | - | - | - | - | - | - | 1.59 | 7.49 |
| BLT | Lake water | - | - | -1.97 | 8.01 | - | - | - | - | - | - | -3.55 | 6.77 |
| XNET | Lake water | - | - | 5.13 | 3.91 | - | - | -21.76 | 5.53 | - | - | - | - |
| WTT | Lake water | - | - | - | - | - | - | -5.80 | 5.33 | - | - | 29.96 | 10.85 |
| HHJL | Well water | -51.61 | -4.05 | - | - | - | - | - | - | -57.13 | -5.32 | - | - |
| ZLT | Spring water | -39.78 | -2.21 | - | - | - | - | - | - | -42.39 | -3.12 | - | - |
| TSJL | Spring water | -48.34 | -4.12 | - | - | - | - | - | - | -51.60 | -3.76 | - | - |
| SMJL | Lake water | 3.23 | 8.33 | - | - | -5.91 | 4.81 | -23.15 | 2.41 | - | - | -3.18 | 6.09 |
| | Well water | -60.93 | -12.36 | - | - | -42.79 | -4.57 | -54.02 | -4.79 | - | - | - | - |
| | Spring water | -56.41 | -5.40 | - | - | -48.92 | -4.89 | -62.29 | -6.08 | -56.03 | -5.22 | - | - |
| NGNE | Lake water | -8.14 | 5.38 | 9.51 | 10.42 | - | - | -18.40 | 3.74 | - | - | 4.40 | 9.00 |
| | Spring water | - | - | -52.18 | -3.27 | - | - | -54.15 | -4.34 | -52.41 | -4.00 | - | - |
| YDET | Lake water | -7.07 | 6.84 | - | - | - | - | -11.83 | 3.90 | - | - | -0.41 | 6.65 |
| | Spring water | -50.71 | -1.28 | -41.24 | -1.27 | - | - | -55.68 | -5.10 | -55.48 | -5.03 | - | - |
| CRGL | Lake water | - | - | - | - | -18.83 | 4.68 | - | - | - | - | -26.15 | 3.17 |
| | Well water | - | - | -42.59 | -3.52 | -41.44 | -3.04 | - | - | -47.84 | -3.39 | - | - |
| | Spring water | -61.39 | -6.31 | - | - | -43.54 | -3.85 | - | - | -59.73 | -5.36 | - | - |

“-” represents no sampling

Results

Characteristics of δD and $\delta^{18}O$ isotopes in different water bodies

The δD and $\delta^{18}O$ isotope compositions of different water bodies are shown in Fig. 3, and the characteristics of isotope changes are shown in Table 3.

From the comparison of δD and $\delta^{18}O$ isotopes composition of different water bodies in the BJD shown in Fig. 3 and Table 3, the local rainwater evaporation line deviates from the Global Meteoric Water Line (GMWL, $\delta D = 8\delta^{18}O + 10$), indicating that the extremely arid environment in the hinterland of the desert caused secondary fractionation of rainwater. The δD and $\delta^{18}O$ isotopes of lake water are distributed on the upper right of the rainwater evaporation line, and the isotope value is the most positive and d-excess is the most negative; the δD and $\delta^{18}O$ isotopes of well water and spring water are distributed on the lower left and the isotopes value is negative, indicating that evaporative fractionation of lake water is the most significant, whereas well water and spring water are less affected by evaporative fractionation. Extending the lake water evaporation line in the reverse

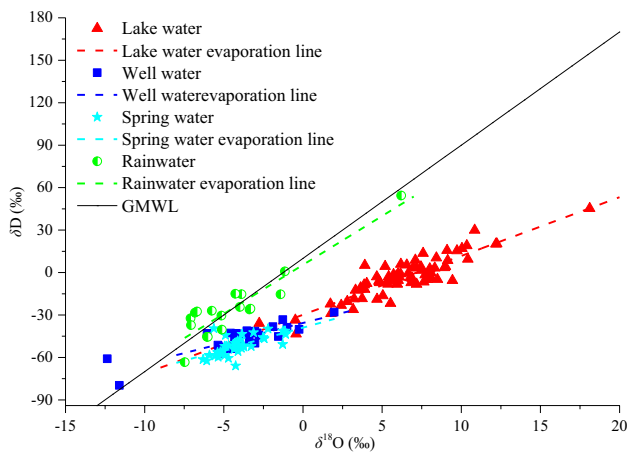


Fig. 3 δD and $\delta^{18}O$ isotope distributions in different water bodies in the Badain Jaran Desert

direction, the evaporation line was within the distribution range of the isotope values of well water and spring water, indicating that well water and spring water were the main sources of recharge for lake water and that groundwater evaporates again after recharging the lake. Comparing the evaporation lines of different water bodies, the evaporation line of lake water is slightly higher than that of well water and spring water, which is close to it, but much smaller than that of rainwater. This indicates that the main source of lake water recharge is groundwater, represented by well water and spring water. It is also affected by a small amount of rainwater recharge; thus, the evaporation line of the lake is situated between the two water types and more closer to groundwater. Comparing the distribution of rainwater and groundwater δD and $\delta^{18}O$ isotopes, it was found that few groundwater isotopes are close to rainwater, but most of the groundwater isotopes are distributed below the rainwater evaporation line, and the mean values of δD and $\delta^{18}O$ isotopes in groundwater are more negative than rainwater. This because shallow groundwater is affected by a small amount of rainwater infiltration, but deep groundwater is not affected by rainwater. These results indicate that the groundwater around the lake is mainly recharged by deep groundwater, and rainwater is not its main source of recharge, which is consistent with the conclusions of previous field rainfall infiltration experiments (Ma et al. 2014; Dong et al. 2016). Although the d-excess of groundwater is negative, it remains as fresh water and is not saline, indicating that groundwater is slightly affected by evaporation and fractionation (Zhang et al. 2011). However, this is not evaporation fractionation after rainwater infiltration, but the result of an extended retention time in the process of groundwater transportation to the desert. The $\delta^{18}O$ enrichment is caused by water–rock interaction and the δD is mostly unchanged (Chen 2012, 2017). If rainwater infiltration heavily to recharge groundwater, the evaporation fractionation of the water should also occur during infiltration (Dong 2011). Therefore, the groundwater isotope value should be more positive than that in rainwater and should be distributed on the rainwater evaporation line or upper right. However, a contrary isotope distribution is evident (Fig. 3). Moreover, the δD and $\delta^{18}O$ results of the sand mountain profile show that the evaporation fractionation of soil water

Table 3 Variation characteristics of δD and $\delta^{18}O$ in different water bodies in the Badain Jaran Desert (‰)

| Samples | Date | Total | Range | | Mean | | Standard deviation | | d-excess | |
|--------------|-----------------|-------|--------------------|------------------|------------|----------------|--------------------|----------------|--------------------|---------|
| | | | δD | $\delta^{18}O$ | δD | $\delta^{18}O$ | δD | $\delta^{18}O$ | Range | Mean |
| Lake water | 2009.09–2015.07 | 76 | – 43.38 to 45.32 | – 2.77 to 18.11 | – 3.03 | 6.45 | 14.27 | 3.07 | – 118.40 to – 8.23 | – 67.25 |
| Well water | 2009.09–2013.10 | 25 | – 79.75 to – 28.00 | – 12.36 to 1.97 | – 46.69 | – 3.9 | 10.04 | 3.02 | – 47.70 to 62.71 | – 8.77 |
| Spring water | 2009.09–2013.10 | 39 | – 65.91 to – 39.53 | – 6.31 to – 1.10 | – 51.66 | – 4.09 | 6.63 | 1.37 | – 37.93 to – 4.62 | – 11.48 |
| Rainwater | 2009.09–2015.09 | 20 | – 63.39 to 54.41 | – 7.47 to 6.20 | – 25.24 | – 4.57 | 23.53 | 3.13 | – 4.07 to 31.58 | 11.32 |

in the 30–50 cm sand layer is significant and the isotope value is positive, and the 70–110 cm soil water isotope is negative (Dong 2011), which is not affected by evaporation fractionation, which also indicates that rainwater is not the main source of groundwater recharge.

Hydrologic partition of lakes

The E/I and hydrologic partition of lakes are shown in Table 4, and the spatial distribution pattern of hydrologic partition is shown in Fig. 4.

From Table 4, the E/I ratios of the 30 lakes calculated by the δD and $\delta^{18}O$ isotopes are between 0.62 and 1.41 and 0.81 and 1.24, respectively, and the mean of both isotopes is

Table 4 Hydrologic partition of lakes in the Badain Jaran Desert based on δD and $\delta^{18}O$

| Lake | E/I (δD) | E/I ($\delta^{18}O$) | E/I (mean value) | Type (mean value) |
|---------|----------------------|--------------------------|--------------------|-------------------|
| XNET | 0.87 | 0.81 | 0.84 | I |
| HBTNE | 0.84 | 0.84 | 0.84 | I |
| BDDH | 0.62 | 0.87 | 0.74 | I |
| BRGLKDH | 0.95 | 0.88 | 0.92 | I |
| ZJGD | 0.86 | 0.89 | 0.88 | I |
| ZLT | 0.88 | 0.93 | 0.91 | I |
| CRGL | 0.68 | 0.94 | 0.81 | I |
| YDET | 1.01 | 0.94 | 0.97 | II |
| NGNE | 1.02 | 0.98 | 1 | II |
| WETBLG | 0.93 | 1.01 | 0.97 | II |
| TMYNH | 1.06 | 1.02 | 1.04 | II |
| TSJL | 0.96 | 1.04 | 1 | II |
| BLT | 1.01 | 1.05 | 1.03 | II |
| BET | 1.04 | 1.06 | 1.05 | II |
| DBST | 1 | 1.09 | 1.05 | II |
| YHJGD | 1.2 | 1.08 | 1.14 | III |
| TMYBH | 1.08 | 1.11 | 1.09 | III |
| DNET | 1.11 | 1.12 | 1.12 | III |
| ZEGT | 1.06 | 1.13 | 1.09 | III |
| HHJL | 1.24 | 1.14 | 1.19 | III |
| BRYKRXH | 1.12 | 1.17 | 1.15 | III |
| ZNET | 1.23 | 1.14 | 1.18 | III |
| BRYKRDH | 1.24 | 1.15 | 1.2 | III |
| TGT | 1.26 | 1.17 | 1.22 | III |
| WTT | 1.08 | 1.17 | 1.13 | III |
| HDGJL | 1.2 | 1.18 | 1.19 | III |
| BDXH | 1 | 1.21 | 1.11 | III |
| TLT | 1.31 | 1.23 | 1.27 | III |
| SMJL | 1.11 | 1.22 | 1.16 | III |
| SMBRJL | 1.41 | 1.3 | 1.33 | III |

“I,” “II,” and “III” represent through-flow lake, terminal lake, and desiccating lake, respectively

between 0.74 and 1.33. Overall, the E/I ratios calculated by the two isotopes are close, but the individual lakes are quite different, which agrees with one previous conclusion (Luo et al. 2017). In order to reduce the fluctuation caused by the difference between the two isotopes, the mean E/I calculated by δD and $\delta^{18}O$ isotopes is used as the basis for the division of lake hydrologic partition. Among the 30 lakes, there are 7 through-flow lakes, 8 terminal lakes, and 15 desiccating lakes. From the perspective of the proportion of lake hydrologic partition, desiccating lakes occupy the highest proportion.

It can be seen from the spatial distribution pattern of lake hydrologic partition indicated by E/I in Fig. 4 that the through-flow lakes are scattered in the desert hinterland and along the southeast edge, terminal lakes are concentrated in the desert hinterland, and desiccating lakes are mainly distributed in the desert hinterland and are scattered along the southeast edge. Combined with the E/I results and lake hydrologic partition, the mean E/I calculated by the δD and $\delta^{18}O$ isotopes of the 30 lakes in the BJD is 1.05, generally belonging to terminal lake. On the whole, the lake group can maintain total recharge and evaporation at the same level, and the evaporation was slightly higher than the total recharge. Accordingly, there is a tendency for the terminal lake to evolve into a desiccating lake, which is consistent with the phenomenon that most lakes in the BJD hinterland can maintain a stable existence all year round and have a tendency to dry up slowly.

Discussion

Factors affecting hydrologic partition and lake group maintenance mechanism

Theoretically, several lakes with $E/I < 1$ are through-flow lakes under the assumption that the lake is stable. In other areas, some scholars have reached similar conclusions when applying E/I to quantify the hydrologic partition of lakes (Bennett et al. 2008; Chen 2017; Gibson et al. 2016b, 2017). However, based on several years of field investigations by the research team and the groundwater and lake water level monitoring results (Fig. 5), except for the BDDH with seasonal drainage channels (Fig. 6), other lakes had no surface runoff outflow. More importantly, the groundwater levels of most lake basins in the desert are higher than their associated lake water level. Most of the most lakes receive groundwater recharge; thus, the possibility of lake water replenishing groundwater is extremely small. If a lake replenishes the groundwater, it will increase the salinity of nearshore groundwater. However, field investigations show that the groundwater at the lakeshore, a distance of 1 m from the lake, is not saline (Dong et al. 2016). Therefore, we are of

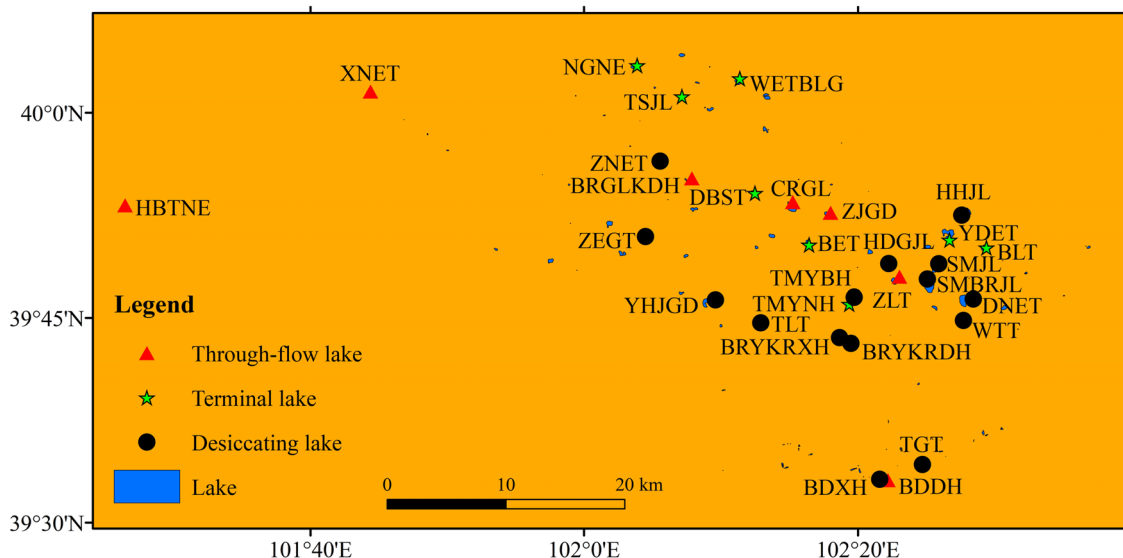


Fig. 4 Spatial distribution of hydrologic partition of lakes in the Badain Jaran Desert based on mean *E/I* of δD and $\delta^{18}O$

the view that lake water recharge to groundwater or lake water outflow is not possible. The reason why several lakes have a small *E/I* in this study is that the δD and $\delta^{18}O$ isotopes used to calculate *E/I* are affected by many factors. These factors include annual and seasonal changes in isotope values, changes in lake water level, and meteorological environmental factors. The ability to identify whether lakes are through-flow lakes based on *E/I* and the lake maintenance mechanism indicated by *E/I* needs to be further analyzed.

Firstly, there are varying degrees of interannual and seasonal changes in lake water levels (Wang et al. 2020), and this will inevitably lead to changes in *E/I*. According to consecutive observations of the groundwater level and lake water level around the eight lakes in the hinterland of the desert (Fig. 5), the groundwater levels and lake water levels decreased from April to October and increased from November to March of the following year, which amplitudes are 24.02–125.31 cm and 24.12–51.57 cm, respectively. This same change pattern of lake water and groundwater indicates the groundwater recharge around most lakes is in a stable state at the interannual scale, which is the main reason the total recharge maintains a stable state, and the lake water level to maintain a stable existence for a long time. However, the water level of a few lakes fluctuates greatly seasonally (such as the HBTNE, ZJGD, BRGLKDH, and XNET in Fig. 1b), which directly affected the *E/I* results (Table 4). According to remote sensing interpretation of the seasonal changes in lake area and field surveys conducted by Zhu et al. (2011), BRGLKDH and XNET in Fig. 1b are nearly drying up, and they are becoming seasonal lakes; therefore, their *E/I* values are too small.

Secondly, the isotope values of lake water during the calculation in this study are the mean values from April to September in 2009–2015, and seasonal differences are the reason for the small *E/I* of some lakes, such as XNET and ZJGD in Fig. 1b (Table 2). Besides, the sampling points of lake water are close to spring water, and the δD and $\delta^{18}O$ isotopes in spring water are negative, which will also affect the results of *E/I*, such as BDDH, CRGL, and ZLT in Fig. 1b. In addition, the isotope value of groundwater takes the mean value of well water and spring water. Although the two values are relatively close, there are spatial and seasonal differences whereby some well water is closer to the surface, the evaporation fractionation is strong, and the isotope value is too high. Moreover, some well water was interfered with by herdsmen, resulting in a high isotope value, resulting in lower total recharge isotope δI and reduced *E/I* calculation results (Eq. 9) in the cases of ZJGD, HBTNE, and BRGLKDH in Fig. 1b. It can also be seen from the 95% confidence interval reported in Sect. 2.3 that the seasonal changes in the δD and $\delta^{18}O$ isotopes of the 30 lakes in this study have an average impact of $\pm 5\%$ on *E/I*, which is similar to that reported by Luo et al. (2017) ($\pm 3\text{--}8\%$); the overall impact is small, but the impact on individual lakes is greater, and the *E/I* calculation results are relatively small.

Finally, the temperature and relative humidity are taken the mean value of April to September in 2011–2015, and the TDS value is the mean of the April and September TDS values in 2010 and 2011. Seasonal differences in these parameters will inevitably cause certain fluctuations in the results. The interannual variations of temperature, relative humidity, and salinity of the BJD were small. The stability

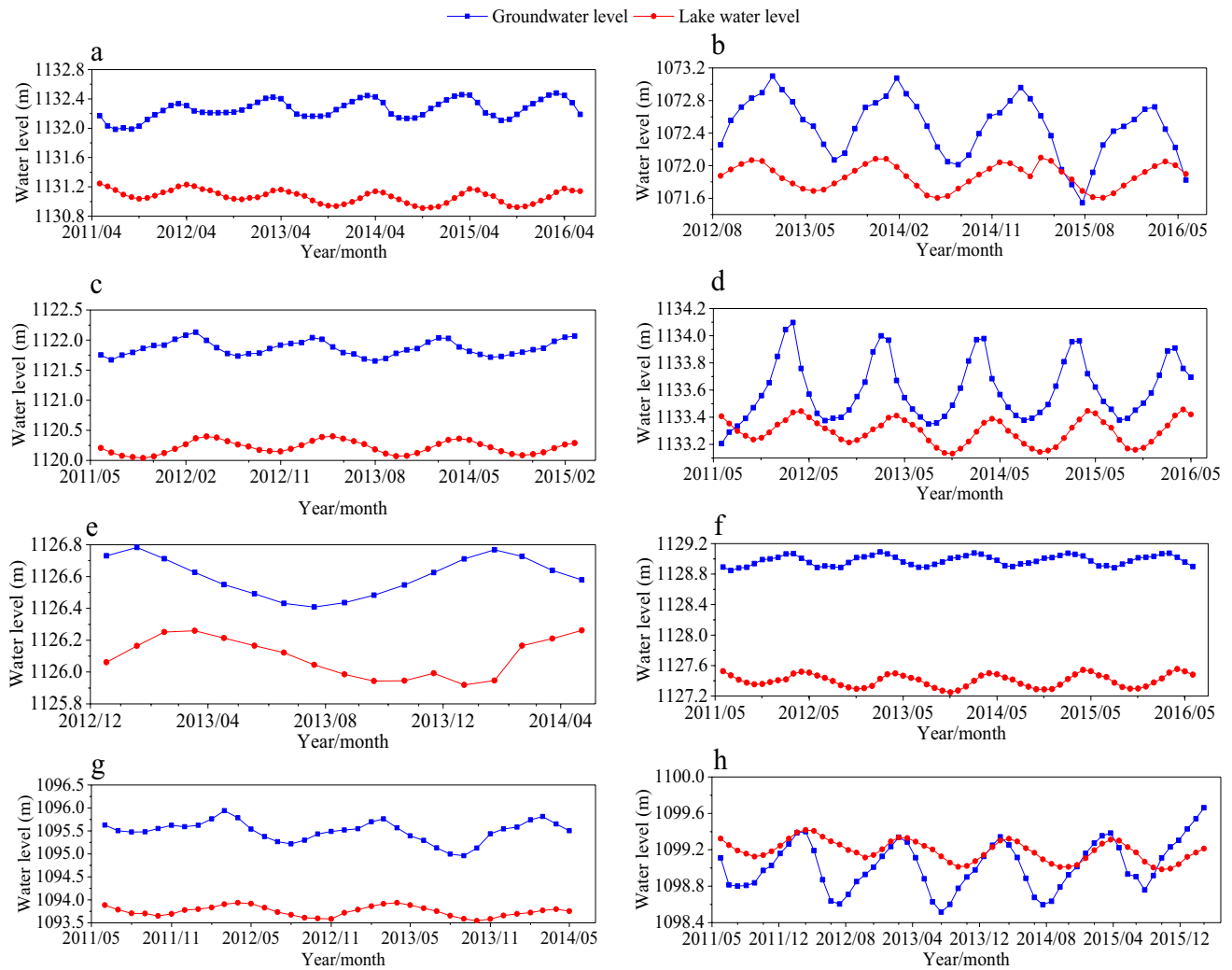


Fig. 5 Monthly changes in groundwater and lake water levels in the Badain Jaran Desert (**a** DNET; **b** HBTNE; **c** BRYKRDH; **d** HHJL; **e** ZLT; **f** SMBRJL; **g** NGNE; and **h** ZNET)

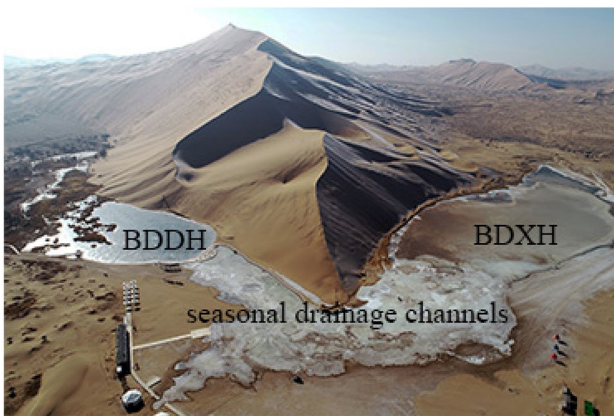


Fig. 6 Badan Lake region in the Badain Jaran Desert

of meteorological factors also results in small fluctuations of evaporation, and the presence of salt effectively reduces the evaporation loss of salt lakes (Wu et al. 2014; Zhang 2020), thus maintaining an *E/I* stability close to 1. Whereas seasonal variations of meteorological factors are large (Fig. 2; Liang et al. 2020; Zhang 2020), the seasonal difference of *E/I* is also large. The fluctuation ranges of temperature and relative humidity before and after the mean value are -38 to 27% and -44 to 46% , respectively, the difference in TDS for the 30 lakes can reach 100 g/L (Zhang 2020), the mean values of water activity coefficient a_w are 0.90 and 0.94 for April and September, respectively, and the resulting change in relative humidity is about 20%, and these factors impact on the *E/I* change.

In summary, the seven through-flow lakes listed in Table 4, except BDDH with seasonal drainage channels, belong to the real through-flow lake. The other six

through-flow lakes in this study may be affected by seasonal differences in lake water level, isotope sampling, and meteorological factors, resulting in these lakes having a small E/I , and they do not belong to the group of through-flow lakes. There are two main reasons for the constant E/I of approximately 1 and the stable existence of lake groups. The first is that the stability of groundwater recharge on an interannual scale ensures the stability of the total recharge. The second is that the small interannual changes in temperature, relative humidity, and TDS and the salinity effect significantly reduce evaporation in salt lakes, thereby maintaining annual evaporation stability.

Groundwater recharge and water outflow of Badandong Lake estimated by E/I

The BDDH is a relatively special weak salt lake within the BJD; its annual mean TDS is low, at 1.65 g/L. For BDXH, which is located on the other side of a sandy mountain from BDDH (Fig. 6), the annual mean TDS is as high as 285.12 g/L. The reasons as to why these lakes are located close together, have a huge salinity difference, and are able to maintain weak salt water all year round, are controversial (Liu et al. 2016; Luo et al. 2016, 2017; Song et al. 2018; Wang et al. 2018). This study found that BDDH is a through-flow lake and that a seasonal drainage channel may be the reason the lake maintains a brackish water state. However, the amount of drainage water needs to be quantified.

When a lake is in a stable state, the outflow water quantity is the difference between the total recharge and evaporation, and the ratio is $1-E/I$. Based on E/I , only need to obtain the precipitation and the area of the lake to determine the groundwater recharge and outflow. The precipitation of BDDH used in this study was based on the ratio of precipitation between BDDH and that recorded by the Alxa Right Banner meteorological station in 2015: 0.78, which translates to 72.69 mm of precipitation at BDDH in 2013. The evaporation and lake area in 2013 are 1955.82 mm and 17,679.73 m², respectively, based on the results of Zhang (2020). The E/I of BDDH is 0.74 (Table 4); based on this, the groundwater recharge and outflow water from the lake can be calculated as 45,442.39 m³/a and 12,149.16 m³/a, respectively. Compared with the groundwater recharge and outflow water volume of other scholars, Luo et al. (2016) used ²²²Rn to estimate the groundwater recharge rate and mean rate of outflow water of BDDH in 2013 as 7.6 mm/d and 1.4 mm/d, which is 49043.57 m³/a and 9034.34 m³/a, respectively. Gong et al. (2016) estimated the groundwater recharge and outflow of BDDH to be approximately 46,710 m³/a and 17,449.89 m³/a based on the assumption that the lake maintains a salt balance. The groundwater recharge calculated in this study is close to that found in the previous study (Gong et al. 2016; Luo et al. 2017), and

the outflow water is between both studies, which is within a reasonable range. Gong et al. (2016) pointed out that the outflow water of BDDH includes the underground runoff at the junction between BDDH and BDXH as well as the amount of water outflow by seasonal drainage channels. Among them, the underground runoff discharge at the junction between the two lakes amount was 1500 m³/a (Gong et al. 2016). Based on this ratio, the outflow water of the seasonal drainage channel is 10649.16 m³/a, accounting for 23.43% of groundwater recharge, which is the discharge water volume that cannot be ignored in the calculation of the lake water balance. The existence of seasonal drainage channels allows the lake to discharge the salt accumulated in summer and autumn in winter and spring, maintaining long-term weak salinity in the lake (Gong et al. 2016; Luo et al. 2017).

Conclusions

Through the analysis of the δD and $\delta^{18}O$ isotopes characteristics of the water bodies in the Badain Jaran Desert (BJD) in northwest China, as well as the study of the hydrologic partition of lakes by the ratio between lake evaporation (E) and discharge (I), the following conclusions were drawn: the fractionation degree of lake water was the deepest, the lake group mainly relies on groundwater for recharge and a small amount of local rainwater for direct recharge, and local rainwater is not the main source of groundwater recharge. The mean E/I ratio calculated by δD and $\delta^{18}O$ of 30 lakes in the BJD ranged from 0.74 to 1.33 (mean 1.05), indicating that lake group in the BJD can maintain similar levels of total recharge and evaporation and that evaporation is slightly greater than total recharge. Moreover, there is an overall tendency for the lake group to evolve toward desiccation. The BJD lake group has stable groundwater recharge with small interannual changes in temperature, relative humidity, and TDS. Moreover, the salinity effect significantly reduces evaporation, which ensures a stable total recharge (I) and annual evaporation (E), and is also the basis for a stable E/I of approximately 1. Among the 30 lakes, only the Badandong Lake can be classified as a through-flow lake. Based on $E/I=0.74$, the water discharged of BDDH by the seasonal drainage channel was approximately 10,649.16 m³/a, which accounts for 23.43% of the groundwater recharge. The saline outflow water discharge is the reason why the salinity of the lake remains low. This study, from the perspective of δD and $\delta^{18}O$ isotopes, explains why the BJD hinterland can maintain the existence of most perennial lakes all year round. Furthermore, this study can provide reference for the investigation of the water cycle process and water balance of lakes in other desert areas around the world.

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Author contributions Xianbao Su and Naiang Wang proposed the idea and designed the study; Chenao Lu and Meng Li collected the samples in field work and analyzed the data in laboratory; Jianxiang Zhang, and Xiao Liu analyzed the results; Xianbao Su, Chenao Lu, and Naiang Wang contributed to the discussion; and Xianbao Su wrote the main manuscript text. All authors approved the final version.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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