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Change of lake area in the southeastern part of China's Badain Jaran Sand Sea and its implications for recharge sources

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Abstract: Understanding the relationship between the changes in lake water volume and climate change can provide valuable information to the recharge sources of lake water. This is particularly true in arid areas such as the Badain Jaran Sand Sea, an ecologically sensitive area, where the recharge sources of lakes are heatedly debated. In this study, we determined the areas of 50 lakes (representing 70% of the total permanent lakes in this sand sea) in 1967, 1975, 1990, 2000 and 2010 by analyzing remote-sensing images using image processing and ArGIS software. In general, the total lake area decreased from 1967 to 1990, remained almost unchanged from 1990 to 2000, and increased from 2000 to 2010. Analysis of the relationship between these changes and the contemporaneous changes in annual mean temperature and annual precipitation in the surrounding areas suggests that temperature has significantly affected the lake area, but that the influence of precipitation was minor. These results tend to support the palaeo-water recharge hypothesis for lakes of the Badain Jaran Sand Sea, considering the fact that the distribution and area of lakes are closely related to precipitation and the size of mega-dunes, but the contemporaneous precipitation can hardly balance the lake water.

Keywords: arid environment; lake change; source of water recharge; climate change

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The Badain Jaran Sand Sea is the second-largest shifting sand sea in China (Zhu et al., 1980). Its unique characteristics, such as the presence of the tallest mega-dunes on Earth (up to 480 m), the mysterious "booming sands" and the long history of the regional Mongolian culture, have made it become a central part of the Alxa Desert Geopark. Researchers have been curious about the geomorphic processes that occur in this sand sea, particularly where the mega-dunes are interspersed with lakes that occur in many low-lying areas throughout the sand sea and that vary in size, shape and salinity (Dong et al., 2004).

The last decade has witnessed unprecedented interest from researchers about the formation of the lakes in the Badain Jaran Sand Sea, and particularly their sources of water supply and their relationships with the mega-dunes, because this information is crucial to support water resources planning in this arid and ecologically sensitive area (e.g. Chen et al., 2004; Dong et al., 2004, 2009; Ma and Edmunds, 2006; Ma et al., 2007; Gates et al., 2008a; Lu et al., 2010; Zhao et al., 2011a). Heated disputes have arisen over the sources of the lake water and three hypotheses have been proposed. The first is that precipitation provides the lake water. Precipitation is either stored in the mega-dunes (Wang, 1990; Hofman, 1996; Jäkel, 1996) or in the mountains south of the sand sea (Dong et al., 2004; Ma and Edmunds, 2006). The second claims that the mega-dune and lake water originates from snowmelt in the Qilian Mountains, which lie more

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than 200 km southwest of the sand sea across a deep and widespread system of faults (Chen et al., 2004; Ding and Wang, 2007). The third suggests that the lakes are residual lakes (Zhang et al., 2002) and represent the remains of mega-lakes that existed in the sand sea between 42 and 18 ka BP. This hypothesis proposes that the mega-lakes shrank to their current size in response to global climate change.

A key issue in these debates is how to assess the significance of climate in terms of its effects on the lake water. To some extent, the changes in the lake area in recent decades, a time when observed meteorological data is available for the surrounding areas, may provide some valuable clues. Changes in lake area can be reliably assessed by comparing time series images (Li et al., 2008; Li and Sheng, 2013). Remote-sensing method is widely used to study the dynamic variations in lakes (e.g. Yao et al., 2013; Zhang et al., 2013). The purpose of the present study is to analyze changes in lake areas in the Badain Jaran Sand Sea using aerial photographs and satellite images, and to relate these changes to climate change during the study period. Attempts are also made to discuss the implications of lake area change for lake recharge sources.

1 Study area and methods

1.1 Study area

China's Badain Jaran Sand Sea (39°20'–42°00'N, 99°48'–104°14'E) lies in the northwestern part of the Alxa Highlands of western Inner Mongolia, covering an area of 49,000 km^2 (Fig. 1a; Dong et al., 2004). The sand sea is bounded to the south by the Heli, Beidai and Heishantou mountains, which separate it from the gobi deserts of the Hexi Corridor. To the southeast, it is bounded by the Yabrai Mountains, which separate it from the Tengger Desert. To the west, it stretches down to the low and flat Gulunai grassland. To the north, it is bounded by the Guaizihu wetland, which merges with the black gobi and the plains of Mongolia. The elevation gradually decreases from approximately 1,800 m in the southeast to 1,000 m in the northwest. The Heihe River to the west is the only permanent river near the sand sea. Precipitation ranges from 40 to 80 mm/a, decreasing from the southeast towards the northwest. There are about 140 lakes in the study area, of which about 70 are permanent lakes (Zhu et al., 2011). The densest occurrence of lakes is in the southeastern section of the sand sea, where more than 100 lakes are concentrated within an area of about 4,000 km^2.

1.2 Methods

We determined the lake areas in 1967, 1975, 1990, 2000 and 2010 by analyzing remote-sensing images using image processing software. These data comprised 1:40,000 aerial photographs obtained in July 1967, Landsat MSS images with a resolution of 80 m obtained in July 1975, Landsat TM images with a resolution of 30 m obtained in July 1990 and 2010, and Landsat ETM images with a resolution of 30 m obtained in July 2000. The aerial photographs were first scanned so they could be analyzed on a computer.

Accurate geometric rectification of the images was performed using version 8.7 of the ERDAS IMAGINE software (ERDAS, Norcross, GA, USA) before measuring the lake areas. This was done as follows: (1) The ETM images from 2000 were accurately rectified using 1:100,000 topographic maps. We selected 30 to 40 reference points, distributed as uniformly as possible throughout each image, to minimize the rectification error, and the actual error was within 1 to 2 pixels (i.e. ≤60 m), and then (2) images from 1967, 1975, 1990 and 2010 were rectified using the accurately rectified ETM images from 2000 by means of image matching in IMAGINE.

Lake areas in each year were identified in the rectified images by using ArcGIS 9.2 (ESRI, Redlands, CA, USA) according to the mapping standard of 1:100,000 maps, then the areas were calculated automatically by the software. The minimum polygons in the TM and ETM images were 3×3 pixels, corresponding to an actual area of 90 m×90 m (i.e. 0.0081 km^2). Approximately the same standard was adopted for the scanned aerial photographs and the Landsat MSS images. Thus, only lakes with an area greater than 0.0081 km^2 were measured in this study.

2 Results and discussion

2.1 Changes in lake areas

As a result of the limited image resolution, we were only able to measure the areas of 50 permanent

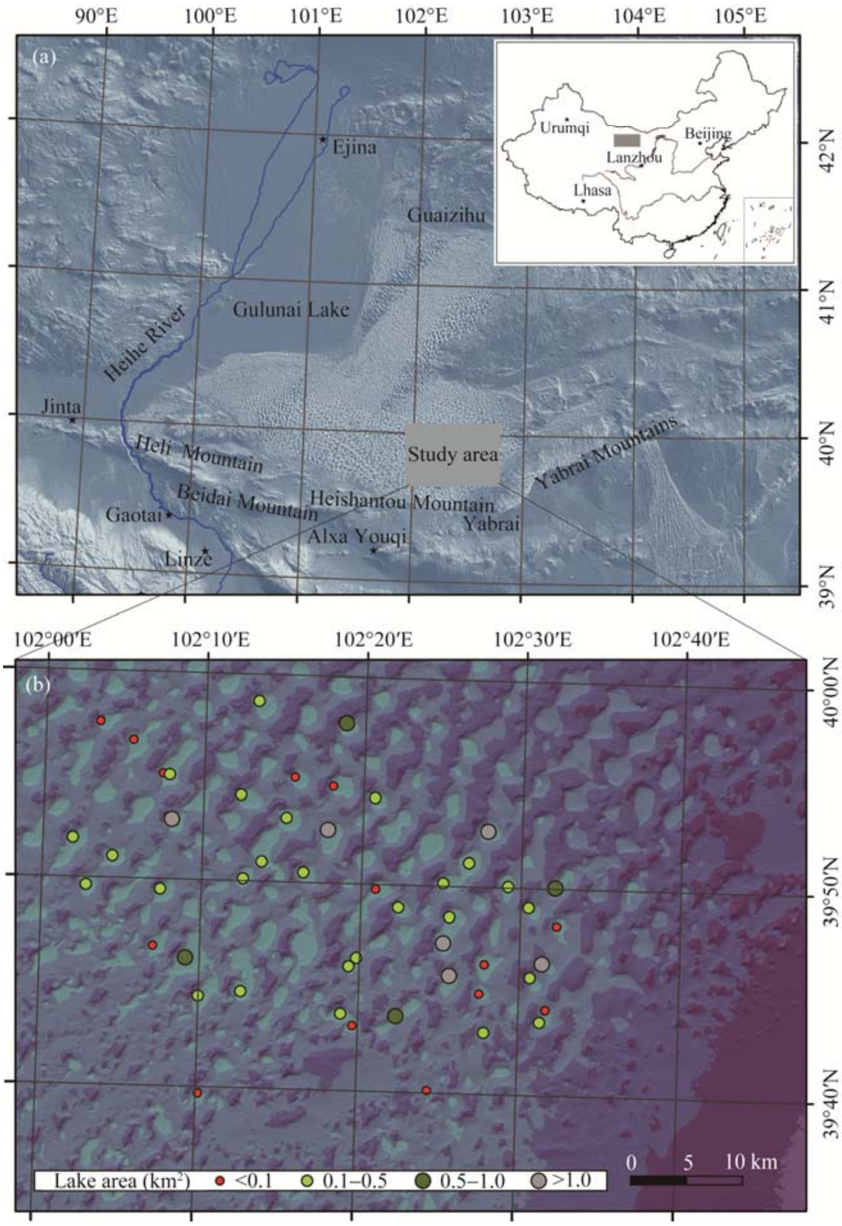

Fig. 1 Geographical location of the study area and topographic map of the Badain Jaran Sand Sea (a), and the distribution of the 50 measured lakes (b). We obtained the lake area based on the data in 2010.

lakes in the study area (about 70% of the total permanent lakes; Fig. 1b; Table 1). Figure 2 shows the changes in the total area of the 50 lakes during the study period. These changes showed different patterns during different periods. In general, the total lake area decreased linearly by about 21% from 1967 to 1990, remained almost unchanged (a slight increase of 0.6%) from 1990 to 2000, and then increased by about 20% from 2000 to 2010. Consequently, the total lake area in 2010 was only about 5% smaller than that in 1967. The relative amplitude of the variation in lake areas differed among the lakes. We used the dimensionless coefficient of variation (CV) to compare the magnitudes of the change.

$$\mathrm{CV} = \frac{\mathrm{SD}}{\mathrm{M}}. \quad (1)$$

Where M is the mean lake area of the four study terms and SD is the standard deviation.

Table 1 Geographical locations and areas of the 50 measured lakes from 1967 to 2010

Lake No.	Center of lake		Lake area (km^2)				
	Latitude	Longitude	1967	1975	1990	2000	2010
1	39°44'11"N	102°31'42"E	0.026	0.016	0.009	0.010	0.018
2	39°57'49"N	102°18'48"E	0.040	0.031	0.011	0.012	0.024
3	39°46'29"N	102°19'49"E	0.027	0.021	0.009	0.016	0.029
4	39°43'01"N	102°27'53"E	0.036	0.021	0.017	0.024	0.030
5	39°57'34"N	102°03'23"E	0.027	0.051	0.024	0.026	0.032
6	39°39'42"N	102°10'10"E	0.060	0.051	0.040	0.030	0.038
7	39°43'35"N	102°31'21"E	0.047	0.026	0.026	0.029	0.041
8	39°43'42"N	102°22'22"E	0.111	0.040	0.008	0.009	0.042
9	39°50'05"N	102°32'08"E	0.024	0.032	0.009	0.019	0.047
10	39°46'25"N	102°31'25"E	0.080	0.049	0.019	0.013	0.050
11	39°54'45"N	102°18'05"E	0.094	0.037	0.036	0.044	0.055
12	39°40'09"N	102°24'26"E	0.058	0.067	0.031	0.038	0.069
13	39°55'08"N	102°07'25"E	0.063	0.068	0.057	0.051	0.086
14	39°54'14"N	102°20'43"E	0.059	0.106	0.018	0.000	0.089
15	39°48'15"N	102°32'17"E	0.087	0.070	0.052	0.079	0.107
16	39°44'26"N	102°10'00"E	0.119	0.118	0.058	0.085	0.108
17	39°50'09"N	102°12'35"E	0.101	0.121	0.101	0.118	0.122
18	39°46'04"N	102°19'21"E	0.165	0.129	0.108	0.120	0.134
19	39°49'07"N	102°30'30"E	0.154	0.117	0.073	0.129	0.142
20	39°55'05"N	102°07'49"E	0.100	0.115	0.066	0.069	0.173
21	39°46'48"N	102°07'04"E	0.245	0.205	0.157	0.148	0.177
22	39°43'11"N	102°19'40"E	0.192	0.150	0.137	0.139	0.179
23	39°55'07"N	102°15'40"E	0.144	0.165	0.008	0.037	0.181
24	39°49'32"N	102°07'26"E	0.220	0.198	0.168	0.171	0.191
25	39°44'54"N	102°27'32"E	0.298	0.192	0.159	0.180	0.200
26	39°45'45"N	102°25'38"E	0.513	0.380	0.229	0.211	0.277
27	39°50'11"N	102°25'08"E	0.297	0.261	0.239	0.215	0.282
28	39°50'59"N	102°13'43"E	0.284	0.360	0.261	0.248	0.292
29	39°49'49"N	102°20'54"E	0.275	0.261	0.243	0.270	0.293
30	39°50'31"N	102°16'21"E	0.269	0.301	0.261	0.264	0.298
31	39°45'44"N	102°30'41"E	0.284	0.235	0.256	0.288	0.306
32	39°52'56"N	102°08'02"E	0.346	0.313	0.268	0.271	0.316
33	39°58'46"N	102°13'17"E	0.387	0.453	0.308	0.312	0.340
34	39°50'06"N	102°29'11"E	0.486	0.395	0.329	0.273	0.366
35	39°51'54"N	102°01'53"E	0.535	0.416	0.393	0.401	0.435
36	39°49'38"N	102°02'47"E	0.423	0.472	0.357	0.382	0.460
37	39°48'58"N	102°22'21"E	0.452	0.460	0.436	0.453	0.468
38	39°51'04"N	102°04'23"E	0.500	0.496	0.448	0.446	0.477
39	39°54'12"N	102°12'19"E	0.359	0.401	0.272	0.281	0.485
40	39°52'38"N	102°17'49"E	0.412	0.371	0.317	0.326	0.535
41	39°44'42"N	102°12'38"E	0.592	0.564	0.471	0.476	0.550
42	39°56'43"N	102°05'29"E	0.557	0.560	0.507	0.530	0.553
43	39°43'45"N	102°18'55"E	0.699	0.533	0.523	0.525	0.580
44	39°48'34"N	102°25'34"E	0.616	0.696	0.626	0.562	0.714
45	39°52'45"N	102°27'51"E	1.206	1.098	1.027	1.004	1.093
46	39°53'09"N	102°15'12"E	1.259	1.204	1.117	1.083	1.188
47	39°46'15"N	102°09'08"E	1.295	1.296	1.082	1.026	1.329
48	39°51'12"N	102°26'42"E	1.469	1.145	1.087	1.022	1.347
49	39°47'18"N	102°25'13"E	1.360	1.367	1.285	1.230	1.359
50	39°46'19"N	102°27'49"E	1.678	1.629	1.335	1.478	1.530

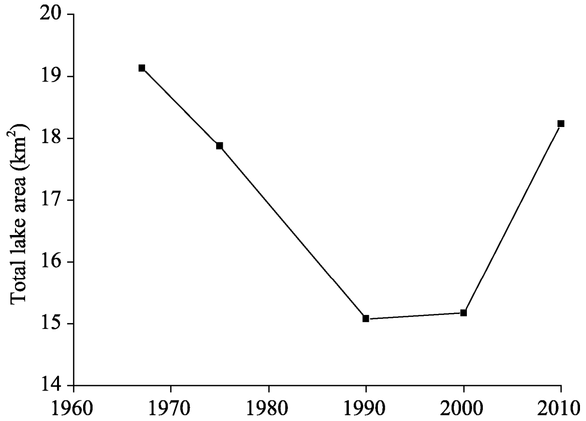

Fig. 2 Changes in the total lake areas of the 50 measured lakes from 1967 to 2010

Figure 3 shows that the smaller the lake area, the more variable its size was during the study period. Compared with 1967, in 1975 the areas of 32 lakes had decreased by 0.8% to 64%, whereas the areas of 18 lakes had increased by 0.5% to 89%. The areas of 49 lakes in 1990 had decreased by 3% to 100% compared with their areas in 1967. The areas of 39 lakes in 2000 had increased compared with these in 1990. All of the lake areas had increased in 2010 compared with these in 1990 and 2000. The areas of 26 lakes even exceeded their areas in 1967 by 3% to 73%.

2.2 Relationships between lake area and climate change

Previous research has suggested that the area of lakes in arid regions, including the Badain Jaran Sand Sea, is very sensitive to climate change both historyically and recently (Zhang et al., 2002; Ma and Edmunds, 2006). Zhu et al. (2011) found that temperature changes created seasonal changes of 13% in the total lake area in the Badain Jaran Sand Sea from late 2001 to late 2002 (Fig. 4). In the present study, we attempted to analyze the relationship between the changes in lake areas and climate change in the Badain Jaran Sand Sea. Unfortunately, there is no meteorological data available for the Badain Jaran Sand Sea itself, so we can only infer climate change based on data from meteorological stations in the area surrounding the sand sea. Precipitation and temperature, which strongly determine the evaporation rate of lake water, are the most important meteorological factors that influence the area of each lake. Therefore, we used temperature and precipitation data from 1960 to 2009 at four stations in north and south of the Badain Jaran Sand Sea (Ma et al., 2011a) to analyze the influence of climate change to lake areas.

The changes in annual mean temperature and annual precipitation respectively at four meteorological stations (Ejina, Guaizihu, Alxa Youqi and Yabrai) were shown in Figs. 5 and 6. Alxa Youqi, which is about 80 km southwest of the center of the lake region, and Yabrai, which is about 60 km southeast of the lake region, best represent the climate near the lake region in the southeastern Badain Jaran Sand Sea. All four stations showed similar increasing trends for annual mean temperature from 1960 to 2009 (Fig. 5). The annual mean temperature increased from 1960 to 2009 at rates of 0.27°C to 0.48°C per decade. The temperature increased more in the north than in the south. However, the temperature change varied

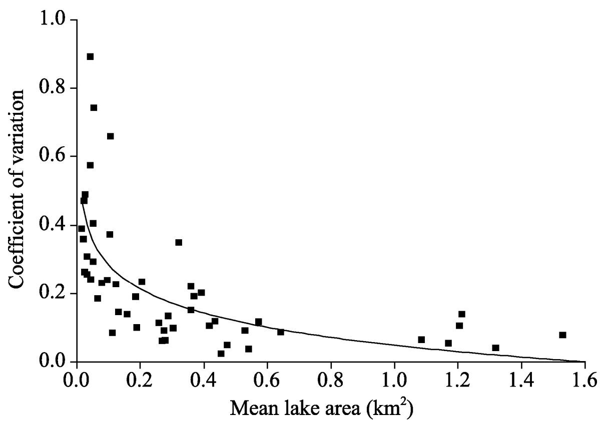

Fig. 3 Relationships between the coefficients of variation and mean lake areas from 1967 to 2010

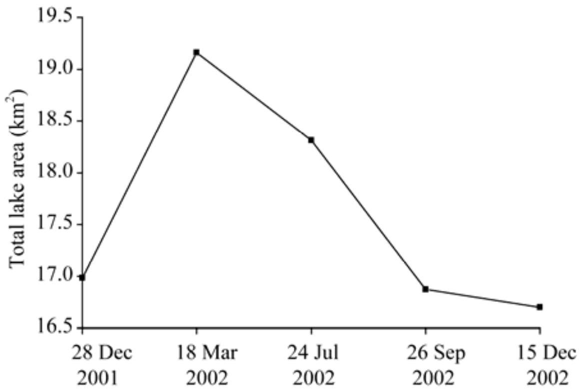

Fig. 4 Seasonal changes in the total lake areas of the 50 measured lakes from late 2001 to late 2002 (cited from Zhu et al., 2011)

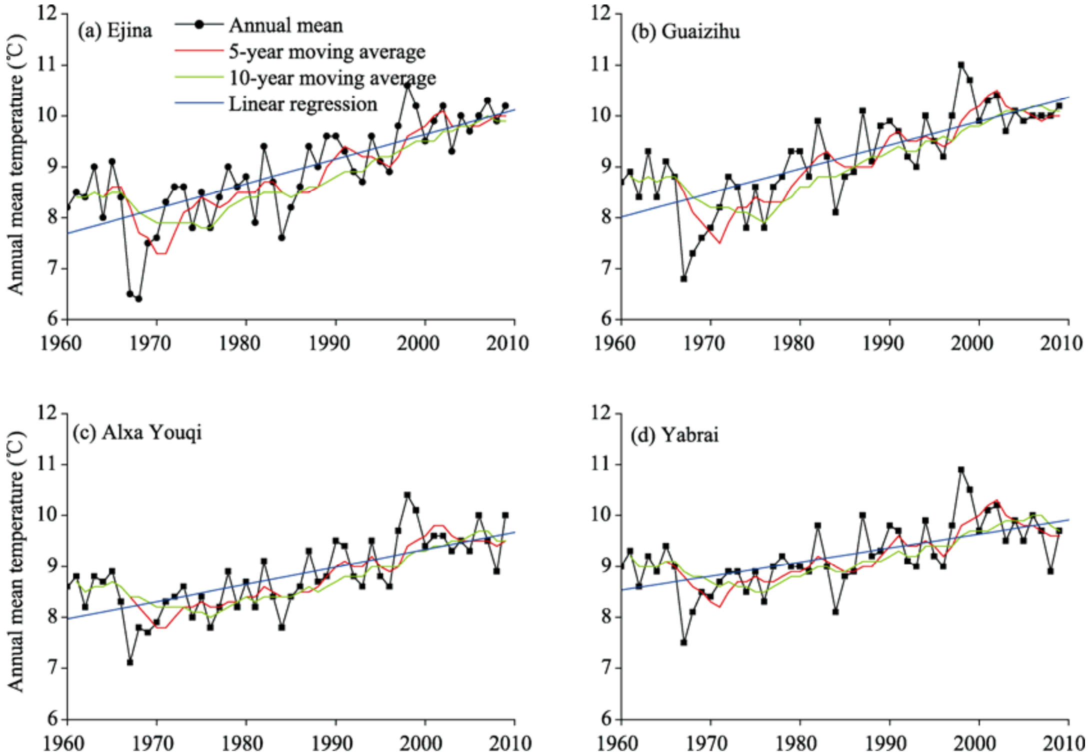

Fig. 5 Changes in annual mean temperatures from 1960 to 2009 at four meteorological stations surrounding the Badain Jaran Sand Sea. The locations of the four stations are shown in Fig. 1.

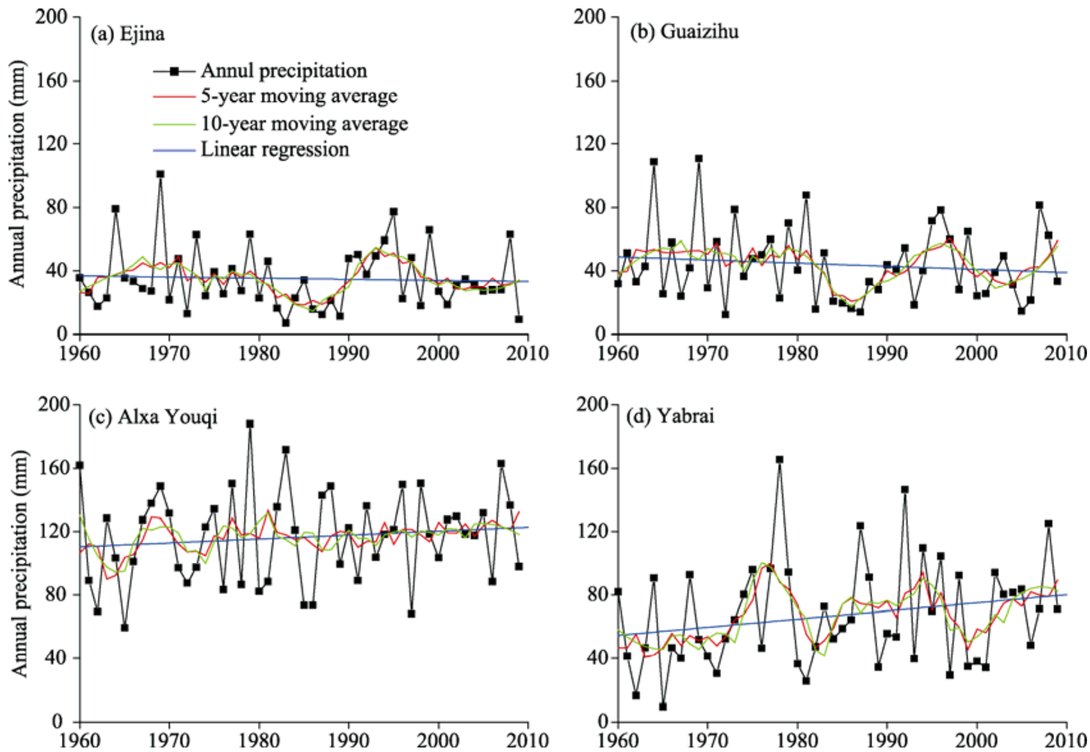

Fig. 6 Changes in annual precipitations from 1960 to 2009 at four meteorological stations surrounding the Badain Jaran Sand Sea

among the different periods. There was an abrupt decrease in temperatures at all four stations in the late 1960s when the minimum temperature occurred and the total lake area was the largest during the monitoring period (Fig. 2). Temperatures gradually increased, though with considerable fluctuation, from the 1970s to 1990s, when the lake area decreased. Between 1990 and 2000, when the total lake area remained almost unchanged, the temperature decreased slightly during the early 1990s and increased abruptly during the late 1990s. From 2000 to 2010, when the total lake area increased, the temperature decreased or remained stable. Therefore, the changes in temperature significantly influenced the lake area: increasing temperatures tended to cause the lake area to shrink.

Changes of annual precipitations in the north and south of the Badain Jaran Sand Sea showed different trends, with a slight decreasing trend in the north but an increasing trend in the south. Here, we have focused on the changes at Alxa Youqi and Yabrai because they better represent the climate of the lake region. At Alxa Youqi, precipitation increased from the late 1960s to about 1970, then decreased slightly during the early 1970s, corresponding to the decrease in the total lake area during this period. Precipitation remained almost unchanged after the 1980s. At Yabrai, precipitation increased during the 1970s, reaching a maximum of 186 mm in 1978. It decreased abruptly during the early 1980s, increased slightly in the late 1980s, and then decreased again during the 1990s. Precipitation increased between 2000 and 2009 while the temperature decreased or remained stable, corresponding to the increase in the total lake area during this period. Therefore, the influence of precipitation on the lake area was less significant than the effect of temperature.

The limited amount of precipitation in the study area suggests that precipitation must recharge the lakes indirectly. Cl^- mass-balance estimates of direct recharge showed rates on the order of 1 mm/a (Gates et al., 2008b; Ma et al., 2009). Most of the precipitation must be stored in the mega-dunes and mountains, such as the Yabrai Mountains to the southeast, before it can flow into and recharge the lakes, leading to a lag effect. For example, a mean residence time of 1,000 to 2,000 years has been inferred for the southeastern margin of the sand sea based on the radiocarbon data (Gates et al., 2008a). However, the lag effect of precipitation on recharging the lakes is complex, as it depends on the amount of precipitation, the region's underlying geological structures, topography and other factors. If the precipitation is sufficient in a given year, it can directly recharge the lakes. This issue should be clarified during future research to fully understand the sources of lake water.

2.3 Implications for recharge sources of lake water

Studies of lake formation in the sand sea have focused on the recharge sources and four hypotheses have been proposed: (1) Direct atmospheric precipitation recharge hypothesis proposes that the lakes are fed by atmospheric precipitation, and is based on the fact that the present lakes in the sand sea are concentrated in the southeast, where precipitation is greatest. (2) Near-source recharge hypothesis asserts that lakes in the Badain Jaran Sand Sea are fed by groundwater from surrounding areas, such as the Heihe River and diluvial fans in the piedmonts south of the sand sea. (3) Remote-source recharge sources refer to atmospheric precipitation and lake water in the Qilian Mountains or even in the Qinghai-Tibetan Plateau. (4) Palaeo-source recharge hypothesis maintains that lake water and groundwater in the Badain Jaran Sand Sea represents water from precipitation that fell in the distant past, when the climate was more humid.

While evidences that support the near-source and remote-source recharge hypotheses are scare, more and more researchers resort to the direct atmospheric precipitation and palaeo-source recharge hypotheses (Dong et al., 2013). A reasonable hypothesis should explain two facts: Why are lakes in the sand sea concentrated in the southeastern part where precipitation is more than that in the other parts, are they related to precipitation? Why does the areas of lakes increase with the increase in the size of mega-dunes, are the lakes related to mega-dunes? The changes in lake areas in the southeastern Badain Jaran Sand Sea from 1967 to 2010 do not appear to be strongly sensitive to changes in contemporary precipitation, but do appear to depend on the annual mean temperature. An interesting question arises about why the lake area began to increase since 1990 even though the precipitation tended to decrease or remain stable. This suggests that a relatively constant recharge into the lakes must exist independent of present precipitation. Although opinions differ about the recharge sources of lake water in the Badain Jaran Sand Sea, robust evidence points toward recharge by the shallow groundwater that forms after precipitation (Ma and Edmunds, 2006; Yang, 2006; Ma et al., 2007; Gates et al., 2008a; Zhao et al., 2011b). However, the current amount of precipitation is low; suggesting that direct infiltration of precipitation is not a volumetrically important source of recharge to the shallow aquifer in the study area.

Investigation of the sources of groundwater recharge into the Badain Jaran Sand Sea using geochemical and isotopic techniques suggested that the mountain range near Yabrai to the southeast is a likely recharge zone, and that the mean residence time ranges between 1,000 and 2,000 years at the southeastern margin of the sand sea (Yang, 2006; Gates et al., 2008a). This means that lake water in the Badain Jaran Sand Sea is of ancient rather than modern origin. That is, precipitation in the past that was stored in the bordering mountains is the source of constant recharge into the lakes.

Although the lake region of the Badain Jaran Sand Sea has an arid climate, with current annual precipitation less than 100 mm, it has experienced some wet periods of different time scales (Yang and Williams, 2003; Li et al., 2005; Ma and Edmunds, 2006; Ma et al., 2009). Li et al. (2005) suggested that the southeastern Badain Jaran Sand Sea has experienced 25 cycles of climatic fluctuations from arid-cold and windy to warm and humid since 150 ka BP in response to fluctuations in the East Asia winter and summer monsoons as a result of large-scale climatic changes during the glacial and interglacial periods. Radiocarbon dating of palaeo-shorelines has shown that lake levels have varied significantly over the last 10 ka and were as high as 15 m above their current positions during the period from 4 to 6 ka BP (Yang and Williams, 2003), which may represent the end of the maximum Holocene humidity in this area.

The recharge history during the last 2,000 years reconstructed using a chloride mass-balance approach revealed relatively dry years in the Badain Jaran Sand Sea during AD 100 to 250, 350 to 600, 870 to 1220, 1330 to 1450 and 1570 to 1720, the 1780s, and 1900 to 1970 (Ma et al., 2009). Precipitation during the wetter periods would have infiltrated into both the bordering mountains and the mega-dunes (Zhao et al., 2011b). This suggests that the mega-dunes surrounding the lakes also supplied (and may still supply) considerable recharge into the lakes. This may explain why the lakes in the Badain Jaran Sand Sea are distributed primarily in the southeast where the tallest mega-dunes develop, and the taller the mega-dune, the larger the lake area. In summary, the groundwater in the mountains south of the lake region and the mega-dunes adjacent to the lakes both recharge the lakes by means of precipitation infiltration. Because of the low modern precipitation, the recharge may originate primarily from palaeo-water from past humid periods in the Badain Jaran Sand Sea.

3 Conclusions

The changes in lake areas, which reflect the water volume, appear to have been most sensitive to temperature changes since 1967 in the Badain Jaran Sand Sea. Precipitation appears to have had a small and non-significant influence on lake area, which is supported by the seasonal changes in the lake area, which depend mostly on temperature. The limited amount of current precipitation in the arid Badain Jaran Sand Sea appears to play little role in recharging the lakes. The sources of recharge appear to be primarily regions outside the lake region (particularly the mountains south and southeast of the region) or groundwater of ancient origin. An increasing body of evidence points toward a palaeo-origin, and the changes in lake areas determined during the present study support this suggestion. Like other regions, the Badain Jaran Sand Sea has experienced alternating wet and dry periods at different time scales in response to global climate change during the Holocene.

Previous researchers have emphasized the importance of shallow groundwater in the mountains bordering the study area, such as the Yabrai Mountains, which have stored palaeo-precipitation by infiltration. However, palaeo-precipitation stored in the mega-dunes surrounding the lakes also appears to be significant. This explains the formation of mega-dunes: fixation and reactivation alternations have played a key role in increasing the dune size, as we previously suggested.

Important issues for future study to clarify the sources of lake water recharge in the Badain Jaran Sand Sea will be to improve our understanding of the region's climate change history and the mechanisms of water transfer in the mega-dunes and bordering mountains.

Acknowledgements

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