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Recharge to the inter-dune lakes and Holocene climatic changes in the Badain Jaran Desert, western China

Xiaoping Yang *, Nina Ma [1], Jufeng Dong [2], Bingqi Zhu, Bing Xu, Zhibang Ma, Jiaqi Liu

Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China

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ABSTRACT

We present new estimates on evaporation and groundwater recharge in the Badain Jaran Desert, western Inner Mongolia of northwestern China, based on a modified Penman Equation suitable for lakes in China. Geochemical data and water balance calculations suggest that local rainfall makes a significant contribution to groundwater recharge and that past lake-level variations in this desert environment should reflect palaeoclimatic changes. The chronology of lake-level change, established by radiocarbon and U-series disequilibrium dating methods, indicates high lake levels and a wetter climate beginning at ca. 10 ka and lasting until the late mid-Holocene in the Badain Jaran Desert. The greatest extension of lakes in the inter-dune depressions indicates that the water availability was greatest during the mid-Holocene. Relicts of Neolithic tools and pottery of Qijia Culture (2400–1900 BC) suggest relatively intensive human activity in the Badain Jaran Desert during the early and middle Holocene, supporting our interpretation of a less harsh environment. Wetter climates during the Holocene were likely triggered by an intensified East Asian summer monsoon associated with strong insolation.

Introduction

China's Badain Jaran Desert in western Inner Mongolia contains some of the tallest dunes in the world juxtaposed with a large number of permanent lakes in the inter-dune depressions (Zhu et al., 1980; Wang, 1990; Yang, 1991; Jäkel, 1996; Hofmann, 1999; Yang et al., 2003). Overlapping geologic formations and hilly basement morphology have been suggested to be primarily responsible for the formation of these megadunes (Yang et al., 2003), while their maintenance over time has been associated with upwelling water in the dune bodies (Chen et al., 2004). Issues associated with the source of recharge for the inter-dune lakes as well as the cause of the long-term stability of the tall dunes remain controversial even after decades of study.

A key question relating these two issues concerns the source of the groundwater recharging these desert lakes. Opinions on the origins of this groundwater vary considerable. Ion chemistry of lakes and shallow groundwater (Yang and Williams, 2003) suggests that direct recharge of local precipitation is the primary source of the groundwater. Jäkel (2002) supported this conclusion by showing that dune morphology causes an increase in rainfall infiltration, with the most significant impact on groundwater recharge associated with winter precipitation. In contrast, Chen et al. (2004) reported that the snowmelt from Qilian Mountains of the northeastern Tibetan Plateau, transported through a system of faults and fractures with a transport time of approximately 30 yr, could be the source of the groundwater. They suggested that groundwater in the Badrain Jaran Desert could be a new water resource and an alternative to water diversion projects. If correct, water diversions could have a significant environmental impact on the dune fields and lakes of the desert. Finally, Ma and Edmunds (2006) have suggested that the groundwater source could be associated with paleowater older than 20 ka from the adjacent Yabulai Mountains that was precipitated during cold/wet intervals.

An understanding of the source of groundwater in the Badain Jaran Desert is significant not only to policy makers for regional planning but also to scientists interested in hydrological cycles in arid environments and climate change in northern China and other arid regions of Asia. While records from a range of sites have shown that Holocene climate was quite unstable in the drylands of northwestern China (He et al., 2004; An et al., 2006) the details are rather controversial. Studies of lacustrine deposits from terminal lakes both south (Chen et al., 2003) and north (Hartmann and Wünnemann, 2009) of the Badain Jaran Desert independently proposed a dry mid-Holocene. However, study of higher shorelines in two lakes within the desert (Yang and Williams, 2003) suggested a wetter early and middle Holocene. The uncertainty here is that the changes of endorheic terminal lakes may be triggered by climatic variation, but it may also be caused by a change in the fluvial dynamics of the lake inflows. The desert lakes may be controlled by local climate but may also be controlled by geological structures that would have a strong impact on the flow regimens of groundwater.

* Corresponding author. Fax: +86 10 62010846.
E-mail address: xpyang@mail.igcas.ac.cn (X. Yang).
[1] *Present address:* Institute of Mineral Resources, Chinese Academy of Geological Sciences, Beijing, China.
[2] *Present address:* Geological Deposit Prospecting and Development Company, Beijing, China.

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As the sand seas cover a large proportion of northwestern China, direct and reliable evidence from the areas of sand seas would be needed in order to have a precise understanding about the environmental changes in these deserts. Located in the latitudes of the global westerlies and on the northern fringe of the Asian summer monsoon (Ren, 1980), the Badain Jaran Desert is an important repository of information about the history of these two different climate systems.

The aim of this paper is to present a relatively realistic estimate of evaporation from the lake and from the land, and the water balance between evaporation and precipitation in this desert. The recharge record of the desert lakes is reconstructed on the basis of hydrogen and oxygen isotopic values of water samples and the strontium and uranium isotopes of sediments. From this record, we attempt to reconstruct the Holocene climatic changes in this desert.

Environmental setting

The Badain Jaran Desert is bounded by the mountains (maximum elevation ~2000 m) to the south and southeast and by palaeo-lake basins or lowlands (~900 m) to the west and north (Fig. 1). With an area of 49,000 km^2, it is the third largest desert in China (Zhu et al., 1980). Elevation in the interior of the Badain Jaran range from 1500 m in the southeast to 900 m in the northwest, producing a regional hydraulic gradient from SE to NW. Surface morphology consists primarily of sand dunes that attain average heights of 200–300 m and rise to 460 m in the southeast. The inter-dune depressions contain a large number of seepage lakes with no surface runoff and which vary considerably in terms of area and salinity (Hofmann, 1996; Yang and Williams, 2003). These lakes are concentrated in the southeast part of the desert (Fig. 2).

Although there are no weather stations in the desert, a few weather stations located in populated areas close to the desert margins (Fig. 1) show that mean monthly temperature varies between ca. −10°C in January and ca. 25°C in July. Mean annual temperature is 7.7°C in the southern portion of the region and reaches 8.2°C in the northwest. The East Asian summer monsoon brings rainfall to the desert from July to September with mean annual precipitation ranging between ~120 mm in the south to 40 mm in the north. Currently this precipitation supports a sparse vegetation cover on the dunes consisting of xerophilous grasses and shrubs with *Artemisia, Agriophyllum, Achnatherum* growing close to the ridges of the megadunes. Around the lakes and springs there is dense cover of native and introduced plants used for animal grazing by local farmers.

On the southern margins of the dune field, semiconsolidated conglomerates underlay aeolian sands. The age of these sediments is considered to be early Pleistocene (Cai, 1986). Jurassic, Cretaceous and Tertiary rocks are distributed along the fringe of the desert (Ma, 2002). The sedimentology and geologic structure of the rocks underlying the dunes are largely unknown, except in some localities where aeolian sands and dunes cover granite hills.

Methods

Field investigations were carried out in the southeastern portion of the desert during field seasons in 2006 and 2007. All locations and

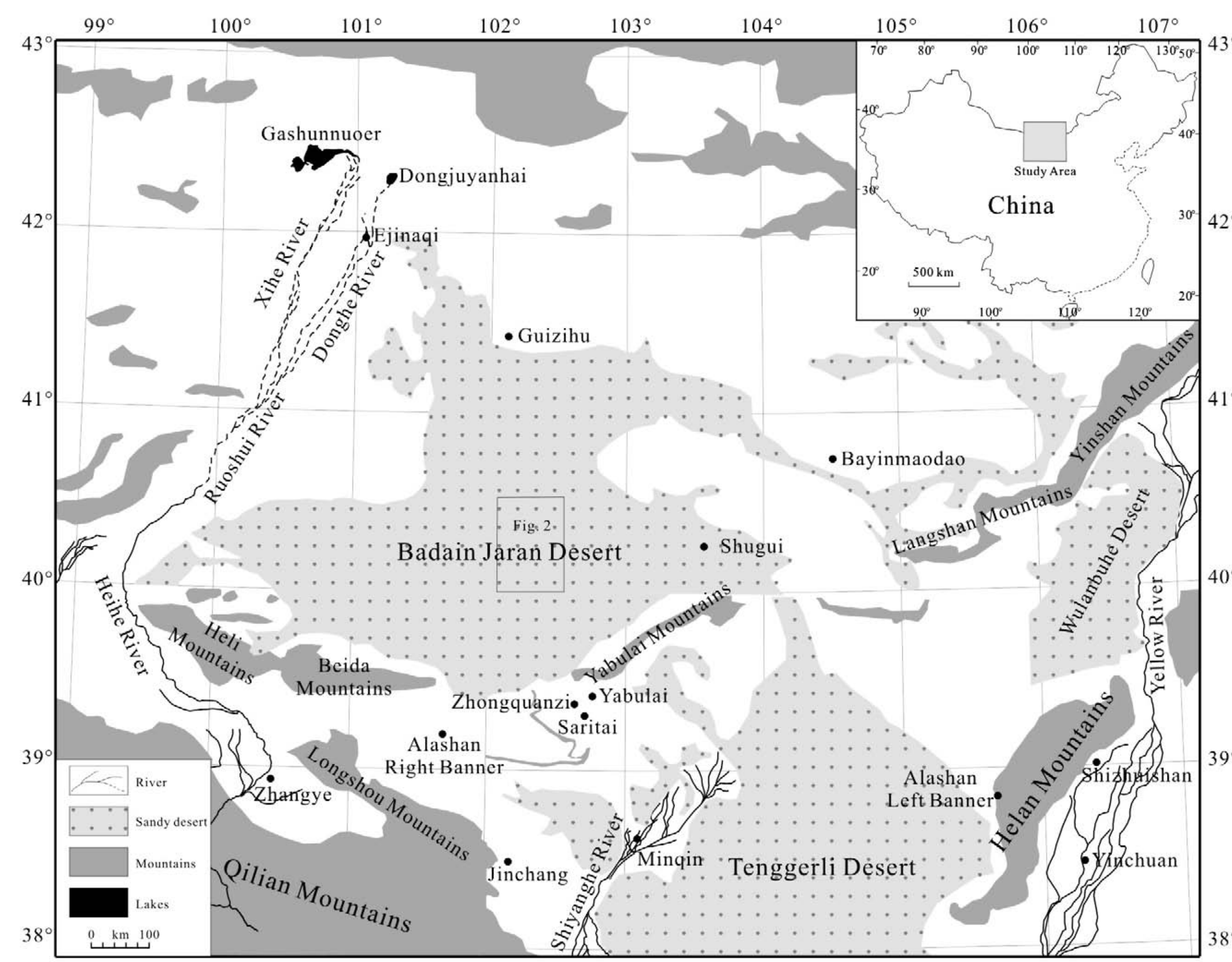

Figure 1. Overview of the study area.

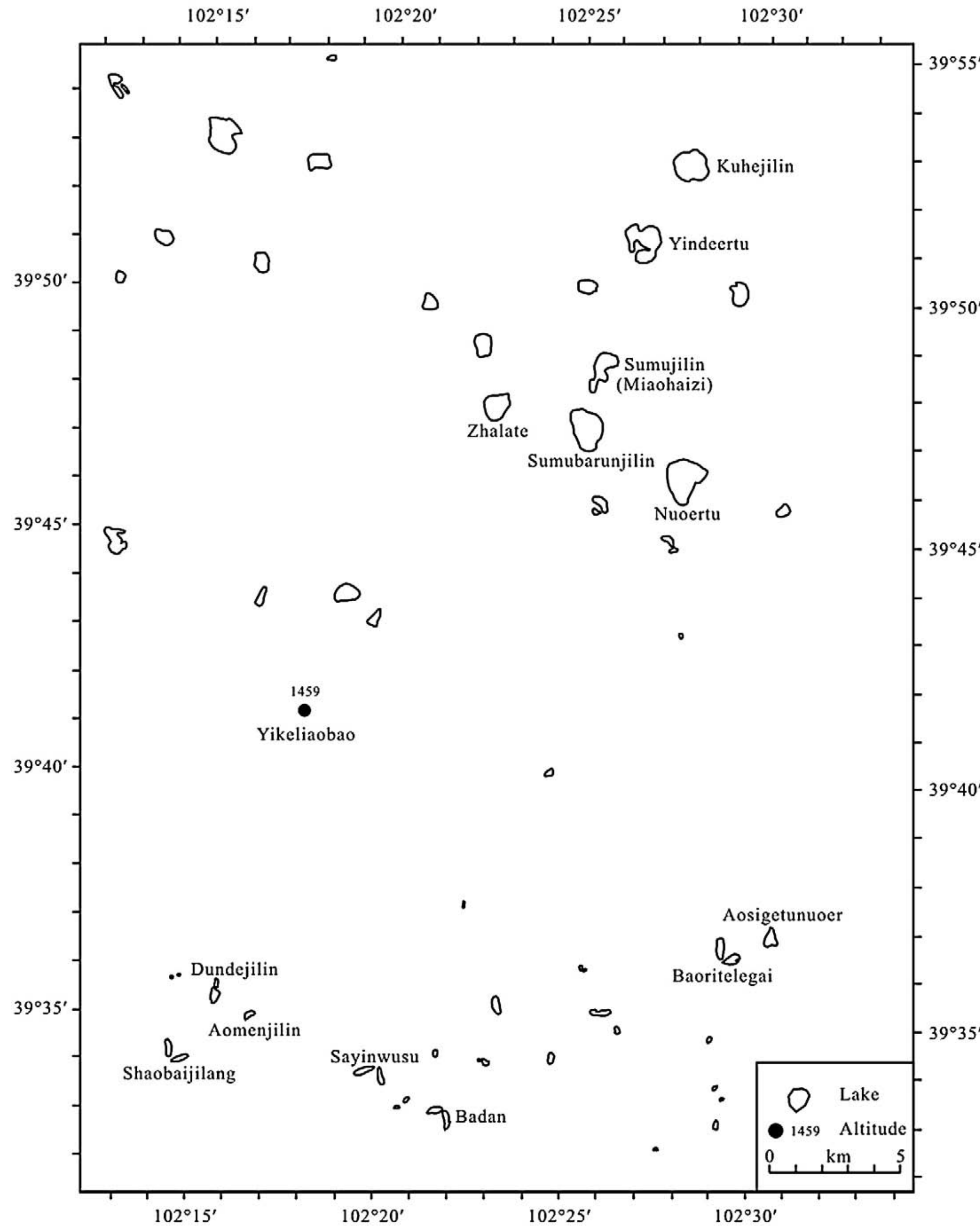

Figure 2. Lakes in the southeastern Badain Jaran Desert with names mentioned in the text.

elevations were recorded using Garmin GPS and topographic maps. The history of lake-level changes was reconstructed by studies of basin floor deposits and palaeo-shorelines. Sediments were identified as being of aeolian or lacustrine origin, based on cementation, bedding, color and texture. The chronology of former high lake stands was determined by dating organic fractions of lacustrine sediments and the inorganic carbon from calcareous gyttja through conventional radiocarbon methods (Table 1) in the Laboratory of Nuclides at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGG-CAS). The ^{14}C reservoir correction used was based on the value obtained from the studies of present-day and Holocene lacustrine sediments of a lake within the study area and suggests that the radiocarbon ages should be corrected on average by -3220 ± 225 yr for the inorganic fraction and -1080 ± 155 yr for organic fraction (Hofmann and Geyh, 1998). A sample of tufa was dated twice using U-series disequilibrium method in the IGG-CAS and produced consistent results (Table 2). Microscopic mineral identifications confirm that the tufa sample is purely carbonate. It was dissolved completely in HCl and spiked with a mixed ^{232}U–^{228}Th tracer. U and Th fractions were separated on anion exchange columns and the uranium and thorium isotopic compositions were determined on an alpha spectrometer (Ma et al., 2004). Ages were calculated following the formula described in Broecker (1963) and Kaufman and Broecker (1965). The remains of snail shells were identified by Prof. Deniu Chen at the Institute of Zoology, CAS.

An inventory of modern lakes at a spatial resolution of 30×30 m was made using LANDSAT ETM^{+} data from September 2000 and July 2002 and 1:100,000 topographical maps. Geometrical corrections and identification and mapping of the lakes were carried out using the digital image-processing software PCI (PCI Geomatics, 1998). The area of modern and former lake surface was calculated with the software

Table 1
Conventional radiocarbon dates from the formerly high shorelines of the lakes in the Badain Jaran Desert.

Field no.	Lab no.	Material dated	Locality	Radiocarbon age (^{14}C yr BP)	Reservoir-effect corrected	Calendar age (cal yr BP)
09-C3	CNR-185	Organic carbon	See Figure 4	5974 ± 183	4894 ± 183	5628 ± 221
09-C02	CNR-186	Organic carbon	See Figure 4	7344 ± 177	6264 ± 177	7144 ± 200
9-03	CNR-173	Inorganic carbon	See Figure 4	7418 ± 78	4198 ± 225	4757 ± 315
09-08	CNR-177	Inorganic carbon	East of Shaobaijilang	7010 ± 86	3790 ± 225	4193 ± 304
10-02	CNR-175	Inorganic carbon	Aomenjilin	11356 ± 180	8136 ± 225	9040 ± 298
10-03	CNR-176	Inorganic carbon	Aomenjilin	7119 ± 87	3899 ± 225	4340 ± 318
12-01	CNR-174	Snail shells	Sayinwusu	9729 ± 121	8649 ± 155	9749 ± 206
15-C1	CNR-183	Organic carbon	Badan	6688 ± 95	5608 ± 155	6425 ± 166
15-C2	CNR-184	Organic carbon	Badan	5404 ± 121	4324 ± 155	4940 ± 253
Ref-1	CG-3448	Organic carbon	Sumujilin	7590 ± 70	6510 ± 155	7408 ± 135
Ref-1	CG-3746	Organic carbon	Kuhejilin	7020 ± 110	5940 ± 155	6790 ± 195
Ref-1	CG-3447	Organic carbon	Nuoertu	6490 ± 75	5410 ± 155	6184 ± 167
Ref-2	Hv 20428	Organic carbon	Zhalate	5220 ± 120	4140 ± 155	4651 ± 191

Calendar age conversions were generated by the CalPal Online Radiocarbon Calibration program (http://www.calpal-online.de). Ref-1 refers to the data in Yang and Williams (2003) and Ref-2 in Hofmann (1999), respectively.

ArcView GIS (ESRI, 1996). The mean error of our image processing estimates is less than ±6% based on comparisons between these data and 17 lakes whose areas were precisely measured in the field.

Evaporation was estimated using a modified Penman Equation (Penman, 1948). We used an approach based on Sene et al. (1991) that is often used to estimate the evaporation from lake surfaces in China (Li et al., 2001; Zeng et al., 2007). Evaporation (E_L) in mm per day was estimated using:

$$E_L = \frac{\delta H / L + \gamma E_a}{\delta + \gamma}$$

where δ = slope of the saturation vapor pressure curve at air temperature t (hpa/°C); H = net radiation, J/(m^2·day); L = latent heat of vaporization (J/kg); γ = psychrometric constant (hpa/°C); E_a = atmospheric conductance (mm/day).

The difference between estimated values and direct measurements in large evaporation pans is <±10% according to experiments carried out in the arid regions of Xinjiang, western China (Zhang and Zhou, 1992; Li et al., 2001). Total monthly mean climatological data (radiation, temperature, air pressure, vapor pressure, wind velocity and sunshine duration) were obtained from the Chinese Meteorological Agency for the period 1961–2001 for four weather stations (Guizihu, Bayinmaodao, Alashan Right Banner and Minqin) located in the margins of the desert (Fig. 1). Relevant parameters for the desert lakes were calculated by mathematical interpolation from these stations modified by elevation. Interpolation of mean annual precipitation in the lake area of the Badain Jaran Desert is ~105 mm/yr.

Water samples from lakes and wells in the study area were collected in September 2006 and May 2007. Total dissolved solids (TDS) and pH were measured in the field with a portable instrument (manufactured by the Eijkelkamp Company of the Netherlands) that automatically corrects for temperature differences. The error is <±1% for the value of pH and <±0.5% for TDS. Replicate samples for further analysis were collected and stored in polyethylene bottles sealed with wax. Cultural artifacts were collected and their identifications were carried out by Prof. Renxiang Wang at the Institute of Archaeology in the Chinese Academy of Social Sciences.

Hydrogen and oxygen isotope ratios in water were determined by Cr reduction (Gehre et al., 1996) and CO_2 equilibration (Craig, 1957) methods, respectively. Samples from five lakes with high salinity were difficult to prepare with the CO_2 equilibration method. Our alternative approach for these samples was to get the H_2O sample first by distillation with the distilled water samples subsequently treated using the CO_2 equilibration method. The measurements were performed using a MAT-252 mass spectrometer for hydrogen and a MAT-253 mass spectrometer for oxygen in the State Key Laboratory of Lithospheric Evolution, IGG-CAS. Stable isotope data for H and O are expressed in δ notation relative to standard mean ocean water (SMOW). The precision of measurements for stable isotopes was ±0.1‰ for $\delta^{18}O$ and ±0.5‰ for δD.

Results

Lake area

Interpretation of ETM$^+$ imagery for the Badain Jaran Desert collected between 2000 and 2002 resulted in the mapping of 142 lakes with an area >0.1 hm^2 (1 hm = 100 m). Modern lakes are concentrated in a geographical area approximately 250,000 hm^2. The total area of these lakes is ~2230 hm^2, with six having an area >100 hm^2 and 46 having an area between 10 hm^2 and 100 hm^2. This estimate is consistent with earlier surveys that mapped 144 lakes in this desert (Zhu et al., 1980). Field observations and interpretation of shorelines in ETM$^+$ imagery show that past lake area of these lakes was significantly larger than at present. We mapped former lakes in 247 inter-dune depressions with a total area of ~21,000 hm^2, or approximately nine times the area of the current lakes. The distribution of lacustrine deposits indicates that there were 69 lakes that covered >100 hm^2 in the former times.

Evaporation from lake surfaces

Average monthly evaporation calculated from the modified Penman Equation between 1961 and 2001 is shown in Figure 3. Monthly evaporation is positively correlated with the monthly mean temperature but negatively with the mean precipitation. As a result, the highest evaporation occurs in May and June, reaching 140 mm (Fig. 3) with the lowest totals occurring in January (29 mm) and December (28 mm). The mean annual evaporation for the same

Table 2
U-series disequilibrium age of the tufa sample from the Dundejilin.

No.	U (ppm)	Th (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{232}Th$	$^{230}Th/^{234}U$	Corrected age (ka)
Yang-1	8.588 ± 0.397	2.304 ± 0.111	1.428 ± 0.018	1.788	0.112 ± 0.003	11.3 ± 0.4
Yang-2	8.249 ± 0.288	2.247 ± 0.106	1.444 ± 0.046	1.809	0.113 ± 0.004	11.5 ± 0.5

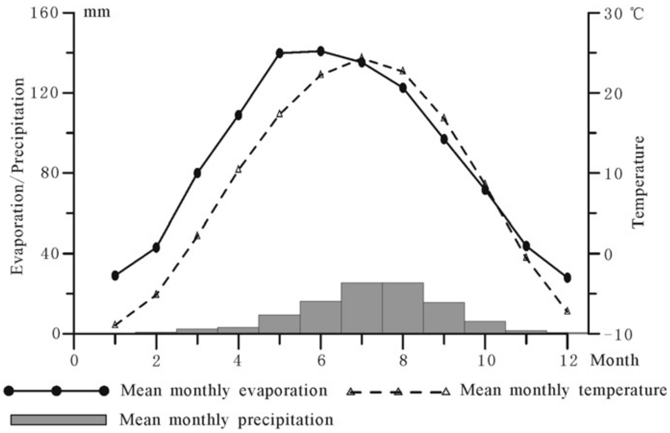

Figure 3. Monthly evaporation from the lake surface in the Badain Jaran Desert according to the modified Penman Equation.

period is 1040 mm, with a maximum of 1260 mm in 1972 and a minimum of 840 mm in 1988. Although the estimated mean evaporation of 1040 mm in the lake areas of the Badain Jaran Desert is not confirmed by measurements using evaporation pans, this value should be realistic because the suitability of this method has been demonstrated in the Taklamakan Desert.

Chronology of high lake stands

In 2006 we investigated four lake depressions and collected bulk sediment samples from the lacustrine deposits. The chronology indicates that all of these lakes experienced high lake levels in the early to mid-Holocene. Black carbon from the highest shorelines of Shaobaijilang Lake (+15 m) were dated to 5628±221 cal yr BP (CNR-185, Fig. 4). Black carbon (+6 m) and calcareous gyttja (+5.5 m) from deposits above the lake surface was dated to 7144±200 cal yr BP (CNR-186) and 4757±315 cal yr BP (CNR-173), respectively (Fig. 4). Calcareous gyttja from the highest shoreline of Aomenjilin (+10 m) was dated to 4340±318 cal yr BP (CNR-176). A sample of calcareous gyttja 2 m above the present lake surface was dated to 9040±298 cal yr BP (CNR-175).

Normally, deposits are younger at locations below the highest lake level. However, in these two cases we believe that younger sediments were removed by wind erosion. Consequently, the older lacustrine sediments are now exposed to the surface. The high lake level (15 m above the present water surface) in Shaobaijilang around 6000 cal yr BP is confirmed by another sample from the eastern shore of the lake, which is dated to 4193±304 cal yr BP (CNR-177). This layer of calcareous gyttja is about 7 m above the present water surface (i.e., 8 m below the highest shoreline), suggesting a lake-level fall of 8 m in ca. 2000 yr.

At Sayinwusu two lakes are divided by 10-m-high calcareous gyttja containing abundant snail shells of *Galba truncatula* and *Gyraulus sibiricus*. These species are normally found in the littoral area of freshwater lakes. In 2006 we found both lakes salty with a TDS of 15.5 and 14.8 g L^{-1}, respectively (Table 3). The presence of snail shells suggests that the lake was filled with fresh water during the earlier high lake stand, dated to 9749±206 cal yr BP (CNR-174).

Lacustrine deposits in the inter-dune depression of Badan show that dunes first formed after a decline of lake levels and dessication of the basins in the mid to late Holocene. Two bulk samples of lacustrine sediments were dated to 6425±166 cal yr BP (CNR-183) and 4940±253 cal yr BP (CNR-184), respectively (Table 1). South of the present Dundejilin Lake is a large area of dried lacustrine deposits and a small hill of tufa 5 m above present lake level. The top layer of tufa is dated to 11.5±0.5 ka by U-series disequilibrium dating (Table 2).

Isotopic composition of water samples

No obvious δD and $\delta^{18}O$ value differences are observed between Yabulai and Left Banner; however, the hydrogen (δD) and oxygen ($\delta^{18}O$) isotopic compositions of groundwater samples (Table 3 and Fig. 5) increase from the marginal zones to the dune fields. δD and $\delta^{18}O$ values in the groundwater of deep aquifers of the desert margins range from −91.1‰ to −45.1‰ and from −10.6‰ to −3.9‰, respectively, while in shallow aquifers in the inter-dune depressions δD and $\delta^{18}O$ values range from −38.7‰ to −26.6‰ and from −3.8‰ to −1.8‰, respectively. The waters in the desert lakes show much higher $\delta^{18}O$ (1.8‰ to 5.9‰) and δD (−32.0‰ to −5.3‰) values.

Ma and Edmunds (2006) examined two of the 21 lakes that we studied. $\delta^{18}O$ and δD from the northern Baoritelegai are 5.9‰ and −13.9‰, respectively, whereas the data from the same lake were respectively 7.0‰ and 5‰ in Ma and Edmunds (2006). Additional data from eastern Baoritelegai Lake are nearly identical to that of Ma and Edmunds (2006).

Evidence of early human activity in the dune field

Although no formal archaeological excavations have been conducted in the sand seas, we were able to collect relicts of Neolithic tools from

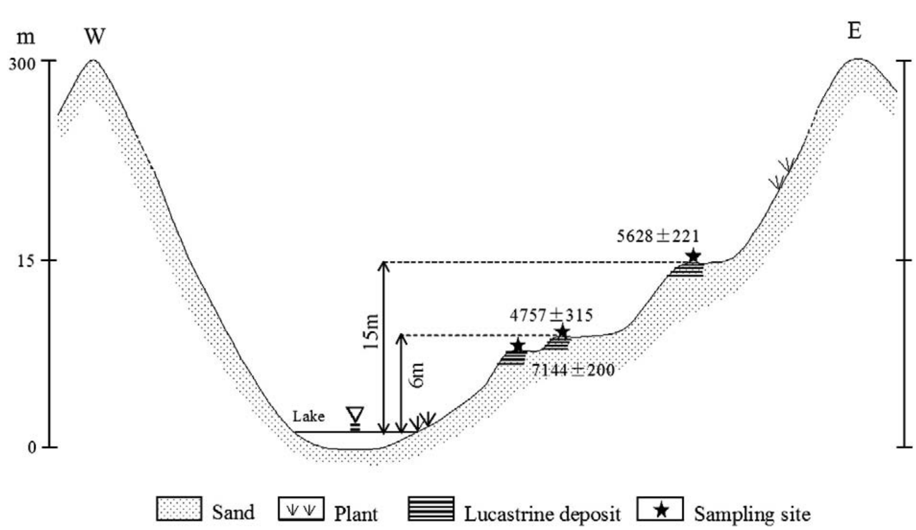

Figure 4. Cross profile of the Shaobaijilang (the western one, for location see Fig. 2).

Table 3
TDS, pH and isotopic compositions of the water samples.

	Sample no.	TDS (g L^{-1})	pH	$\delta^{18}O$ (‰)	δD (‰)	Site	Depth of the lake or well
Lakes	06-01	0.41	8.90	5.9	−5.3	South margin	<1 m
	09-L01	2.02	9.28	4.5	−7.3	Shaobaijilang S	1.5 m
	09-L02	1.49	9.37	3.6	−9.8	Shaobaijilang M	<1 m
	09-L03	1.76	8.88	3.6	−9.6	Shaobaijilang W	1.8 m
	10-1	8.10	9.82	5.8	−5.4	Dundejilin	1 m
	10-2	1.55	9.64	3.1	−12.6	Aomenjilin	1 m
	12-01	13.30	9.45	5.8	−5.3	Sayinwusu S	1.2 m
	12-02	15.50	9.22	5.1	−6.2	Sayinwusu M	<1 m
	12-03	>100	10.33	5.7	−5.3	Sayinwusu H	<1 m
	12-04	14.80	9.30	4.4	−7.2	Sayinwusu N	1.5 m
	14-01	>100	10.45	4.4	−21.3	Badan NW1	<1 m
	15-2	25.90	8.98	5.9	−5.4	Badan NW3	<1 m
	15-3	7.50	9.70	4.6	−7.3	Badan NW3	<1 m
	15-4	>100	11.00	2.5	−14.2	Badan W	<1 m
	15-5	>100	/	5.5	−6.1	Badan NW5	<1 m
	15-6	>100	10.39	2.2	−32.0	Badan S1	<1 m
	15-7	>100	10.37	3.8	−16.9	Badan S2	<1 m
	15-8	1.68	8.65	5.6	−10.9	Badan E	1.5 m
	16-2	1.54	10.02	5.9	−13.9	Baoritelegai N	2 m
	16-3	1.27	9.61	3.4	−10.2	Baoritelegai E	1 m
	16-4	1.02	8.56	1.8	−18.5	Aosigetunuoer	2 m
Wells in the Dune area	13-01	0.51	8.15	−3.8	−38.7	Badan	3 m
	15-01	0.67	8.01	−4.0	−33.6	Badan	60 m
	16-1	0.62	8.19	−1.8	−26.6	South margin	6 m
Wells in the area of Yabulai	17-1	1.89	8.04	−7.3	−59.9	Well no. 12	80 m
	17-2	2.59	7.97	−7.5	−60.3	Well no. 2	116 m
	17-3	6.20	7.80	−7.8	−63.3	Well Ganjia	102 m
	17-4	1.48	7.71	−9.6	−91.1	Well no. 3	110 m
	17-5	12.30	7.55	−7.1	−52.8	Well no. 7	138 m
	17-6	3.24	8.78	−4.9	−50.5	Well Beiliang	60 m
	18-1	0.82	8.00	−7.2	−57.5	Mountain Yabulai	Artesian
Wells in Zhongquanzi	17-7	0.77	8.27	−4.0	−45.1	Zhongquanzi 1	60 m
	17-8	0.76	8.60	−4.6	−53.4	Zhongquanzi 4	60 m
Wells in Left Banner	20-1	0.55	7.71	−9.4	−67.7	Chahaertan	120 m
	21-1	2.19	7.77	−9.7	−69.8	Sarihuode	120 m
	21-2	0.76	8.10	−10.7	−74.4	Yaoba	60 m
Well in Minqin	MQ-01	0.68	7.75	−9.7	−69.4	North of Minqin	108 m

Several samples were taken from the same site because there are several lakes or wells there; these samples are marked by an extensional character such as "Shaobaijilang W" or "Badan NW1." See Figures 1 and 2 for location of the sites.

dune surfaces in the general vicinity of Shaobaijilang, Sayinwusu and Dundejilin and a significant number of pottery shards around the lakes. The pottery shards belong to two epochs. The first, a red pottery with intercalation of sand, is from the period of Qijia Culture (ca. 2400–1900 BC), a civilization between late Neolithic and early Bronze Age. The other pottery found dates from the Ming and Qing dynasties (i.e., the last 600 yr). Few artifacts were found dating from the period between Qijia Culture and Ming Dynasty (1900 BC–AD 1400).

Discussion

Water balance and recharge of the inter-dune lakes

Earlier case studies have shown that the modified Penman Equation used here is suitable for arid regions in northern China. Evaporation, calculated according to this equation, is consistent with the values measured in a 20-m^2 large evaporation pan at regional weather stations with a difference <±10% (Zhang and Zhou, 1992). Based on this equation, mean annual evaporation from Lake Bosten in Xinjiang, northeastern Tarim Basin, should be ~980 mm. This estimate is nearly identical to the measured value from a large evaporation pan (Wang, 1993). Since annual temperature at Lake Bosten is lower than in the Badain Jaran Desert, higher evaporation (1040 mm) from the lakes in the Badain Jaran Desert is reasonable. Taking into account the error associated with the estimate, mean annual evaporation from lake surfaces in the Badain Jaran should fall between 940 and 1150 mm, significantly less than the ~4000 mm quoted in earlier studies (e.g., Chen et al., 2004).

Evaporation from land surfaces (E_s) is usually much lower than from open water (E_l). This relationship is given by:

$$E_s = K \times E_l$$

where K is a constant that varies depending on local environmental conditions. Studies in Xinjiang (Tang et al., 1992) have shown that K varies between 0.07 and 0.30 across the region, with drier areas having lower K values. For the Taklamakan Desert, the value for K is 0.07. Since the Badain Jaran Desert is slightly wetter than the Taklamakan, we estimate its K value to be ~0.10. Therefore, mean evaporation from the land surface in the area surrounding lakes in the Badain Jaran is ~100 mm (1040×0.10 mm). For comparison, mean annual evaporation from the land surface has been measured at 25–50 mm in the drier Taklamakan Desert (Tang et al., 1992) and 160 mm in the wetter Maowusu Sandy Land (Liu et al., 2008). Our estimate for the Badain Jaran falls close to an interpolated value between these two known measurements.

Regional totals of precipitation (P) and evaporation (E) in the area of desert lakes in the Badain Jaran are estimated as 2.63×10^8 m^3 and 2.71×10^8 m^3, respectively [($P=250{,}000$ (hm^2, the study area)$\times10^4\times105\times10^{-3}$ ~ 2.63×10^8 m^3 while $E=248{,}000$ (hm^2, the area of land)$\times10^4\times100\times10^{-3}+2230$ (hm^2, the area of water)$\times10^4\times1040\times10^{-3}$ ~ 2.71×10^8 m^3)].

According to this preliminary calculation, total rainfall (P) approximates total evaporation (E). Although such a balance calculation is by no means precise and is sensitive to the derivation of K, it indicates that the water loss via evaporation might be much

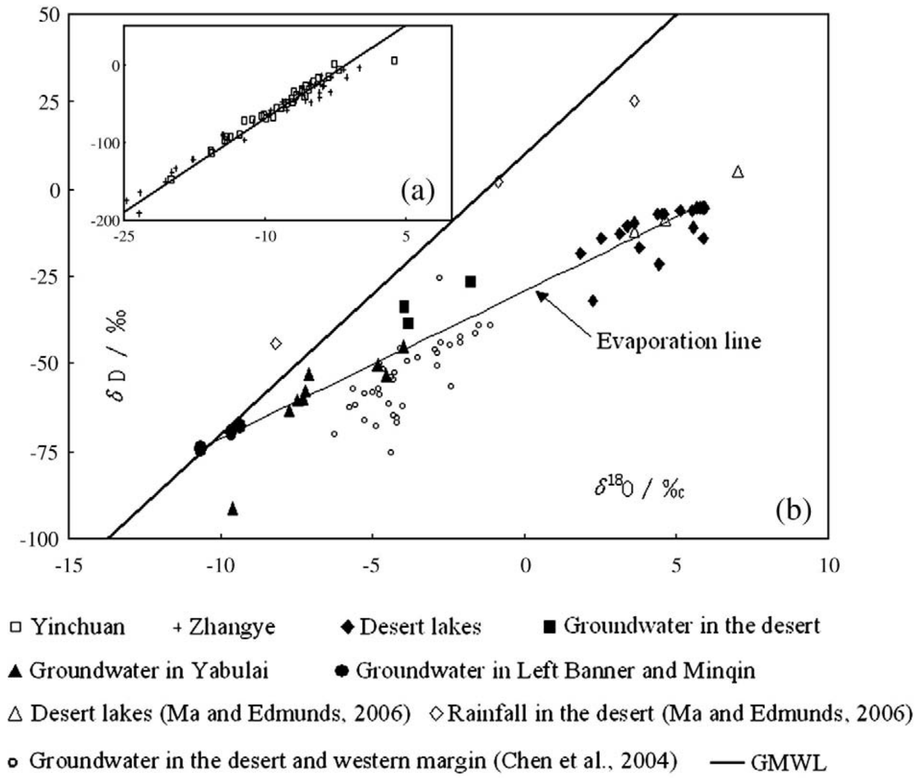

Figure 5. Isotopic compositions in the rain of the IAEA stations (a; for locations of Yinchuan and Zhangye see Fig. 1) and the water samples taken from the Badain Jaran (b; for sampling sites see Fig. 2 and Table 3). GMWL = global meteoric water line.

smaller than previously suggested (e.g., Hofmann, 1999; Chen et al., 2004; Gates et al., 2008a). These higher estimates of evaporation have been derived from weather station records measured using metal evaporation gauges with a diameter of 20 cm. This measurement technique is not consistent with boundary conditions in the field.

This preliminary water balance calculation indicates that local rainfall could be an important source for the recharge of these desert lakes and is supported by the relatively high tritium concentrations in the shallow groundwater in the Badain Jaran Desert (Yang and Williams, 2003; Gates et al., 2008b). However, due to significant topographic variation in this region (Fig. 1), at this time we cannot say with certainty whether any other potential source might also be crucial to the recharge of these desert lakes.

Our interpretation of the water balance in the Badain Jaran and recharge of these desert lakes should be verified by systematic dating of groundwater samples in the study area. More precise groundwater ages in both shallow and deep aquifers would be very helpful to answer this question. Two issues, however, make the dating a challenging task. First, sampling of deep groundwater characteristics requires deep wells. No such wells exist within the dune fields. Second, dating techniques for the groundwater in these lakes need to return ages unaffected by the occurrence of calcium carbonate, as indicated by the large reservoir effect in the radiocarbon ages of lacustrine sediments from the dune fields (Table 1).

Mean annual evaporation, calculated using the modified Penman Equation, suggests a ~5 mm mean annual groundwater recharge rate across the dune surfaces. Using a chloride mass balance model, Ma and Edmunds (2006) suggested that the mean annual recharge rate would be 0.95–1.33 mm, while Gates et al. (2008a) arrived at a value of 1.4 mm.

Gates et al. (2008b) dated the shallow groundwater in the southeastern margin of the desert to 1–2 ka by radiocarbon methods without considering reservoir effects and by assuming that carbonates are just of minor amount in the silicate desert sands. However, calcium carbonate is between 0.5% and 2.5% by weight in the dune sands of Badain Jaran Desert (Li and Yang, 2004) and approximates 23% in the calcareous layers (Yang et al., 2003). These values are sufficiently large to potentially cause reservoir impact on the radiocarbon ages of shallow groundwater. The alkaline character of the water samples, as shown by their pH (Table 3), is caused in part by calcium carbonates found in the aquifer and in the unsaturated zone. We believe that recharge rates calculated on the basis of chloride mass balance should also be treated with caution, since chloride is assumed to be derived only from rainfall (Ma and Edmunds, 2006; Gates et al., 2008a). In the Badain Jaran Desert, dune sand depositional processes are accompanied by the deposition of salty dust blown in from the inter-dune depressions on windy days. Wang et al. (2004) reported relatively high Mg, Na, Cl and S contents in the wind-eroded dust originating from the lower reaches of the Ruoshui River (Fig. 1). Therefore, a considerable amount of the chloride in the dune sands may be derived from evaporites that have been transported by aeolian processes. These evaporites are common in inter-dune depressions and in the palaeo-lakes in the region and are mined occasionally by local residents.

Hydrogen and oxygen isotopic compositions of water samples collected during this study demonstrate a positive correlation of the isotopic δ values with their TDS and a negative relationship with the depths of wells from which the groundwater samples were collected (Table 3). The isotopic composition of modern precipitation varies considerably in this desert environment. Although there are no desert stations recording isotopic compositions of rainfall, two stations, Zhangye in west and Yinchuan in southeast (Fig. 1) are located nearby and provide information on isotopic values. Southeastern monsoons pass Yinchuan before arriving in the Badain Jaran while rain from westerlies pass Zhangye before reaching this desert. Rainfall from both stations shows a large variation of δD (−191.4‰ to 5.1‰) and $\delta^{18}O$ (−27.7‰ to 3.9‰) (Fig. 5a). The lower values occur in winter months, whereas higher values are recorded during the summer months (IAEA, 2008).

The values of the groundwater samples from the desert and the desert margins are within the range of variations recorded in these two weather stations. Hydrogen and oxygen isotopic values show that both lake water and groundwater in the desert and along its margins are along an evaporation line (Fig. 5b). It is difficult to precisely judge whether the low values in the deep wells on the desert margins were caused by modern winter rainfall or by palaeo-water precipitated during cold geological periods. As the rainfall in the southern margins of the desert is mainly from East Asian summer monsoons, a meaningful amount of groundwater recharge during the cold geological periods is hardly possible due to reduced rainfall caused by weaker summer monsoons. But the rainfall during the glaciations would be of importance for the recharge if it was derived from the westerlies.

Yang (2006) measured oxygen isotopes from 24 water samples from the shallow aquifers in the Yabulai Mountains. Since the depth of these wells is generally between 1 and 6 m and the water has a high concentration of tritium, it is assumed that the shallow groundwater is recharged primarily by local rainfall. The δ^{18}O values from this aquifer range between −8.6‰ and −0.4‰ (Yang, 2006), similar to those in the groundwater samples measured in this study. The δ^{18}O values indicate that there is no fundamental difference between the deep groundwater (well depth between 60 and 138 m) and shallow groundwater in the desert margins including the area of the Yabulai Mountains, meaning that the waters in the shallow and deep aquifers may be derived from the same source. The lower ^{234}U/^{238}U ratio of the tufa from Dundejilin (Table 2) indicates that it was formed in shallow water, as higher ratios are commonly found in the deep groundwater (Osmond and Cowart, 1992).

Remote water as the source of groundwater recharge in the Badain Jaran Desert was inferred initially from the isotopic composition of a snow sample from the Qilian Mountains (Chen et al., 2004). We believe this hypothesis needs to be further examined because rainfall on the margins of the desert (at Zhangye and Yinchuan) may have similar isotopic compositions (Fig. 5a). Furthermore, during winter the isotopic values at these two stations are very similar to those of the snow sample. Two other arguments for a remote source of groundwater can be interpreted differently as well. First, the travertine-like calcium carbonate deposits in the hypersaline Lakes Nuoertu and Yindeertu was suggested as evidence for water originating from deep carbonate layers through fractures (Chen et al. 2004). However, the Badain Jaran Desert travertines are similar to tufa towers reported from other salt lakes in the world, which occur when evaporative hyperalkaline conditions are associated with relatively high ambient temperatures. These kinds of travertines are dominantly microbial and physico-chemical constructions, and they are different from the “freshwater” thermal and hydrothermal calcium carbonate deposits that invariably lack in situ macrophyte and animal remains (Ford and Pedley, 1996). In Yindeertu (Fig. 2), plants grow quite densely on the travertine tower. Second, the ^{87}Sr/^{86}Sr ratio of the tufa samples ranges from 0.710 to 0.713, and Chen et al. (2004) suggested that this result was due to the potential contact of groundwater with overlying ^{87}Sr-enriched rocks during upwelling from deep layers. We hypothesize that this tufa was probably precipitated from shallow groundwater stored in the dune sands, because the ^{87}Sr/^{86}Sr ratio of dune sands in the Badain Jaran is in the range of 0.711–0.712 (Chen et al., 2006).

Climate during the Holocene

Although it is not clear whether the paleo-lake areas in the Badain Jaran Desert were inundated simultaneously, we believe that there must have been at least a period that was much wetter than at present. The age of the highest lake stands from the four lakes studied bracket the interval between 4000 and 7500 cal yr BP. Lacustrine deposits occurring at intermediate lake levels were dated to 7500–10,000 cal yr BP. From this evidence we conclude that the Badain Jaran desert climate was relatively wet during the early Holocene and reached maximum wetness during middle Holocene. The occurrence of Neolithic relicts and pottery of the Qijia Culture dating from the middle Holocene confirms that human occupation was common around the desert lakes, indicating a relatively good environment with high water availability. While this conclusion is consistent with results from earlier studies from other lakes in the Badain Jaran Desert (Hofmann, 1999; Yang and Williams, 2003), the present study suggests a longer and more intensive duration of increased precipitation in the desert area. These lacustrine deposits and palaeo-shoreline palaeoclimatic archives directly show that the inter-dune lakes are recharged mainly by local precipitation. The current lack of lakes in the northern Badain Jaran Desert is a result of a decrease in mean annual rainfall since the middle Holocene.

Our interpretation of the Holocene climate history of the region, based almost entirely on characteristics found within the Badain Jaran Desert, is different from some of earlier reconstructions drawn from lacustrine sediments in the drainage basins of adjacent regions (e.g., Chen et al., 2003, 2008; Hartmann and Wünnemann, 2009). Although palaeoclimatic reconstructions in the arid regions of China have largely been inferred from the studies of lacustrine deposits in the drainage basins of the rivers (for an overview see Yang and Scuderi, 2009), we believe that other factors including climate in the remote headwater areas of these rivers and change of river courses (quite common in arid regions) would have strong impact on such lake systems and may make some of these earlier interpretations questionable.

The similarities between our Badain Jaran Desert climate reconstructions and similar reconstructions from the Sahara and Arabian deserts support this conclusion. Various records and palaeoenvironmental simulations show that it was much wetter in the Sahara of northern Africa during the early and middle Holocene (e.g., Schuster et al., 2005; Renssen et al., 2006). In the arid to hyper-arid southeastern part of Arabia, frequent variation in precipitation intensity during the Holocene have been recognized (Parker et al., 2006). These dunes became stabilized and vegetated with a C3-dominated savanna grassland and with inter-dune lakes formed in response to the incursion of the Indian Ocean Monsoon at approximately 8500 cal yr BP. The Indian Ocean Monsoon weakened ca. 6000 cal yr BP with the dune reactivation and accretion (Parker et al., 2006).

Lake-level changes in the Badain Jaran Desert are consistent with the general trends of Holocene monsoon variations in east and south Asia. Numerical simulations indicate that the amplitude of the summer–winter seasonal cycle was greater than at present and caused distinct Holocene precipitation maximums at 8000–7500 and 4500 cal yr BP over central Asia (Bush, 2005). Precisely dated cave deposits show that the Indian and East Asian summer monsoons were enhanced at the onset of the Holocene, were strongest in the early and middle Holocene, and then weakened after the mid-Holocene (Fleitmann et al., 2007; Yuan et al., 2004; Shao et al., 2006). This pattern follows variations in summer insolation at low latitudes (Kutzbach, 1981).

Conclusions

A modified Penman Equation approach, combined with weather data from AD 1961 to 2001 from the margins, has produced the first realistic estimate of the mean annual evaporation from lake surfaces and dune slopes in the Badain Jaran Desert. Our results suggest that the mean annual evaporation is ~1040 mm from the lake surface and ~100 mm from land surfaces in the southeastern part of the desert. Both values are much lower than previously published in literature. Consequently, about 5% of the modern precipitation could be recharged to the groundwater. We think that our estimate of the mean annual evaporation from the lake surface is realistic. However, our interpretation of the mean annual evaporation from the land surface will need to be verified by future research.

Contradictory to conclusions drawn from chloride mass balance and radiocarbon data of shallow groundwater, our water balance calculation suggests that local rainfall may make a significant contribution to the recharge of the groundwater. Owing to distinct topographical variations in the region, precise ages of water samples from various aquifers are needed to ascertain whether other sources might be crucial to the recharge. The hydrogen and oxygen isotopic values show that the lake water and groundwater in the desert and in its margins are principally linked by an evaporation line, suggesting that the lake water and groundwater could be from the same source, namely local and regional precipitation. The tufas in the desert lake should have been formed by shallow groundwater, because the strontium ratios of the tufas are consistent with those of the dune sands in the desert.

The shells of the freshwater snails in the lacustrine deposits of these newly studied lakes suggest that the present salty lakes were filled with fresh water at ca. 10 ka. Although most of the palaeo-shorelines have not been dated, available data indicate that the total lake area was probably nine times as large as at present during the middle Holocene. Neolithic relicts and pottery of Qijia Culture confirm that human occupation occurred around the desert lakes during the early and middle Holocene, suggesting that this area was able to support a significant population at that time. We hypothesize that the recharge and lake-level change in this desert directly reflect rainfall variations within the desert rather than from distant areas and that the wetter climate that filed these lakes could have been triggered by a strong East Asian summer monsoon associated with strong insolation during the early to mid-Holocene.

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