Groundwater and lake evolution in the Badain Jaran Desert ecosystem, Inner Mongolia

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Abstract The amount and timing of aquifer recharge and the evolution of lakes and groundwater in the south-eastern Badain Jaran desert of Inner Mongolia, with high megadunes, has been investigated using stable isotopes and hydrochemistry. Unsaturated zone moisture profiles down to 22 m have recorded recharge over 1185 years. Small but finite amounts of recharge are recorded with mean recharge rates of 0.95-1.33 mm $year^{-1}$, determined using a chloride mass balance technique. The unsaturated profile also acts as a unique archive of hydrological and climate change. Before 1300, it was relatively dry but distinct wet periods may be recognised during 1340-1450, 1500-1610 and 1710-1820. Since the mid 1800s, the climate shows a trend towards greater aridity. The interdune lakes are generally fresh but locally, hypersaline lakes are found in juxtaposition. This implies that in general, the lakes have low residence times and flow back into the dune system, but sedimentary obstruction locally prevents outflow and extreme evaporation occurs. The stable isotope records show that the lakes are fed by palaeowaters which on the basis of other proxy data must predate the Last Glacial Maximum. Their recharge source is problematic but most likely this derives from a diminishing water table extending some 30 m south to the Yabulai Mountains.

Résumé Le taux et la fréquence de la recharge aquifère ainsi que l'évolution des lacs et de l'eau souterraine du Sud Est du désert de "Badain Jaran" (Mongolie intérieure), avec ses hautes méga-dunes, ont été étudiés à l'aide d'isotopes stables et de l'hydrochimie. Les profils d'humidité de la zone non saturée effectués jusqu'à 22 mètres de profondeur enregistrent des recharges jusqu'à 1185 ans. Des recharges faibles mais claires sont enregistrées, elles montrent une moyenne de 0.95 – 1.33 mm/an à l'aide de la méthode du bilan des chlorures. La zone non saturée fournit aussi une archive unique des changements hydrogéologiques et climatiques. Avant 1300 ans après JC, la région était relativement sèche, pourtant, des périodes humides peuvent être reconnues entre 1340–1450, 1500–1610, et 1710–1820 ans après JC. Depuis le milieu du $18^{éme}$, le climat montre une tendance à une plus grande aridité. Les lacs inter duniaires contiennent générallement de l'eau douce mais localement, des lacs hypersalins sont trouvés en juxtaposition. Ceci implique que l'eau des lacs ont un faible temps de résidence, et qu'elles retournent au système dunaire; locallement, des colmatages sédimentaires limitent cet écoulement et une évaporation importante apparaît. Les enregistrements des isotopes stables montrent que les lacs sont alimentés par des eaux anciennes qui sur la base d'autre données antidatent le maximum de la dernière période glacière. Cette source de recharge est problématique, ce qui découle certainement de la diminution du niveau phréatique qui atteint 30 mètres au sud des montagnes de "Yabulai".

Resumen Se ha investigado la cantidad y edad de recarga del acuífero y la evolución de los lagos y agua subterránea en el sureste del desierto Badain Jaran del Interior de Mongolia, con megadunas altas, utilizando hidroquímica e isótopos estables.Se han analizado perfiles de zona de humedad no saturada de hasta 22m de profundidad los cuales registran recarga por más de 1,185 años. Se ha determinado en base a técnicas de balance de masa de cloruro la presencia de cantidades pequeñas pero finitas de recarga con un ritmo medio de recarga de 0.95-1.33 mm $año^{-1}$. El perfil no saturado también actúa como un archivo único de cambio climático e hidrológico. La región fue relativamente seca 1300 A.C. pero pueden identificarse diferentes periodos húmedos durante 1340–1450, 1500–1610 y 1710–1820 A.C. Desde mediados de la década de 1800 el clima muestra una tendencia hacia mayor aridez. Los lagos interdúnicos son generalmente de agua fresca pero se ha encontrado en yuxtaposición lagos hipersalinos. Esto implica que en general los lagos tiene

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bajo tiempo de residencia y fluyen de regreso hacia el sistema de dunas, aunque obstrucción sedimentaria local previene el flujo y ocurre evaporación extrema. Los registros de isótopos estables muestran que los lagos son alimentados por paleoaguas las cuales en base a datos proxy tuvieron que haberse formado antes de la Última Glaciación Máxima. Su fuente de recarga es problemática pero muy probablemente esto se deriva de un nivel freático descendente que se extiende unos 30m al sur de las montañas Yabulai. Evolution de l'eau souterraine et de lacs dans l'écosystème du désert de “Badain Jaran”, Mongolie interieure.

Keywords Hydrochemistry · Groundwater recharge · Paleohydrology · Unsaturated zone · Badain Jaran Desert

Introduction

The Badain Jaran Desert (Fig. 1) is located in the centre of the Alxa Plateau, north of the Qilian Mountains and the Tibetan Plateau. It lies in western Inner Mongolia from 39°20′N to 41°30′N and 100 to 104°E. It is the second largest desert in China with an area of 49,200 km^2. The desert consists of a regular series of crescentic megadunes with a relative height of 200–300 m above sea level (m a.s.l.), between which occur groundwater fed lakes (Hofmann 1996; Zhu 1999). There has been no significant present day or prehistoric human interference of the region, and being a pristine location, it is ideal for reconstructing past changes and present trends in the hydrological cycle. It forms part of the Gobi Desert and is situated at the limit of the East Asian Monsoon, which controls the region's precipitation.

This unique desert environment with its lakes attracted several scientific investigations such as the Sino–Swedish expedition in the 1930s, to investigate the terminal lakes (Norin and Hedin 1980). The working group for desert control of the Chinese Academy of Sciences carried out a comprehensive survey of the physical geography and social economy in the 1950s and 1960s (Yu et al. 1962; Sun and Sun 1964). The Sino–German expeditions in 1980s and 1990s focused mainly on the palaeoclimatic, geomorphological and sedimentological aspects of the dunes and lakes (Hofmann 1996; Jäkel 1996).

The climatic evolution of the Gobi Desert during the late Pleistocene is now becoming quite well established via radiocarbon dates on lacustrine deposits and lake level fluctuations in the Tengger Desert, some 200 km to the east of the region (Pachur et al. 1995; Wünnemann et al. 1998; Dong et al. 1995). The general picture that emerges is that a prolonged cooler and wetter period prevailed from 39,000–20,000 years BP. The period from 20,000–13,000 years BP was marked by a hyperarid phase with increased Aeolian activity and decreased lake levels linked to a weakened summer monsoon (An et al. 1991). The dune accumulations have probably taken place during successive hyperarid periods with strong westerly winds during successive stages of the late Pleistocene (Yang 2000). The Holocene was marked by arid phases interrupted by several millennial scale humid phases. The period since about 3,000 years BP is considered to have been one of increased aridity during which time the climate deteriorated severely, desertification process prevailed, sand dunes intruded and erosion occurred (Zhang et al. 2000).

Understanding the origins and evolution of groundwater in this arid region of China is important for many reasons. It is first of all unlikely that there could be any appreciable modern recharge in regions with less than 200-mm rainfall (Edmunds and Tyler 2002), but this needs to be tested at local scales. Fresh groundwaters are nevertheless to be found beneath much of the Gobi Desert and understanding their origins and evolution is important for the decision-making processes regarding sustainable development of the region. Groundwater also sustains several important oases across north-west China (Geyh et al. 1996) and Inner Mongolia, which is of importance both for habitation as well as sustaining wetlands. It has been suggested (Chen et al. 2004) that groundwaters in this region are modern, derived from the Qilian Mountains, and even provide the moisture source for the high dunes; this hypothesis has been rejected (Edmunds and Ma 2005).

Of special interest in the present context, however, is the possibility that water retained in the unsaturated zone may preserve a record of history of recharge and hence climate over the decadal to millennial scales (Edmunds and Tyler 2002). Finally, the existence of groundwaters dated relatively using stable isotopes, provides confirmation of major wet episodes in the past which helps to confirm results from other environmental and historical archives.

The objectives of the present study are to explain the origins of the lake system within the Badain Jaran Desert dunefield by sampling representative lakes and the groundwaters that feed them, supported by data from local groundwaters. Isotopic and geochemical analyses are used to determine the likely age and origins. Unsaturated zone profiles have been used to estimate the modern recharge rates and also to investigate the records of recharge and climate over a period of 1,000 years, which may provide a parallel to results on the palaeoecology of the lake sediments and ice cores.

Fig. 1 The south-eastern Badain Jaran Desert in its regional geological and topographical setting north of the Yabulai Mountains in Inner Mongolia. The line of cross section (*AB*) in Fig. 2 is shown. Locations of lake, shallow well (W) and groundwater samples are indicated as well as the rainfall gauging station (Zhongqanzi). The detailed inset shows the exact sampling locations in relation to the megadunes and lakes with juxtaposition of fresh and saline waters. *SW1*, *BA1*, *BA2* refer to the sites of unsaturated zone profiles at Sayinwusu and Baoritelegai

Hydrogeology and environment

The desert is bounded by the Yabulai Mountains (with maximum elevation 1,957 m a.s.l.) in the southeast

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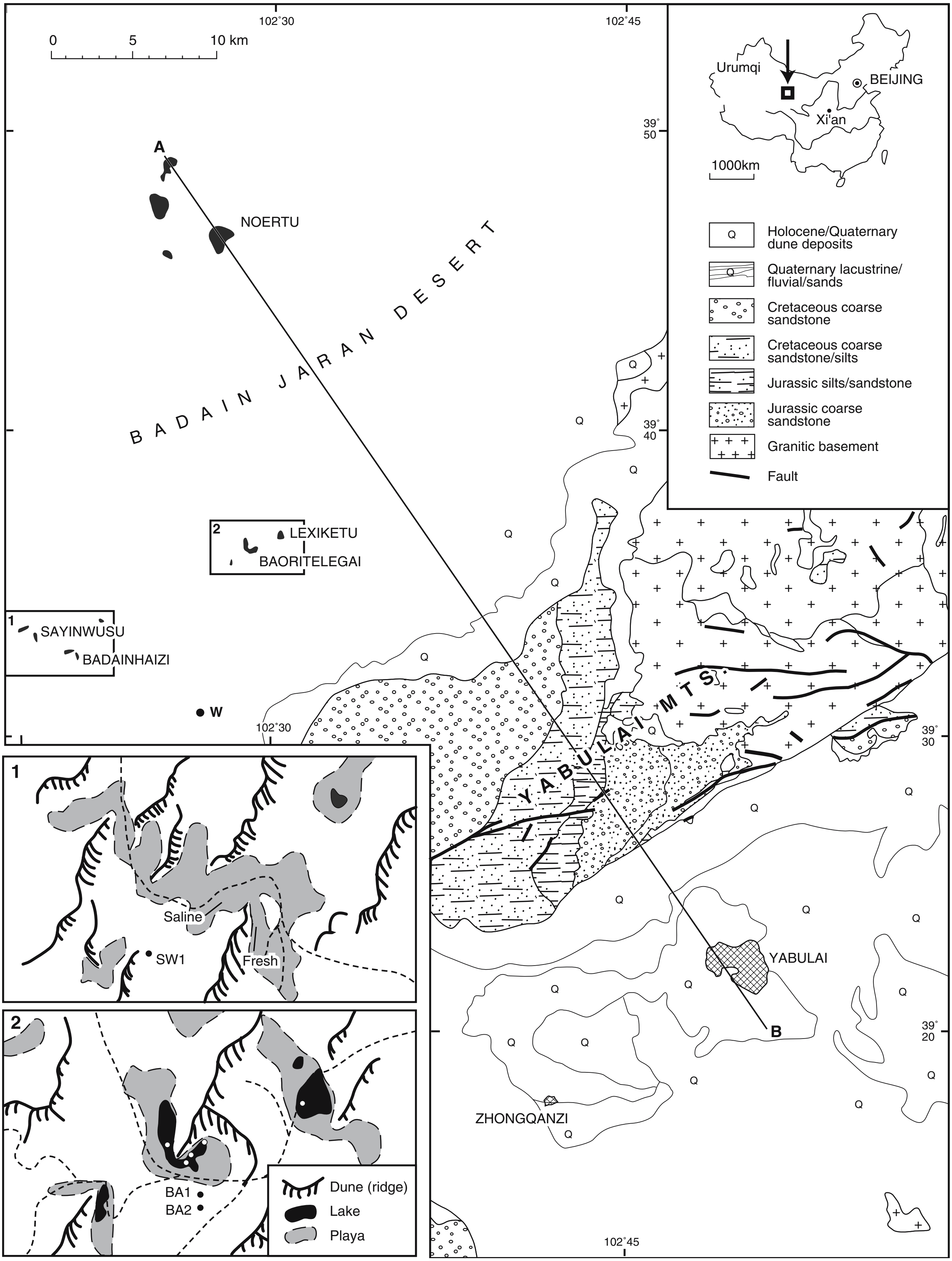

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(Fig. 1) and the Longzhou Mountains (maximum elevation 1,963 m a.s.l.) in the south. In the west and north the region extends down to the low and flat areas of the Gurinai grassland and the Guezi Hu wetlands about 1,000 m a.s.l. Among the highest megadunes in the SE part of the desert, more than 100 lakes of different size are concentrated within an area of approx. 4,000 km^2. The lakes show a wide range of salinity from place to place. The shallowest lakes are between hyposaline (3–20 g L^{-1}) and mesosaline type (20–50 g L^{-1}). Some of them are even subsaline (<3 g L^{-1}) such as Baoritelegai and Badainhaizi lakes. The oval-shaped deeper lakes to the north such as Noertu (Hofmann 1996) are hypersaline (>50 g L^{-1}) and salinities in these lakes may range from 97 to 334 g L^{-1}.

A strong seasonal east Asian monsoonal regime, which reaches the margins of the desert in summertime, is responsible for rainfall from July to September, while in the wintertime, cold and dry continental air masses with temperatures below zero frequently influence the area (Zhang and Lin 1992). The mean annual precipitation measured within the area at Zhongqanzi (Fig. 1) from 1956 to 1999 is 89 mm, whilst potential evaporation is around 2,600 mm. The lakes are seepage lakes with no surface runoff. Many of the lakes are surrounded by a strip of dense meadow vegetation (*Polypogon monspeliensis, Triglochin maritima, Carex sp., Achnatherum splendens , Glaux maritime*) up to a few metres in extent. In some saline lakes, small travertine islands are found where fresh groundwater emerges under pressure from the lake bottom (Hofmann 1999). Some lakes also show a sharp decrease in conductivity near the lake bottom indicating sub-lacustrine inflows of water of low salinity. These observations suggest that the area is underlain by artesian groundwater. Profiles of the lake sediments suggest that the hydrological system has been in existence for at least 33,000 years, although between 30,000 and 12,000 years BP there is lack of evidence of lake formation. However, a period of activity coincided with the Holocene climatic humidity optimum, especially between 7,500 and 5,500 years BP (Hofmann 1999).

Little data on the hydrogeology and deep geology of the area are available with no drilling at all beneath the Badain Jaran dune area. A schematic cross-section from the mountains across the area of desert is shown in Fig. 2 based on the limited near-surface available evidence. The Badain Jaran Desert tectonically belongs to the basin depression of the Alxa platform. Rocks of Jurassic, Cretaceous and Tertiary age outcrop at the fringe of the basin, whilst the centre of the basin is occupied by Quaternary sediments. Faults of Hercynian age became reactivated during the Yenshan movement (Tibetan uplift), which led at the same time to the uplift of the peripheral mountains, the basin settlement, and the deposition of the Jurassic and Cretaceous sequence. Expansion of the depression continued into the Cenozoic era, resulting from the Himalayan movement, during which time the Tertiary red-bed sequence was deposited. Renewed tectonic movement during the Quaternary led to a series of fault terraces in the Badain Jaran region with deposition of terrestrial sediments.

The Lower Pleistocene sediments (in turn overlying Pliocene), are comprised of semi-consolidated piedmont conglomerate and sandy conglomerate, which undergoes gradual transition towards finer grained and well-stratified fluviatile and lacustrine facies. The Middle and Upper Pleistocene sediments are mainly fine grained or clayey sediments of lacustrine and fluviatile origin; further details of which are given in Cai (1986).

The mainly Holocene Aeolian sands are deposited unconformably above the older sediments and form the dominant desert landscape as well as the major phreatic aquifer in the Badain Jaran Desert. The lake district is divided into a northern and southern part by a 10 km wide strip of land with no lakes. There is evidence that this is controlled by an anticlinal structure (Hofmann 1999). Hofmann (1999) has suggested that the northern lakes could be fed by modern groundwater recharge, and those in the south by a regional groundwater flow system. The aquifer of fine sand varies in thickness from below 5 m to above 100–200 m.

Methods

Field work took place during the summer of 1999, during which samples of groundwater, lakes and rain were taken for isotopic and chemical analysis as well as two profiles of sand from a site near Baoritelegai (Fig. 1). Following preliminary interpretation of these data, a further sampling campaign was conducted in 2000, during which samples were taken from the few available shallow wells in the Yabulai Mountain area, as well as from Baoritelegai and

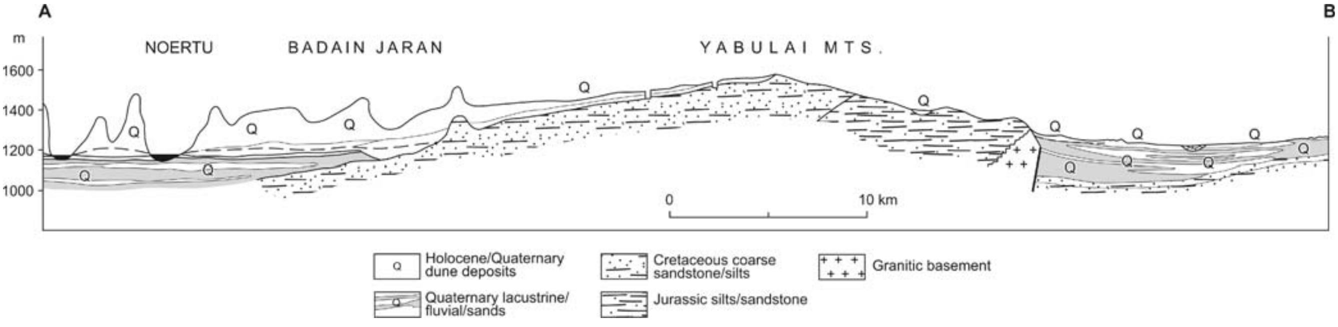

Fig. 2 Cross-section southeast to northwest from the Yabulai Mountains to show the likely geological succession beneath the desert

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Lexiketu lakes and groundwaters feeding the lakes (Fig. 1). Heavy rain (approx 70 mm) occurred during one storm during this field campaign and it was possible to collect samples as well as hail from a storm at Yabulai (outside the area). All samples were filtered (0.45 μm membrane filters) and an aliquot was acidified with 1% HNO_3 for analysis of trace elements. Unacidified samples were collected for anion analysis as well as for stable isotope analysis. Owing to the shallow water table, it was not possible to sample for tritium or carbon-14 because of the risk of atmospheric exchange with modern humidity or carbon. A third field visit took place in September 2002 at Sayinwusu during which a third profile was augured to a depth of 22 m and further lake samples were obtained (Fig. 2).

On site analysis included temperature, specific electrical conductance (SEC) and total alkalinity (as HCO_3^-) by titration and pH. Chloride, NO_3−N, Br and F were analysed by automated colorimetry. Filtered and acidified water samples were analysed for major cations, SO_4, and trace elements either by ICP-OES (inductively coupled plasma optical emission spectroscopy) or ICP-MS (inductively coupled plasma mass spectrometry). Calibrations for cation analyses were performed using appropriately diluted standards and both laboratory and international reference materials were used as checks for accuracy. Instrumental drift during ICP-MS analysis was corrected using In and Pt as internal standards. Samples for stable isotope analysis (^{18}O, ^{2}H) were measured by isotope ratio mass spectrometry. Determining the ionic balance provided an internal check on the quality of the data; the balance lay within ±6% except for four samples. Precision of measurement for stable isotopes was ±0.1‰ for $\delta^{18}O$, and ±2‰ for $\delta^{2}H$.

Samples of sands from the unsaturated zone from two areas some 400 m apart in the southern Badain Jaran Desert, near to the Baoritelegai and Sayinwusu lakes, were taken by hollow stem hand augur (Edmunds et al. 1988) for investigation of the moisture content and unsaturated zone chemistry to obtain data on modern recharge rates and to determine recharge history. These samples were taken for comparison with the isotopic and chemical compositions of the lakes and springs, as well as to compare the unsaturated zone recharge record (as a proxy for climate) with that of the shallow lake sediments. Water was extracted by elutriation. Samples were homogenised over sample intervals of 12–25 cm. To a 50 g sand sample, 30 ml of distilled deionised water was added to elute the solutes (for Cl and NO_3-N). Supernatant solutions were recovered after 1 h of agitation, and then after centrifugation. Sands were dried at 110 °C and moisture contents reported on a wet weight basis. Deuterium was measured by mass spectrometry following direct reduction of the moist sand over zinc shot (Darling and Talbot 1989).

Estimations of groundwater recharge were carried out using the chloride mass balance (CMB) technique (Allison and Hughes 1978; Edmunds et al. 1988). In this method, the degree of enrichment of Cl in the moisture is inversely proportional to the amount of recharge taking place. Chloride is assumed to be derived only from rainfall and to remain inert during the recharge process. In this remote region consisting of dune sands, these assumptions are considered valid, as conditions compare well with similar regions with Quaternary dune sands where the technique has been applied. It is also assumed that homogeneous moisture movement (piston flow) is taking place with no by-pass (matrix) flow. This assumption is also valid in this fine-grained and homogeneous unconsolidated material. Uncertainties in the approach lie in the measurement of Cl in rain and unsaturated zone moisture. The latter present no problem, but the present study relies on restricted measurements of the total Cl deposition. It is also assumed that the wet deposition approximates to the total deposition; it has been assumed that any dry deposition during the dry season will be in a steady state of movement with no net aerosol deposition to the surface.

In order to provide accurate recharge estimates using the CMB approach, continuous monitoring of rainfall chemistry is necessary over several years and data on spatial variability need to be considered. So far, there are limited data globally and especially in China on Cl in rainfall. During the HAPEX SAHEL experiment in Niger, in a continental location (Goutorbe et al. 1997), samples of rain were collected from six stations and measured for amount, chloride and isotopic data (Goni et al. 2001). The range in weighted mean values at the six stations varied from 0.26 to 1.43 mg L^{-1} Cl in a similar setting to the present study.

The direct recharge (R_d) may be calculated using the formula:

$$R_d = PC_p / C_s$$

where C_p is the mean chloride in rainfall, P is the annual rainfall amount and C_s is the mean chloride concentration in the unsaturated zone (Edmunds et al. 1988). The recharge history may be determined using the cumulative Cl in the profile as an indicator of age and knowing the volumetric moisture contents (Stone 1992; Cook et al. 1992).

The age or residence time (t) represented by Cl at depth z can be evaluated by dividing the cumulative total mass of chloride from the surface to that depth by the annual Cl input (Tyler et al.1996):

$$t = \frac{1}{PC_p}\int_0^z \theta(z)C_s(z)dz = \frac{1}{PC_p}\int_0^z \rho_b(z)M_s(z)dz,$$

where θ is the volumetric water content, ρ_b is the dry bulk density, and M is the mass of Cl per mass of dry soil.

Results and discussion

The results of stable isotope analyses for unsaturated zone moisture, rainfall, lake and shallow groundwater of the

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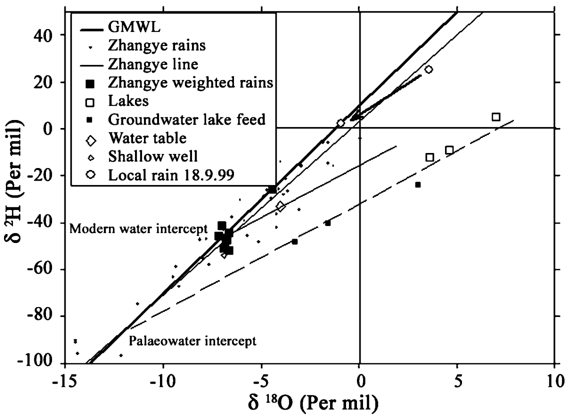

Fig. 3 Plot of δ^{18}O vs. δ^{2}H for rain, lakes and shallow groundwaters in the region of the southeast Badain Jaran Desert. Local rain refers to a single storm at Baoritelegai; the *arrow* shows the progression from light to heavy rains. Water table refers to saturated sands found at the base of the unsaturated zone at BA2. The shallow well is shown as *W* in Fig. 1

Baoritelegai area were used to construct the delta diagram (Fig. 3). Chemical data were also obtained for rain, lakes, shallow groundwater, as well as the moisture profiles and are summarised in the trilinear plot (Fig. 4). The evolution of each system (rainfall, lakes/groundwater and unsaturated zone) is discussed in turn.

Rainfall inputs to the region

Precipitation data are available for several meteorological stations around the study area, including Lanzhou, Yinchuan, Lhasa and Zhangye, although chemical data are not generally available. Zhangye lies some 150 km southwest of the Baoritelegai area and data taken from the IAEA database from 1985 to 1996, were used and are compared to the global meteoric water line (GMWL). Values of deuterium (δ^{2}H) and oxygen-18 (δ^{18}O) in precipitation vary over a large range from –174 to 5‰ and from 24.7 to 0‰ respectively, but the local line is quite similar to the GMWL with an equation of $\delta^{2}H=7.38\delta^{18}O+3.19$ and an r^2 of 0.97. The local line reflects only slight enrichment in moisture due to evaporation of the monsoon air mass. The weighted mean rainfall values at Zhangye station for seven non-consecutive years between 1986 and 1996 lie around −7‰ δ^{18}O (Fig. 3). This value, indicative of the heaviest rains, is most likely to be representative of present day local recharge. During the field work a very heavy storm occurred (18 September 1999) and the isotopic composition of the initial rains and the main storm are shown in Fig. 3. The isotopic composition moved during the storm from a slightly enriched composition towards and along the meteoric water line, in line with the so-called amount effect (Clark and Fritz 1998).

Chemical results for rainfall and hail sampled during the 1999 rainy season are shown in Table 1. The rainfall samples with a concentration of 1.49 mg L^{-1} Cl are from a heavy storm, some 50 mm, estimated to be the majority of the yearly rainfall. From the discussion above, the heaviest rains are probably representative of bulk local rainfall. Samples of rain were subsequently collected from the nearest meteorological station at Zhongqanzi, which had a long-term annual average (1957–1999) of 89 mm. The

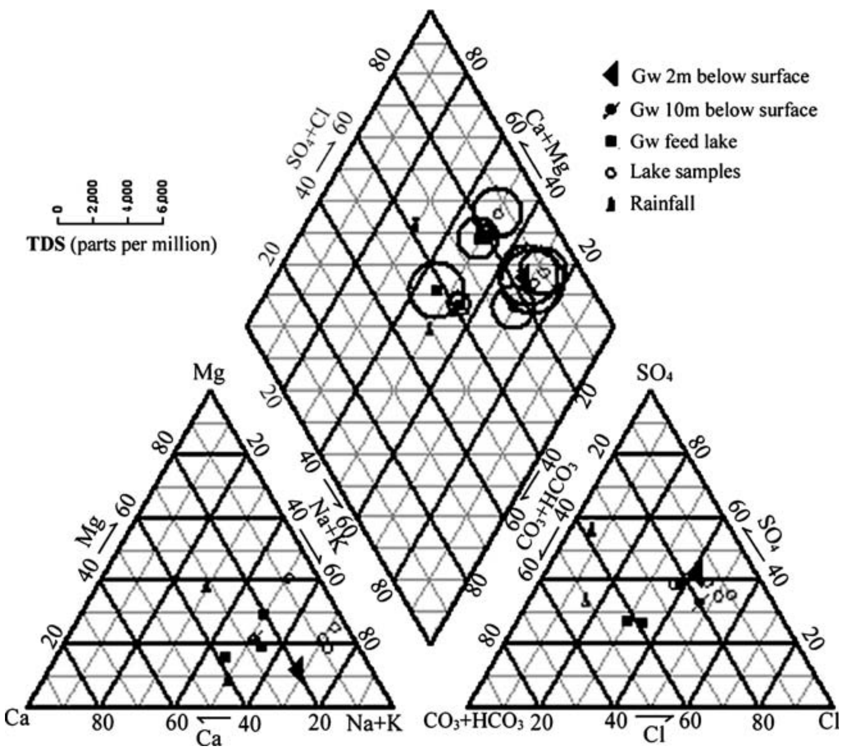

Fig. 4 Trilinear plot of rain, lakes and shallow groundwaters of the Badain Jaran Desert

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Table 1 Precipitation analysis from the Badain Jaran Desert. All chemical results in mg L^{-1}

Site name	Units	Baor(a)	Baor(b)	Yabulai
Precipitation		First rain	Heavy rain	Hail
Date		18.9.1999	18.9.1999	20.9.1999
pH (field)			7.85	
Cl	mg L^{-1}	36.5	1.49	2.65
SO_4			4	28.7
HCO_3			8.1	25.9
NO_3-N			0.13	0.26
Na			2.5	7.8
K			0.9	1.6
Ca			2.14	8.04
Mg			0.22	5.51
Br			<0.02	<0.02
F			0.01	0.06
Si			<0.07	0.47
Ba			0.002	0.013
B			<0.2	<0.2
Li			<0.009	<0.009
Fe			0.05	0.31
Mn			0.009	0.026
Sr			0.011	0.079
Al			0.014	0.24
Zn			0.013	0.012
$\delta^{18}O$	‰	3.6	−0.9	−8.2
$\delta^{2}H$	‰	25	2	−44

BAOR Baoritelegai
Stable isotope results in per mil (‰) vs. standard mean ocean water (SMOW)

weighted mean Cl for storms collected during 2001–2002 was 1.5 mg L^{-1}. A chloride value of 1.5 mg L^{-1} thus seems a reliable value for calculations of the input value in recharge calculations.

The pH of rainfall is alkaline and the excess of Na over Cl combined with a strong excess of non-marine sulphate, together with the overall chemistry, indicate some solute contribution from terrestrial sources during passage over land. The nitrate concentration is low (0.13 mg L^{-1} as NO_3-N) and corresponds to a NO_3/Cl wt ratio of 0.58.

Lakes and shallow groundwaters

The isotopic and chemical data for the groundwaters and lakes are shown in Table 2. The groundwater data include those samples feeding the lakes as well as water at the immediate water table beneath the augured profile at BA1 (see below) as well as one shallow well (Hong Gouzing) some 20 km south of the lake and the high dunes. These samples probably represent the only accessible samples of groundwater in the immediate area, which is remote and devoid of settlement.

The isotopic composition of the lakes and the shallow groundwaters feeding the Baoritelegai and Lexiketu lakes show strong evaporation and are interrelated along a line that intercepts the local meteoric line at around −12‰ $\delta^{18}O$ (Fig. 3). This implies that the groundwaters and the lakes are genetically related and that these are unrelated to modern recharge which has a weighted mean value that is lighter by some 5‰ $\delta^{18}O$. The lakes and inflowing groundwaters, therefore, originate as palaeowaters formed under a cooler climate and/or to a remote source rather than modern recharge. In this context, it is noted that the weighted mean composition of modern high altitude precipitation at Lhasa is 13.7‰ $\delta^{18}O$.

The groundwaters feeding Baoritelegai lakes have a neutral pH and a total mineralisation in the range 720–1,180 mg L^{-1} which is only slightly less than the lakes (1,340–1,790 mg L^{-1}). This suggests that little evaporation is occurring and that these lakes are kept fresh by water continuously moving out of the system towards the north (implied regional flow direction). The total mineralisation at the nearby Lexiketu Lake is also similar but the absence of NO_3 (and the presence of Fe of 1.94 mg L^{-1}) suggests anoxic conditions. There is a dramatic contrast, however, between the two lakes less than 500 m apart in the Badain Haizi region (Fig. 1; Table 2). The easterly lake is brackish with a pH of 8.6 and TDS of 1,800 mg L^{-1}, while the westerly lake is highly alkaline (pH value of 10.6) and with total mineralisation of 400 g L^{-1}. From other studies, the lakes in the southern Badain Jaran Desert show a full range of salinities (Hofmann 1996). The larger and deeper lakes belong to the hyposaline type (3–20 g L^{-1}), whilst the small and shallow ones are maybe subsaline (<3 g L^{-1}) such as Baoritelegai and east Badainhaizi lakes. Small travertine islands may form where the artesian springs of freshwater exist. A sharp decrease of conductivity may be found near the lake bottom in some locations of a lake indicating groundwater inflows of lower salinity (Hofmann 1996).

The major ion compositions are summarised on the trilinear diagram (Fig. 4). There is a wide mix of compositions. The lakes are shown clearly to evolve by evaporation from the shallow groundwater. The stable isotope results confirm that evapotranspiration must be a significant process. The lakes have a higher pH and total mineralisation compared to the shallow groundwater feed as a result of the evapotranspiration and biogeochemical processes.

Trace element compositions (Table 2) may be used for further characterisation of the groundwaters and lakes. The ratio Br/Cl is significantly lower than the marine value (3.53×10^{-3}) and indicates that significant uptake of non-marine aerosol over land (for the unsaturated zone source) has occurred, and during passage through the aquifer, the salinity was derived from a non-marine evaporite source. The high nitrate concentrations suggest aerobic conditions (except in the Lexiketu springs) and the moderate levels of some metals forming oxy-anions (As, Mo, Cr and U) are consistent with aerobic conditions being present. The Baoritelegai springs have high Mn concentrations.

Unsaturated zone profiles

Data available for the moisture in the unsaturated zone include moisture content (MC), Cl, NO_3, as well as $\delta^{2}H$ for one profile BA1 and these are shown as a function of depth in Figs. 5, 6 and 7.

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Table 2 Chemical and stable isotope data for shallow groundwaters and lakes from the Bain Jaran Desert

Groundwaters							Lakes				
Site name	Units	Badain Jaran dunes	Baoritelegai	Baoritelegai	Lexiketu	Baor3	Baoritelegai E	Baoritelegai N	Lexiketu	Badainhaizi	Badainhaizi
Comment		Dug well	Spring	Spring	Spring	Water table				Fresh	Saline
Latitude		39°32	39°37	39°37	39°37	39°37	39°37	39°37	39°37	39°33	39°33
Longitude		102°26	102°30	102°30	102°31	102°30	102°30	102°30	102°31	102°22	102°12
Well depth	(m b.g.l.)	2	0.7	0.5	0.5	16					
pH (field)			7.41	7.33	7.08	NA	9.22	9.21	9.33	8.6	10.8
TDS	(mg L^{-1})	1716	1177	723	1590	556	1337	1788		1826	398000
Cl		383	234	122	244	130	410	454	232	378	119000
SO_4		517	319	129	300	124	364	533	333	252	39800
HCO_3		231	234	235	589	93.9	132	248	261	172	75620
NO_3-N		31.1	2.4	10.3	<0.01	14.8	<0.5	<0.5	<0.01		
Na		403	196	124	224	102	325	416	293	398	151400
K		3.6	31.3	12.9	11.3	9.7	16.2	32.5	15.5	16.7	12500
Ca		95.6	78.1	55.2	163	49.8	34.8	17.2	30.9	144	7960
Mg		37.3	68	24.4	42.9	24.2	45.4	81	49.8	136	3980
Br		0.45	0.32	0.14	0.27	0.17	0.38	0.55	0.26		
F		2.04	1.56	0.92	0.31	1.05	1.60	3.24	2.31		
Si		8.65	10	7.86	11	7.08	7.9	2.56	<0.07		
B		0.9	0.5	0.4	0.4	415.3	0.5	0.9	0.6		
Fe		0.27	0.22	0.03	1.94	< 5	0.17	0.16	0.03		
Sr		2.28	1.27	0.62	1.44	694	1.2	0.25	0.9		
Li	(μg L^{-1})	34.4	21.6	10.3	16.7	13.4	33.4		25.5		
Al		7.1	94.3	42.9	12.8	6.9	3.1		43.9		
Cr		2.2	4.8	1.1	0.2	1.4	0.2		0.2		
Mn		1.1	50.4	34.5	3160.7	1.3	2.1		12.5		
Co		0.2	0.8	0.2	4.9	0.3	0.3		0.2		
Ni		2.2	4.9	1.2	5.9	6.2	1.2		1.4		
Cu		2.0	5.3	1.0	0.4	6.0	0.3		0.5		
Zn		3.7	3.9	1.2	1.4	12.9	1.1		1.5		
As		6.3	1.5	2.4	7.1	8.4	7.7		5.8		
Rb		1.0	13.6	6.1	2.9	4.3	6.4		5.5		
Mo		9.6	5.5	1.6	3.4	3.2	3.3		8.3		
Sb		0.2	0.6	0.3	0.2	<1.0	0.6		1.2		
Ba		28.3	35.6	33.6	51.8	277.9	32.8		28.4		
U		16.1	23.4	7.4	27.3	5.3	5.7		31.2		
$\delta^{18}O$‰	SMOW	−3.8	3.0	−1.6	−3.3		3.6	7.0	4.6		
$\delta^{2}H$‰	SMOW	−49	−24	−40	−48		−12	5	−9		
Br/Cl	(10^{-3})	1.17	1.37	1.15	1.11	1.31	0.93	1.21	1.12		

SMOW standard mean ocean water, *NA* not applicable

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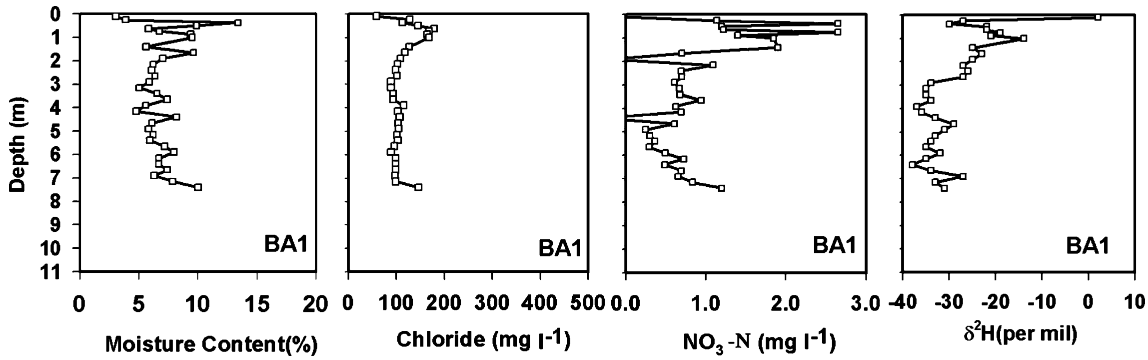

Fig. 5 Unsaturated zone profile to 7.5 m BA1. Moisture content, Cl, NO_3-N and δ^2H

There are considerable differences both in shape and magnitude of the moisture contents, mainly in response to lithology and texture. The mean MC in BA1 is 7.0%, BA2 is 5.9% and SW1 3.5% and the relatively high contents indicate the fine-grained nature of the sands. The moisture contents show distinct differences in the upper 1 m that reflect seasonal variations (before or after rains). These zones of moisture fluctuation are restricted here approximately to the top 1 m, above the zero flux planes (Wellings and Bell 1982) and within this zone the stable moisture contents (corresponding to the specific capacity of the sediment) are restricted. The Cl concentrations proportional to evapotranspiration are generated before they are transmitted to the profile (Cook et al. 1992). Profile BA1 was obtained in September and shows high moisture in the upper 1m with an average of 7.74% following the rainy season. A second profile BA2 was obtained in June following the very long dry season and has a drier profile in the upper 1 m with an average of 1.7%. In profile BA2, which just reached the water table, there is a noticeable change in moisture content corresponding to the capillary fringe starting at 8.2 m rising to 18.1% at 10 m, the maximum augured depth.

The presence of several peaks and troughs in the chloride profiles must be proportional to the amount of evapotranspiration and hence to oscillating recharge rates and past climate. In the Badain Jaran Desert, anthropogenic effects and internal contributions of Cl are non-existent, so that the averaged profile Cl values provide a long-term record of recharge rate over the time interval reflected by the profile. In these fine-grained sands, piston flow of moisture takes place in the unsaturated zone and, as discussed by Cook et al. (1992), a record of recharge history is also preserved. The oscillations of chloride show that neither the recharge rate nor the climate has been constant.

The summary of recharge related calculations for the three profiles is shown in Table 3. Cl concentrations in the BA1 profile show a mean value of 100 mg L^{-1}, with a range from (29 to 424 mg L^{-1}. In BA2 profile, the concentration of chloride has a mean value of 106 mg L^{-1} with a range from 33 to 207 mg L^{-1}. It is noted that the Cl concentration varies little through the capillary fringe and into the water table (130 mg L^{-1}; see Table 2), which suggests that there is chemical continuity from the unsaturated zone across the water table into the upper aquifer. The average chloride in SW1 profile is higher than at the other site with a mean value of 168 mg L^{-1} Cl, ranging from 53 to 982 mg L^{-1}.

The stable isotope profile (δ^2H) correlates well with the chloride profile in BA1 (Fig. 5), such that enrichment in the heavy isotope corresponds to higher chloride concen-

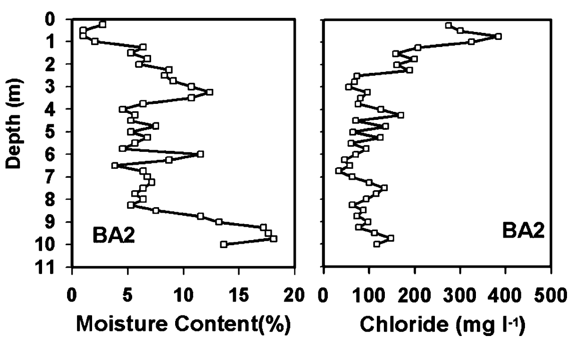

Fig. 6 Unsaturated zone profile to 10 m BA2. Moisture content and Cl

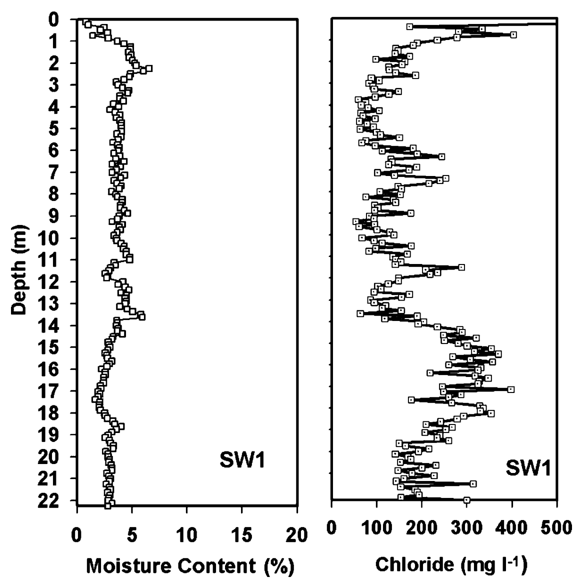

Fig. 7 Unsaturated zone profile to 22.5 m SW1. Moisture content and Cl

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Table 3 Estimates of mean annual recharge using chloride in the unsaturated zone with corresponding residence times for moisture over the sampled intervals

Profile	Sampling interval(m)	No. samples (n)	Mean rainfall (mm year^{-1})	Mean Cl in rainfall (mg L^{-1})	Mean Cl in profile (mg L^{-1})	Mean recharge (mm year^{-1})	Residence time (years)
BA1	0–7.4	33	89	1.5	100.4	1.33	520
BA2	0–10	40	89	1.5	106.2	1.26	812
SW1	0–22.5	178	89	1.5	168.	0.95	1185

trations, in line with evaporative trends retained in the profiles. Periods with higher rainfall and lower evapotranspiration are less enriched in the heavier isotope than those with low rainfall.

General discussion

The overall results may be considered to evaluate the recharge rates and history of recharge as well as limits to the evolution of the hydrogeology of the region. In this context, it is noted that the geochemical and isotopic data are used to derive physical values such as recharge and aquifer dimensions, as well as an indication of the natural pristine (baseline) water quality.

Recharge rate and recharge history

The main recharge estimates and residence times are summarised for the two areas (Baoritelegai and Sayinwusu) in Table 3. These have been calculated using the only available rainfall data; however, the input value of 1.5 mg L^{-1} is probably robust having been recorded at two locations close to the area. The higher chloride value for moisture in profile SW1 (168 mg L^{-1} Cl) corresponds to a mean annual recharge of 0.95 mm, the record representing the average over the timescale of 1,185 years. For the area of Baoritelegai, the mean Cl values of 100 and 106 mg L^{-1} Cl correspond to recharge rates of 1.33 and 1.26 mm year^{-1}, the records representing residence times of 520 and 812 years respectively.

The cumulative chloride and estimated chloride age are shown in Fig. 8 from the three profiles under the corresponding chloride flux of 133.5 mg m^{-2} year^{-1}. The use of constant flux in the chloride age calculations is of course likely to be a simplification of the total deposition corresponding to likely changes in environmental and climate conditions over the last 2,000 years (especially anthropogenic effects on aerosol composition during the industrial era). The cumulative profiles emphasise the similar recharge rates at Baoritelegai, while the lower recharge rate at the more westerly Sayinwusu site is emphasised.

This area of China presents an excellent location for the reconstruction of the palaeohydrology, since the dune sands are fine grained and preserve relatively high moisture content so that longer timescales are preserved. In addition, the low but finite recharge rates of around 1 mm year^{-1} give the possibility to study timescales up to 2,000 years within, say, 30 m of the unsaturated zone. The presence of the megadunes, and the accompanying thick unsaturated zones, suggest that is a real possibility. The present three profiles allow an investigation of past recharge rates over some 1,200 years in 22 m of profile.

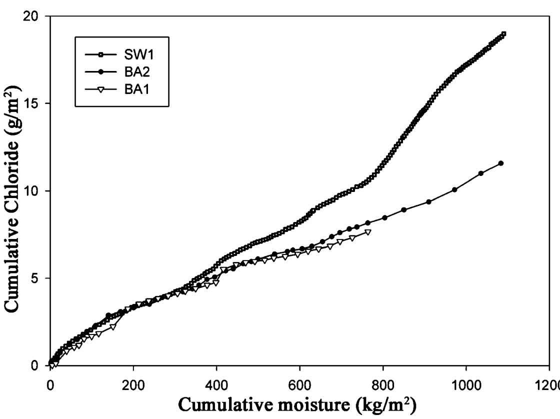

Fig. 8 Cumulative chloride vs. cumulative moisture for three unsaturated zone profiles

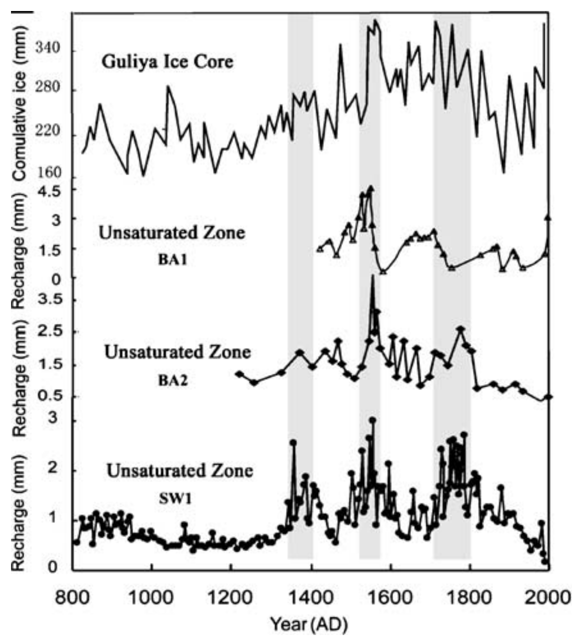

Fig. 9 Reconstruction of variation in recharge rates for the past 1,200 years from the unsaturated zone profiles at BA1, BA2, SW1. These have been derived from the Cl profiles and timescales constructed using a spread sheet model based on Cook et al. 1992, using locally derived values of Cl flux and bulk density. The recharge rates correspond to wetter or drier climates and these records are compared with cores from the Guliya ice sheet (Shi et al. 1999)

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The three profiles are shown in Fig. 9 against time where the calibration has been made using a spread-sheet model based on Cook et al. (1992). The precision of interpretation of the records is limited by the sampling interval (represented by approx 15 cm of core) to about 10 years and will be at best 20–30 years. For the longest record at Sayinwusu (1,185 years), important oscillations in recharge and climatic trends at the century scale are evident; the long-term low recharge rates beforeAD 1300 suggest that drought episodes were occurring in the "Medieval Warm period" (AD 1000–1300). Following this, there are three distinct high recharge stages indicated between AD 1340–1450, 1500–1610, 1710–1820. The highest recharge rates of 3.03 mm occurred in the AD 1550s, and then in AD 1350 and 1780, the relatively high recharge rates of 2.55 mm and 2.73 mm respectively. Since the mid nineteenth century, the recharge rate has decreased dramatically towards the more arid climate of modern times. This interpretation is well validated using the other two profiles at Baoritelegai, suggesting that similar recharge and climatic signals should be widely preserved across a wide region of northern China with similar terrain.

The unsaturated zone presents a new archive for this region for the interpretation of past climates; however, an initial comparison is made here with the Guliya ice core from Tibet. The Guliya ice cap (35.2°N, 81.5°E, 6,200 m a.s.l.) lies on the western part of the Kunlun Mountains on the Qinghai-Tibetan Plateau, where a 308.7-m ice core that includes the last 2,000 years in its upper part, has been obtained (Yao et al. 1996; Shi et al. 1999). Decadal accumulation rates were reconstructed using the oxygen isotope data from AD 300, over which period the average annual accumulation of ice was 252.6 mm. The accumulation had been generally lower than average before AD 1410. In the 1450s and 1530s, high accumulations of 351.8 mm and 366 mm $year^{-1}$ are recorded with the maximum cold event in 1520s and continual high precipitation in 1550s with 427 mm $year^{-1}$ ice accumulation. From the 1550s to the end of the eighteenth century, the accumulation and the temperature were higher than average, but in the nineteenth century the temperature and precipitation were lower than average, subsequently showing some increase in the twentieth century.

Correspondence between the ice cores and the unsaturated zone records for the main wet and dry phases during 800–1900 is quite good. The correlation with the ice record during the dry episodes of 1450–1500 and 1610–1710 is moderately good; the correlation with that during wet phases of 1500–1610 and 1710–1820 is much better. Highest precipitation in 1550s corresponds to the peak in recharge rate of 3.03 mm in 1550s. However, there is apparent divergence of trend between the two records since the beginning of the 1900s. This may be a result of the poorer resolution of the unsaturated zone record at the very top of the profile, since all data, including the topmost 1 m, have been used in the reconstruction. During the warmer twentieth century, the ice core recorded an increasing trend of precipitation, whilst the recharge rate remained similar to that of nineteenth century drought. Contrary to the ice core records, several other studies indicated that the climate of arid to semi-arid desert regions in mid-latitude China is marked with warmer and drier trends during the twentieth century (Shi and Zhang 1995; Zhang 1996). This may be the indication of large-scale climate differences between mountain regions and the desert basin since the end of the Little Ice Age.

Groundwater recharge and origins

The present-day Badain Jaran Desert region is hyperarid with modern precipitation below 100 mm $year^{-1}$. Under these conditions, it is unlikely that significant recharge to sustain the lakes can occur. Results from the studies of the unsaturated zone in the southern desert confirm that small amounts of recharge do occur around 1 mm $year^{-1}$ and that these rates have oscillated in line with climatic changes in the historical period, although only increasing to around 3 mm $year^{-1}$. Results from two locations some 30 km apart suggest that there is little spatial variability in recharge rates. These results suggest that previous interpretations (Yang 2002) on the basis of tritium evidence for a modern rainfall source of recharge to the lakes cannot be valid. The penetration rates for tritium under the observed moisture regime would not exceed 1–2 m. The evapotranspiration rates in any case far exceed any modern inputs and the lakes therefore cannot be sustained by rapid recharge through the dunes.

No radiocarbon samples were taken from the springs and shallow groundwaters (due to risk of exchange with modern CO_2) but an age in excess of 20 ka is inferred from the stable isotope data. This age assumes that the period of the last flacial maximum (LGM) was hyperarid and no recharge occurred (An et al. 1991). The relationships in Fig. 3 show that the shallow groundwaters and the lakes are genetically related by an evaporative line, which intercepts the GMWL at around –12.5‰ $\delta^{18}O$, which is some 5‰ lighter than the composition of modern groundwater recharge. This suggests a palaeorecharge source from a time of much wetter climate and is consistent with results from the nearby Minqin Basin (Ma et al. 2005).

The geological succession is not known in detail but the hydrogeological cross section (Fig. 2) suggests that Pleistocene lacustrine and fluviatile sediments are present and, by extrapolation from the outcrops to the south, impure Cretaceous sandstones would be present beneath. It is also assumed from the topography that the closest recharge source would have been in the Yabulai Mountains some 30 km to the south. Here there is evidence of glacial-fluvial fans and lake terraces dating to the last glacial maximum (Hoevermann et al. 1998). The terraces of lakes Guzihu, Gurinai, Kashunnuer and Sugunuer, approximately 100 km to the west of the area (and not shown in Fig. 1) also suggest a regional water level some 20–30 m higher than today. The high lake level of Kashunnuer occurred during the period between ca. 34,000–20,000 years BP (Pachur et al. 1995), and the

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molluscs from the highest terraces of Sugunnuer were radiocarbon dated to 33700±1300 years BP (Norin and Hedin 1980). Thus, it is probable that the source of water sustaining the lakes of the Badain Jaran Desert is part of a declining piezometric system dating from prior to the LGM. Assuming a flow path of 30 km and a minimum travel time of 20,000 years, then a travel velocity of 1.5 m year^{-1} would seem reasonable; more details of the hydrogeology of the region to the south are required to verify and expand the regional flow hypothesis.

Conclusions

Based largely on isotopic and chemical evidence an advance on our understanding of the hydrological system of the Badain Jaran Desert system has been given. This is an area of sparse hydrogeological information and the geochemical approach provides empirical indications on recharge rates and groundwater residence times. The stable isotope relationships indicate clearly that there can be no genetic relationship between the lakes and modern recharge. The lakes, however, are clearly derived from a groundwater source with the same signature. This source must be palaeowater from a time when the climate was much wetter than today and from other archive evidence this would seem to be in excess of 20,000 years BP, prior to the aridity of the LGM.

The lakes are, however, generally of fresh water, although with variable compositions which suggest some in-basin biogeochemical modification. The evaporation rates are high and the only slight increase in chemical composition and isotopic enrichment suggest low residence times and spring outflow decreasing northwards along the regional gradient. The presence of local hypersaline lakes (400 g L^{-1} total mineralisation) in close proximity to fresh waters such as at Badainhaizi, suggests an artesian source and with local sedimentary conditions preventing an outlet and promoting extreme evaporation; the presence of travertine spring mounds in the saline lakes as described by Hofmann (1996) further supports the idea of an artesian pressure. This raises the possibility that the aquifer system may not be phreatic but that the groundwater is provided by upward leakage from a confined system, possibly aided by faults. In this case, a regional aquifer system possibly continuous from the foothills of the Tibetan Plateau may be present (although the strong E–W structural elements would limit groundwater flow).

The megadune system of the Badain Jaran, built of unsaturated fine-grained sands in excess of 100 m, provide an excellent location for application of investigation of recharge and recharge history. The modern rainfall of 89 mm year^{-1} sustains recharge of about 1 mm year^{-1} and so far 22 m of sands have been sampled with a record approaching 1,200 years. As well as providing a robust record of recharge history, this is also an independent record of climate change which represents a new archive for this region and compares with similar records from other continents as described by Edmunds and Tyler (2002). There is good correlation between the unsaturated zone archive and the ice core record from the Guliya ice cap on the Tibetan Plateau.

The results have important implications for water resources and the future of this region. It is clear that the groundwater is non-renewable and exploitation of the reserves is inadvisable. Development of this aquifer would soon lead to the desiccation of the lakes and the destruction of the fragile ecosystem. However, this also represents one of the most remarkable desert landscapes in China if not in the world, with (almost) a pristine environment and ecosystem. It is worthy of conservation, possibly as a World Heritage Site and its economic value resides in tourism and conservation not as a site for agriculture or expanded human settlement.

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