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Chemistry and late Quaternary evolution of ground and surface waters in the area of Yabulai Mountains, western Inner Mongolia, China

Xiaoping Yang *

Institute of Geology and Geophysics, Chinese Academy of Sciences, PO Box 9825, Beijing 100029, China

Abstract

In the extensive area of western Inner Mongolia, China, the water demand of local residents often depends mainly on shallow aquifers, although scientific investigations of the quality and formation of the groundwater are still lacking. In this study the chemistry and isotopic composition of groundwater and lake water samples collected at 22 sites in the area of Yabulai Mountains (Fig. 1) in western Inner Mongolia were analysed. Chemical water analysis included the determination of Na^+, K^+, Ca^{2+}, Mg^{2+}, Li^+, NH_4^+, Al^{3+}, Co^{2+}, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, F^-, PO_4^{3-}, HBO_2 and SiO_2, and ^{18}O and tritium isotopes. Solute concentrations in groundwater show significant differences within the study area, while the water of the three lakes is dominated by sodium and chloride. This study reveals the importance of spatial variation of groundwater chemistry in an arid environment that has a relatively homogeneous lithological basement. The heterogeneity of groundwater chemistry suggests that the shallow groundwater in western Inner Mongolia is mainly recharged by infiltration of local rainfall. The relatively high tritium content indicates that the water in the shallow aquifer of the study area is generally not older than 100 years. Former shorelines in the lake basin of Shugui (Fig. 1) suggest the presence of a much larger lake in the past under a wetter climate than present hyper-arid conditions, presumably because of increased East Asian monsoon intensity during the middle Holocene. In the vicinity of commune administrations that have higher population density, the TDS of ground water is also higher, probably owing to water pollution.

Keywords: Ground water; Desert; Lake; Water chemistry; Paleoclimatology; China

1. Introduction

In the large area of western Inner Mongolia, China, domestic water supply often depends on shallow ground water because individual families normally live in the vicinity of their pastoral lands, and are isolated from large communities. Shallow groundwater is critical to local residents, both directly in terms of drinking water and indirectly by sustaining steppe vegetation needed by livestock. Domestic water uses, together with evapotranspiration and seepage to inland lakes, are the main sources of shallow groundwater consumption in western Inner Mongolia, because streams are absent, and wells extracting deep groundwater (regardless the water quality and availability) are often beyond a family's economic capacity.

Water resource and water quality issues recently have come to the forefront of regional development in western China, and particularly in western Inner Mongolia. The estimation of groundwater availability and recharge mechanisms in such a region is a difficult task because of the small amount available and its temporal and spatial variability. Literature concerning the ground and surface water in this extensive region, particularly on details of water chemistry, is scanty. A better understanding of the chemistry and evolution of surface and ground water will play an important role in developing future strategies of sustainable development. This area is also important to global change studies because of its location on the northern margin of the East Asian summer monsoons, and at the latitude of global westerlies (e.g. Yang et al., 2004). It is clear that salt lakes in western China are important archives of paleoclimatic history (e.g. Chen and Bowler, 1986). However, detailed studies of saline lakes in China have been carried out mainly in large lakes,

* Tel.: +86 10 62008389; fax: +86 10 62032495.
E-mail address: xpyang@263.net.cn.

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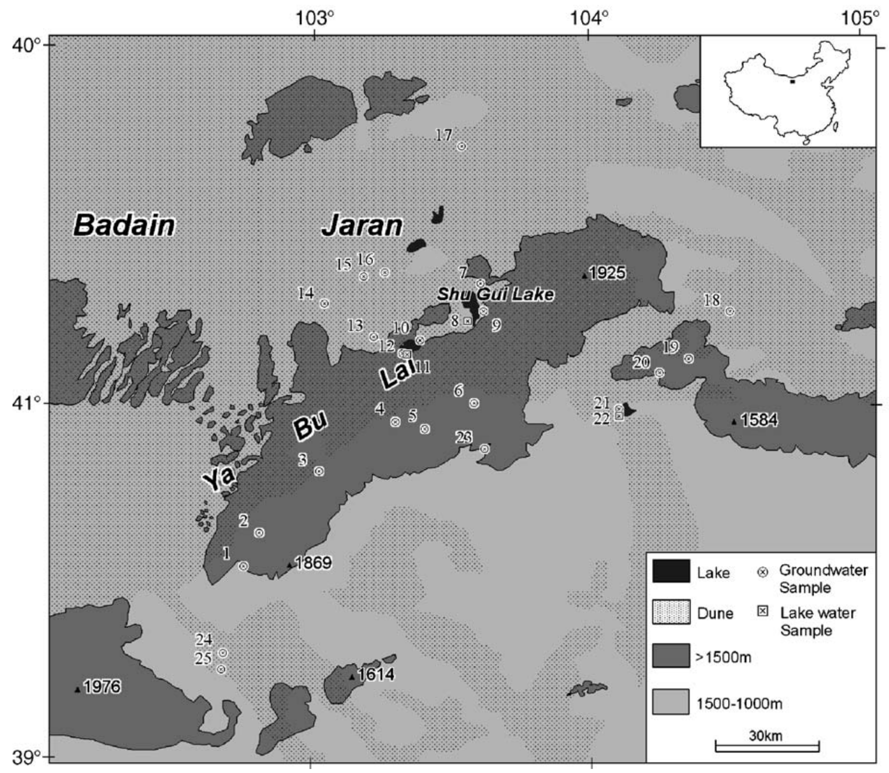

Fig. 1. Overview of the study area with indication of sampling sites.

such as Qinghai Lake (see Williams, 1991 for an overview). Investigations of the lakes in the inter-dune basins of the Badain Jaran Desert revealed that there have been dramatic climate changes in these extremely arid regions during the Holocene (Yang and Williams, 2003).

Table 1
The TDS (g/l), pH, main ions (mg/l) and tritium concentrations in the groundwaters and lakes in the area of the Yabulai Mountains (see Fig. 1)

Sample	Depth (m)	TDS	pH	K^+	Na^+	Ca^{2+}	Mg^{2+}	Li^+	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	F^-	PO_4^{3-}	HBO_2	SiO_2	Tritium (TU)
1	4	0.87	7.8	7	199	64	28	0.01	<1	191	198	268	17	1	0.07	2	13	27.1±0.58
2	2	1.46	7.8	13	318	95	46	0.02	<1	215	289	556	30	2	0.13	4	16	21.29±0.51
3	3	2.59	7.7	11	620	132	104	0.03	<1	146	657	949	69	4	0.13	7	11	10.64±0.43
4	4	0.77	7.7	5	142	80	28	0.01	<1	237	109	214	40	1	0.21	2	16	54.67±0.74
5	5	1.05	7.7	4	212	104	32	0.02	<1	270	231	313	3	3	<0.04	2	12	44.59±0.60
6	6	0.48	7.7	4	56	78	16	<0.01	<1	124	90	112	48	0	<0.04	1	8	48.22+0.66
7	2	1.59	7.6	4	462	42	36	0.04	<1	369	367	391	37	5	0.06	8	13	29.06±0.57
9	3	0.70	7.8	18	155	32	35	0.02	<1	168	197	134	37	1	0.05	2	12	1.31±0.37
10	2	0.48	7.4	8	1 03	43	20	0.02	<1	290	84	61	4	1	0.12	1	21	1.08±0.37
12	2	0.52	7.7	10	69	72	29	0.01	<1	266	105	90	8	1	0.04	1	16	1.4±0.35
13	2	0.56	7.8	18	113	35	26	0.02	<1	201	108	96	59	2	0.10	1	11	2.33±0.30
14	3	3.93	8.1	17	1223	68	50	0.10	<1	839	1121	864	43	7	0.16	18	25	2.31±0.27
15	3	1.30	7.8	28	356	38	34	0.05	<1	383	304	244	66	6	0.19	6	36	7.56±0.38
16	3	1.25	8.0	17	385	25	19	0.02	<1	356	276	286	40	6	0.26	8	11	0.62±0.32
17	3	9.51	8.0	13	2648	464	142	0.22	<1	216	3064	2863	22	3	<0.04	24	12	30.16±0.63
18	5	7.26	7.7	8	2114	191	148	0.16	<1	414	1866	2550	36	7	0.34	30	13	4.35±0.39
19	1	0.93	8.2	5	262	27	23	0.04	<1	258	228	190	11	2	0.12	2	15	16.15±0.44
20	2	0.50	7.7	6	71	62	21	0.02	<1	124	118	114	32	0	0.15	1	11	38.68±0.66
21	3	0.60	8.3	21	157	23	12	0.09	<1	212	111	103	36	5	0.29	4	14	1.02±0.33
23	1	1.12	7.7	23	285	55	40	0.02	<1	554	292	75	/	1	0.93	3	19	
24	120	1.79	8.3	26	515	26	44	0.05	<1	237	420	574	28	5	0.08	7	8	0±0.33
25	3	0.72	8.0	6	188	36	28	0.03	<1	306	110	176	44	3	0.27	2.51	10	27.26±0.56
8	lake	353	9.8	7073	128700	<0.01	29	<0.01	994	1683	180953	30993	6	5	12.4	661	21	
22	lake	125.52	8.9	3393	41335	62	1809	19.00	351	105	58758	18341	14	8	<0.04	517	6	
11	lake	17.18	9.7	282	5766	4	294	0.35	708	1161	6679	2587	1	6	0.06	54	9	

Using the area of Yabulai Mountains (Fig. 1) as an example, this paper provides insight into the chemistry of ground and surface water in western Inner Mongolia. The recharge mechanisms of groundwater and the hydrological evolution in this region during the later Quaternary are also discussed.

2. Regional setting

The area around the Yabulai Mountains belongs to the eastern part of the hyper-arid zone in northern China (e.g. Domrös and Peng, 1988). Owing to the strong influence of Mongolian–Siberian air masses in winter and the slight impact of monsoons from the Pacific in summer, the study area is characterized by cold winters and hot summers. A weather station in the vicinity of the southwestern edge of the mountains records a mean annual precipitation of ca. 120 mm and a mean annual temperature of 7.7 °C during the past four decades.

The Yabulai Mountains have a gentle slope towards the Badain Jaran Desert to the west (Fig. 1) and a steep slope on the east side. The mountain range stretches ca. 100 km in a NE–SW direction, and consists mainly of Precambrian granitoid rocks covered by thin Quaternary deposits, such as alluvium and aeolian sand. The highest peak of the mountains is 1925 m above sea level (asl). The top of the mountain range is a planation surface at an elevation of ca. 1800 m asl. Landforms produced by aeolian deposition, denudation processes, and weathering are widely present on the slopes of the mountains. West of the Yabulai Mountains is the Badain Jaran Desert with high and abundant sand dunes. Under predominantly northwesterly winds, sandy dunes migrate from Badain Jaran to the Yabulai, and even to the southeast of the mountains. Thus there are sandy dunes in the mountainous terrain.

One of the remarkable landscape features of western Inner Mongolia is the occurrence of a large number of the permanent lakes in the inter-dune depressions (Yang and Williams, 2003; Hofmann, 1999; Yang, 1991). Permanent lakes are also present in the foreland endorheic depressions of the Yabulai Mountains (Fig. 1). There are grasses, shrubs and semi-shrubs both in the mountains and in the dune areas, and their abundance is clearly influenced by micromorphology. Plants grow quite well along the ephemeral streams on the slopes and in the forelands of the mountains. Relatively speaking, the mountainous region is better vegetated than the sand seas.

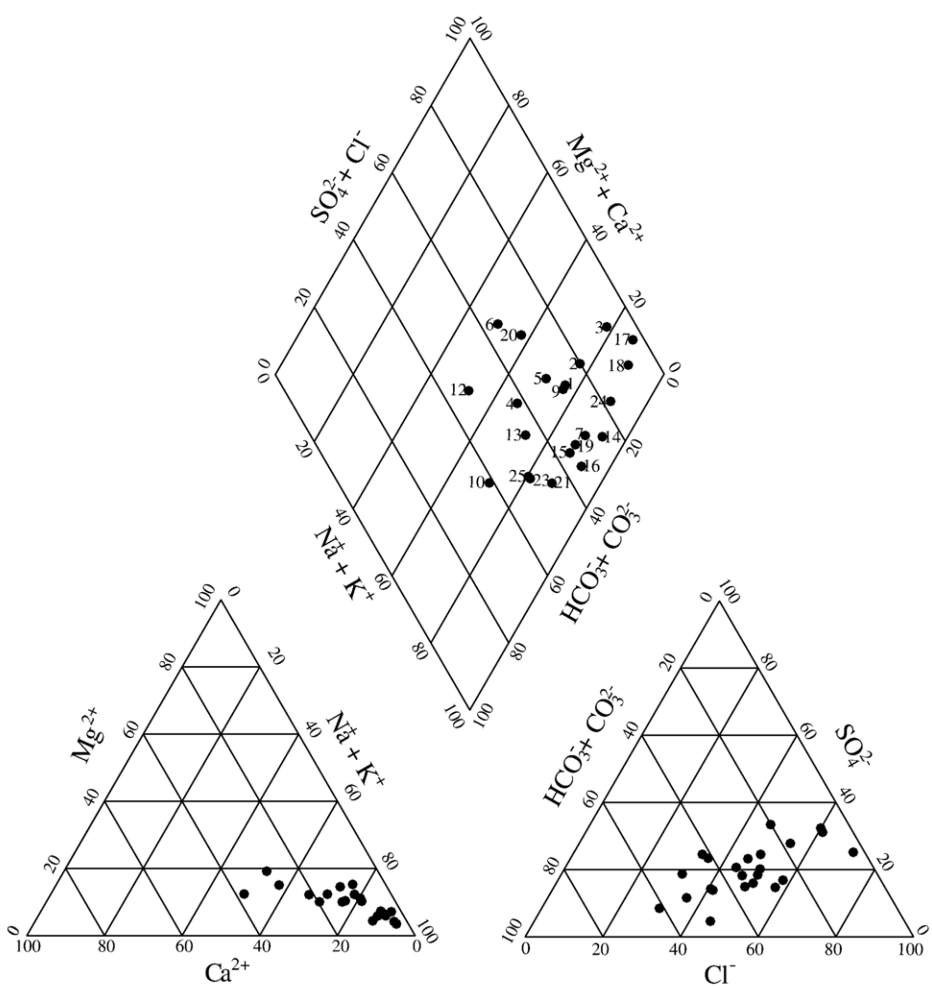

Fig. 2. Trilinear diagram for groundwater samples (mol/L).

3. Methods

Most water samples were taken with a bucket from wells reaching shallow aquifers at 2–6 m below the surface, and from lake surface. The sample 24 was pumped to the surface from a depth of 120 m. They were collected in polyethylene bottles in September and October 2000, and were filtered through a 0.45 μm membrane filter in the field and analysed in the Institute of Geology and Geophysics, Chinese Academy of Sciences (CAS) and in the Chinese Geological Academy of Sciences shortly afterwards. Analysis of water samples included total dissolved solids (TDS), pH, and ion concentrations. Ions were mainly measured with a DX600 Dionex ion-chromatograph, but titration, turbidimetry, spectrophotometry and atomic absorption spectrometry were also employed. The concentration of ions was determined in accordance with instrument manufacturers' instructions confirmed by the National Technology Agency of China (1996).

The pH and TDS were measured by potentiometric determination and evaporation in the laboratory, respectively. All groundwater samples were also analysed for ^{18}O and tritium content. The oxygen isotopic content was measured by using the MAT-252 spectrometer at the Institute of Geology and Geophysics, CAS, and reported in the conventional δ notation 'per mil' as a deviation from the SMOW (Standard Mean Ocean Water). The measurement errors should be less than ±0.2‰. To examine the tritium content, the water samples were condensed through electrolysis and then measured by liquid scintillation counting, and the results were reported in tritium units (TU). The maximum measurement uncertainties of tritium results are less than ±0.74 TU. The aeolian sediments samples were taken from 50–100 cm deep, freshly dug holes, collected in metal tins and dated by thermoluminescence techniques in the Guangzhou Institute of Geochemistry, CAS.

4. Results

Major physio-chemical and chemical properties of the water samples are listed in Table 1. Data representing the relative abundance of the major cations and anions are shown in Fig. 2 for groundwater and in Fig. 3 for lake water. The relationship between total dissolved solids and cation ratios, and the ratios between sodium and chloride in the groundwater are represented in Figs. 4 and 5, respectively.

The analytical data (Table 1) show that the groundwater at various sites is different in terms of mineralization, with TDS ranging from 0.48 to 9.51 g/L, the mean being 1.82 g/L. Half of the investigated samples belong to fresh water (TDS < 1 g/L), and the remainder to brackish water (TDS 1–35 g/L). All groundwater is alkaline, and pH values range from 7.4 to 8.3, with an average value of 7.84.

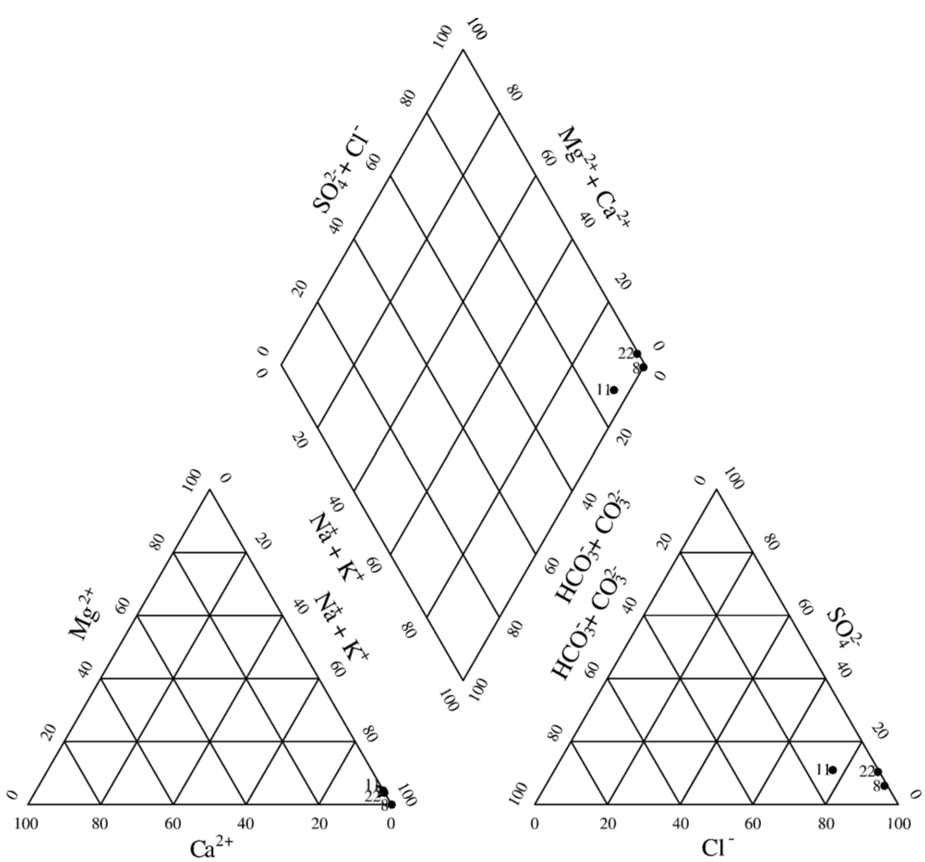

Fig. 3. Trilinear diagram for lake waters (mol/L).

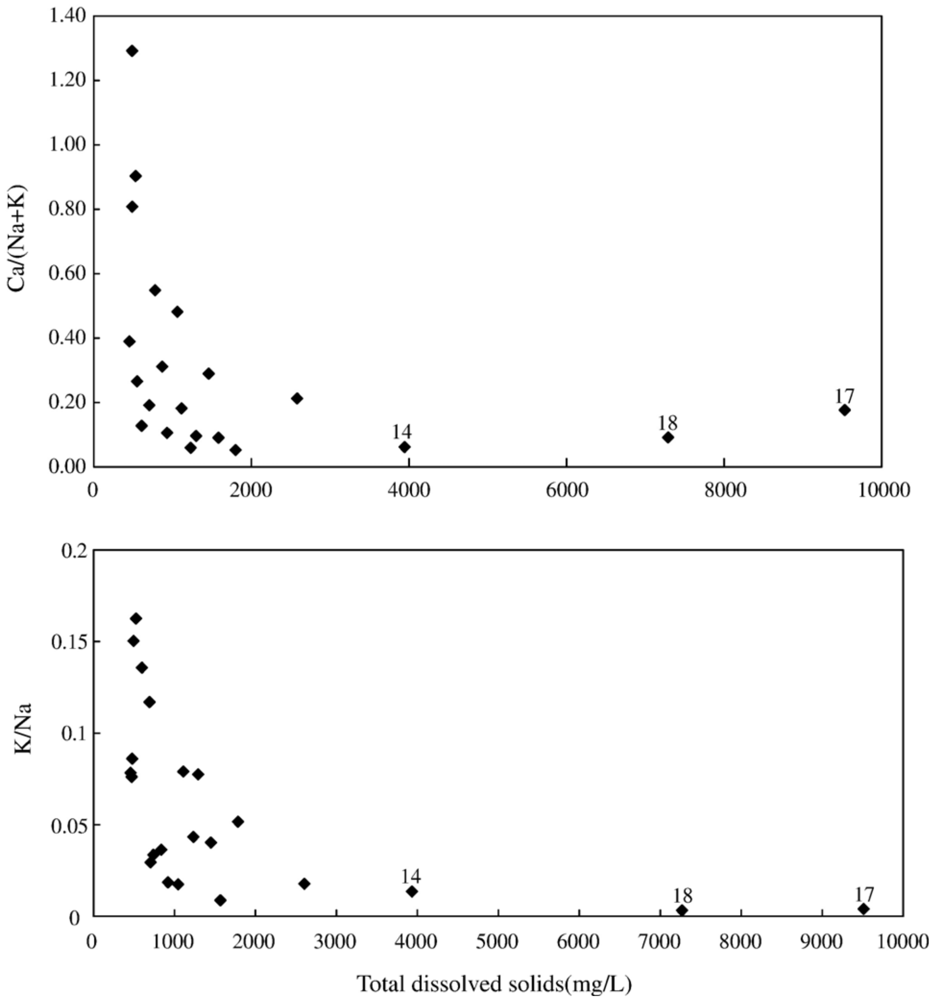

Fig. 4. The relationship between cation ratios (mg/L) and total dissolved solids in the groundwaters.

The water in the lakes is also alkaline, with pH values ranging between 8.9 and 9.8. The water in Shugui Lake (sample 8) and Baxingaole (sample 22) are brines (TDS > 100 g/L), whereas the water in Buerde Lake (sample 11), on the eastern margin of the Badain Jaran Desert, is only brackish (TDS 17.18 g/L). There are also differences in major cation concentration between groundwater and lake water samples. In the groundwater, sodium, calcium, magnesium and potassium are relatively important among the cations, and chloride, bicarbonate, sulphate and nitrate are significant

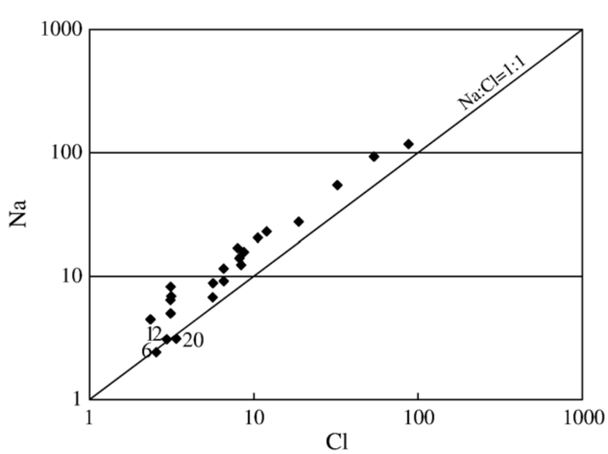

Fig. 5. The relationship between Na^+ and Cl^- (meq/L) in the groundwaters.

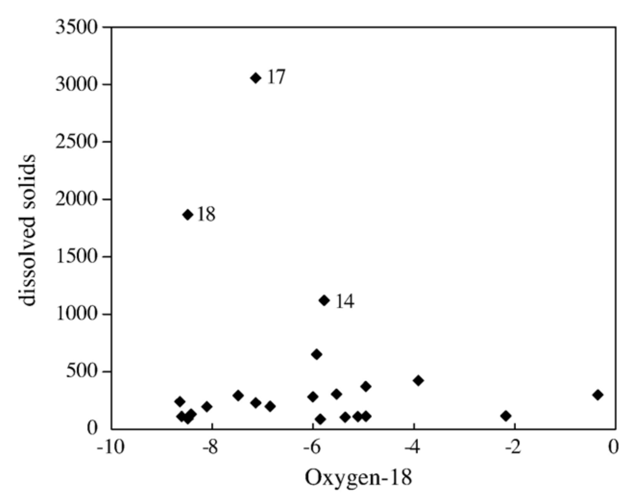

Fig. 6. The relationship between dissolved solids represented by chloride (mg/L) and ‰ $\delta^{18}O$ in the groundwaters.

among the anions (Table 1, Fig. 2). In the lake water, sodium and potassium are predominant while the relative abundance of calcium and magnesium is quite insignificant. Among the anions, there is a predominance of chloride and sulphate, but a much lower abundance of carbonate and bicarbonate (Fig. 3). The ionic ratios Ca/(Na+K) and K/Na (mg/L) for this groundwater are highly variable (Fig. 4).

The Li^+ concentration is less then 0.5 mg/L in all groundwater and lake water samples, except for sample 22 taken from Baxingaole Lake, where it is 19 mg/L. Generally speaking, the concentrations of NH_4^+, Al^{3+}, Co^{2+} and PO_4^{3-} are quite low, both in groundwater and in lake water samples. In most samples, Al^{3+} and NH_4^+ concentration is <0.04 mg/L and <0.08 mg/L, respectively. PO_4^{3-} is 12.4 mg/L in the Shugui Lake (sample 8); otherwise it is less than 0.34 mg/L, while Co^{2+} is less than 0.002 mg/L in all samples.

The groundwater samples have a mean isotopic content of −6.13‰ $\delta^{18}O$, but have a wide range of values from −8.58‰ to −0.36‰ $\delta^{18}O$. The water from the lakes is strongly depleted, and the $\delta^{18}O$ value in the three investigated lakes is 4.72 (Sample 11), 4.43 (sample 8) and −0.23‰ (sample 22), respectively. The ^{18}O contents for all investigated groundwaters are plotted in a diagram against total dissolved solids represented by chloride concentration (Fig. 6).

The tritium content ranges from 0.62 to 54.67 TU in the shallow groundwater (Table 1). Tritium was not detected in the water sample from a 120-m deep well (sample 24), although the measurement error of this sample was ±0.33 TU.

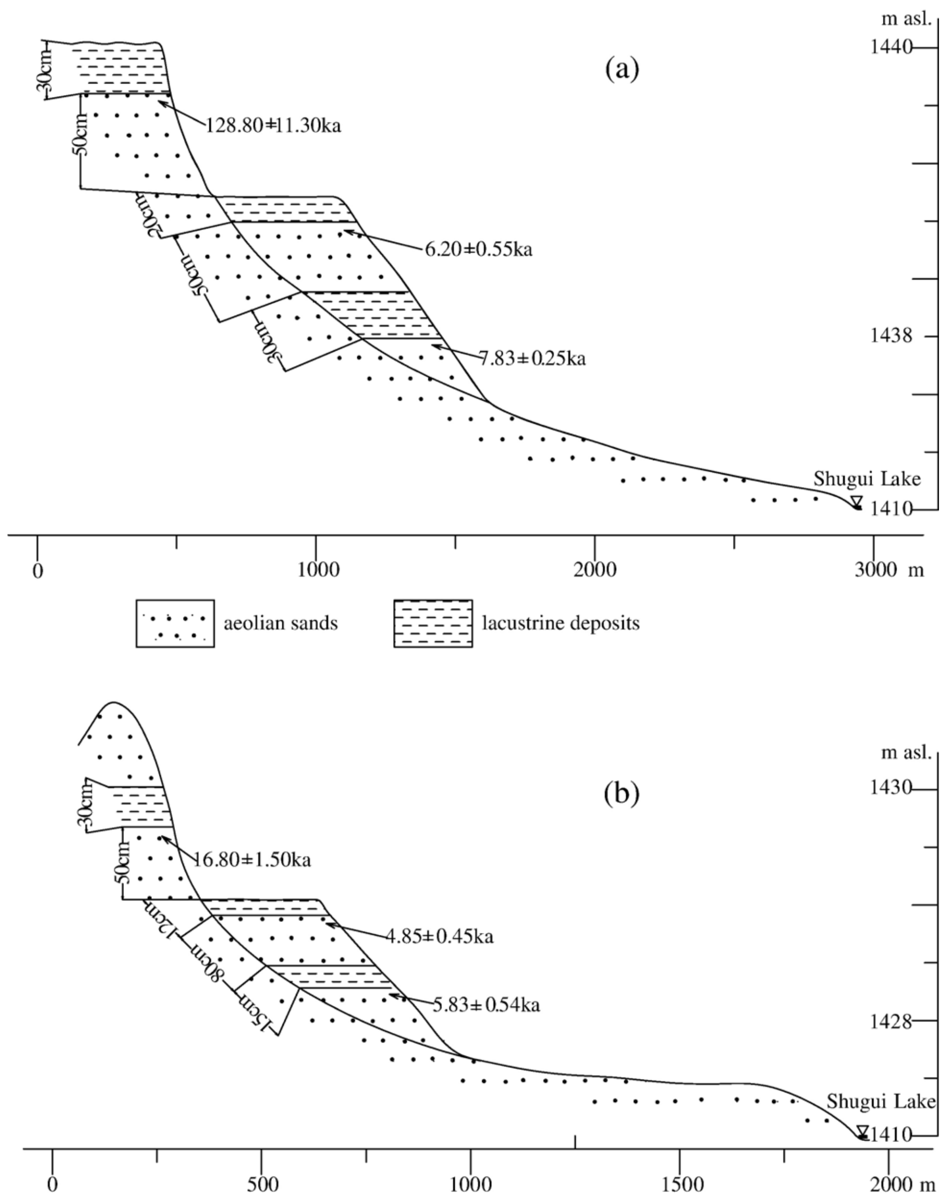

Fig. 7. Two stratigraphic sections (2 km apart) of the former shoreline ca. 20–30 m above present lake level in Shugui Lake basin (Fig. 1). The chronology is based on thermoluminescence dating.

Interbedded lacustrine and aeolian sediments are preserved ca. 20–30 m above the present lake level of Shugui Lake. The lacustrine layers, each with a thickness of ca. 12–30 cm, suggest that the lake level has changed quickly over quite a large height range and the duration of high lake level might be not very long because of the intercalated aeolian sands. The thermoluminescence ages from two independent profiles indicate that a rise in lake level occurred on two occasions in the middle Holocene. However, the higher lake levels probably were formed much earlier, at ca. 16 ka BP and 128 ka BP, respectively (Fig. 7).

5. Discussions

Chemical weathering of the sediments, dissolution of secondary carbonates and ion exchange between water and clay minerals are key processes controlling the chemistry of groundwater in many places. Most minerals dissolve slowly, therefore higher TDS water should occur where the water contacts more soluble minerals for longer periods of time (e.g. Fitts, 2002). That is why the TDS of ground water tends to be higher than the TDS of surface water at a given location. The difference in TDS between samples 24 and 25 might originate from the residence time associated with water depth. The deeper groundwater (sample 24 from a 120 m deep well) contains more inorganic solutes than the shallow groundwater (sample 25 from a 3-m deep well in the vicinity of the location of sample 24, see Fig. 1). The much lower tritium content of sample 24 (Table 1) also confirms an older age for the deeper groundwater. The large variation in Ca^{2+} and Na^{+} concentrations in the groundwater samples from the study area (Table 1 and Fig. 2) may theoretically reflect local mineralogical changes in the sediments and in the carbon dioxide produced by biological processes in their surface layers. However, biogenic weathering might not be a key factor, because the groundwater here is alkaline in general (Table 1). The CO_2 reactions in the ground are possibly not very active at many sites because of alkaline conditions and limited vegetation on the surface. It is assumed that the age difference on a decadal scale does not make a strong impact on the solute concentrations, because there is not a clear correlation between total dissolved solids and the tritium content in the shallow groundwater (Table 1). The heterogeneity of the ionic ratios (Fig. 4) may also be caused by local variations in the mineralogy of the groundwater reservoir and geochemical process occurring in the aquifer. Principally, the amount of sodium rises as the chloride content increases in the investigated samples (Fig. 5), supporting the view that geochemical processes play a role in the chemistry of groundwater. Referring to the Na/Cl ratios, three samples (sample 6, 12, 20) with lower TDS lie very close to the 1:1 ratio line (Fig. 5), indicating that sulphate and other salts are more abundant in the ground water with higher TDS. The regolith and geomorphological parameters controlling ground temperature may play a large role in the water chemistry. Data from the arctic-oceanic Latnjavagge drainage basin of northern Sweden also show that water chemistry may vary considerably in a small area with very homogeneous lithology. In areas of shade, cold ground and thin regolith, the TDS of shallow groundwater is low, whereas the TDS is high in areas exposed to intensive radiation. Solution of lithological components is controlled to a large extent by the ground temperature in a periglacial landscape (Beylich et al., 2004). The regolith in our field area varies in thickness from less than a metre to more than 5 m between upper and lower slope segments.

The possible mechanisms for shallow groundwater recharge in the areas of the Yabulai Mountains are: (1) direct infiltration of rain into the ground; (2) infiltration through seasonal streambeds; (3) recharge from potential deep groundwater. The first two processes are thought to be significant, but the third may be much less important, because the Yabulai Mountains form a single range in a desert landscape. Based on the relatively high tritium contents (Table 1), it is concluded that the shallow ground water in the study area is generally not older than 100 years. Therefore, the recharge of the shallow groundwater is mainly local precipitation that infiltrates downwards quite quickly owing to the sand cover and the loose nature of the regolith. Due to the large temporal and spatial variability of rainfall, infiltration is related to the amount of precipitation of each event. From dried channels in the fields one can assume that there may be ephemeral streams and ponds in the study area when it rains. As a result, the overall recharge process is quite heterogeneous. The clear difference in ion concentrations and in isotope contents (oxygen and tritium) suggests that the hydraulic relationship between various sampling sites is weak.

Evaporation probably does not influence the salinization of groundwater substantially, because the $\delta^{18}O$ value clearly varies between samples with a similar amount of total dissolved solids. Besides, the $\delta^{18}O$ values are relatively low in the samples with the highest TDS (samples 17, 18 and 14, Fig. 6). This is consistent with the fact that there is no clear correlation between total dissolved solids and tritium concentrations. The mean value of the $\delta^{18}O$ in the rainwater in the 1990s was $-6.27‰$ in Zhangye (Zhang et al., 2001) located ca. 200 km west of the study area, and is very similar to the mean value in this groundwater. The large range in $\delta^{18}O$ values (Fig. 6) suggests not only the heterogeneity of the recharge conditions in the shallow aquifers, but also a possible mixing with enriched waters that could be in the deeper aquifers. However, the input from other regions (via surface runoff or groundwater inflow) seems to be rather insignificant in the local water cycle. This study suggests that a large proportion of rain is added to the shallow groundwater system because of rapid infiltration in the sandy sediments. Observations, and interviews with local residents, suggest that the water from the shallow aquifer can meet the water demand of inhabitants with traditional life styles and adequate livestock grazing in this desert environment.

The water samples from the areas where the community administrations are located show much higher TDS (samples 14, 17 and 18) than samples from more rural areas. This is probably caused by two processes: (1) direct pollution reflecting increased population density and (2) re-seepage of wastewater. It appears that the wastewater can infiltrate into the drinking water systems quickly, because the housing, and therefore waste and dung depot, are very close to the wells. The high concentration of nitrate in these samples (Table 1) is probably related to the decomposition process of untreated waste. In fact, the nitrate concentration is quite high in the majority of the ground water samples from the entire study area (Table 1 and Fig. 1). Earlier studies of the ground water in the Badain Jaran Desert show similar phenomena (Yang and Williams, 2003). In the desert environment both humans and their animals depend on the wells to get drinking water. Therefore human influence is quite strong around the wells and the dung depot is often located not far from the wells. This may be the reason for the high concentration of NO_3^- in the water samples. The PO_4^{3-} concentration is as high as 0.34 mg/L in the sample 18, but much lower in other two samples. There is no wastewater treatment system in this region yet. In the interests of the health of local residents it is necessary to add sewage treatment.

Comparing the groundwater chemistry of the study area to other arid and semi-arid environments yields interesting results. The $\delta^{18}O$ in the ground water in northern Cameroon, western Africa, varies over a much smaller range, from −5.39‰ to −3.72‰ (Njitchoua et al., 1997). Studies in the semi-arid Ilullemeden Basin of Niger, found that the shallow groundwater is characterized by low pH, ranging from 5.3 to 6.5, and high $\delta^{18}O$ with an average value of −3.98‰, similar to the oxygen-18 weighted annual mean of modern rainfall (Le Gal La Salle, 2001). In semi-arid northeastern Nigeria, groundwater is recharged to a large degree by infiltration through inundated plains, in addition to the recharge via direct infiltration of rain and river waters. The annually recharged water volume of the shallow aquifer is to a large extent removed by evapotranspiration due to a relatively dense vegetation cover (Goes, 1999).

From field observation, it is assumed that the lakes of the Yabulai Mountains are mainly recharged by groundwater, because there is neither surficial inflow nor outflow. It has been suggested that Li^+ in thermal springs is associated with water from deep sources (Williams, 1991). Therefore, it may be that the recharge of the Baxingaole Lake (sample 22) is partly from deeper groundwater, based on its high Li^+ concentration. The low Li^+ content in the other samples might be seen as evidence that the shallow ground water system is not recharged by the deep groundwater system to any great degree. At present, Baxingaole is the largest of the three lakes and has relatively low TDS. Compared with the chemistry of groundwater samples, the proportions of sodium and chloride are much higher in the lake water (Figs. 2 and 3). From a global point of view, the dominant ions in most saline lakes are Na^+ and Cl^-, and occasionally in some less saline lakes, Na^+ and HCO^-/CO_3^{2-} (e.g. Day, 1993). It is reasonable to believe that the brines of these lakes were formed by long and intensive evaporation, because Na^+ and Cl^- are often associated with evaporites. In general, major ions in saline waters were derived from the catchment or the substratum (e.g. Kilham, 1990). However, atmospheric precipitation should not be ignored as a potentially significant source of ions (Eriksson, 1985) in the water of the study area because of frequent dews and rimes. It was estimated that Cl^- accumulation might amount to as much as 156 g/m^2 in 1000 years in an area with a mean annual rainfall 400 mm and Cl^- concentration in rain of only 11 ueq/L (Bosman and Kempster, 1985).

In many large saline lakes of Mongolia, Cl^-, SO_4^{2-} and HCO_3^- are almost equally predominant anions, while Na^+ and K^+ are strongly dominant cations. The salts of these lakes were thought to have originated from high evaporation and soil salinization (Egorov, 1993). The salinity of the Mongolian lakes increases eastwards, consistent with the trend of increasing aridity. Both natural climatic changes and irrigation activities have caused decadal variations in the salinity in the Mongolian lakes (Egorov, 1993). From limnological analysis of different world regions, it was concluded that large, deep, saline lakes often contain alkaline, sodium rich waters with considerable chloride, sulphate, and carbonate plus bicarbonate (Melack, 1983). The chemistry of shallow lakes in the study area is, to a considerable extent, consistent with those of large lakes. Also, from this point of view, it appears that the enrichment of the ions in the lakes has been mainly caused by evaporation, rather than through the quality of the recharged water. There is a need to monitor the seasonal variations of salinity in the groundwater and in lake water in the study area. Local residents have noticed a clear increase of lake level in Shugui Lake (Fig. 1) as the ground frost melted in spring.

The palaeo-shorelines and thermoluminescence chronology (Fig. 7) show that a much higher lake level has occurred twice in the Shugui basin during the middle Holocene. This was probably associated with a wetter climate caused by an increase of summer monsoon intensity. The ages of ca. 128 ka and ca 16 ka indicate that Shugui Lake has experienced a long evolutionary history, and high lake level may have occurred during recent glacial periods. This again could be seen as evidence for climatic instability in the study area. Although not always synchronous, late Quaternary wetter epochs have also been identified in other parts of western China. From the studies of palaeo-shorelines and lacustrine deposits in the Badain Jaran Desert, it was concluded that the climate in this desert was less arid in the early and middle Holocene than during the last 4000 years (Yang and Williams, 2003). Multi-proxy investigation of sediment cores from Lake Qinghai suggested an increased inflow of sediment-laden water into the lake at ~11,600 to 10,700 ^{14}C years B.P. caused by a climatic change towards wetter and warmer conditions. An abrupt rainfall increase in the catchment at ~10,000 ^{14}C years B.P. changed the site from a playa lake environment to a deeper lake under a warm and wetter climate (Yu and Kelts, 2002). A dry episode at ~11,000–10,000 ^{14}C years B.P. was recorded in the cores of Qinghai Lake (Yu and Kelts, 2002), and somehow correlates with the thick aeolian sand accumulated in the basin of Shugui Lake.

Due to the uplift of the Tibetan Plateau, the late Cenozoic climatic changes in western China involved a general reduction in precipitation, so that western China and Mongolia changed from being generally humid to being arid. Most lakes in Inner Mongolia, Qinghai and Tibet occupy basins along fault lines, in grabens and other tectonic, as well as deflation depressions where increasing aridity has caused the development of endorheic drainage basins. The high salinity of the three lakes investigated in this study suggest that they originated from intensive evaporation associated with the arid climate and their palaeo-shorelines record the abrupt changes of climate during the late Quaternary. The dunes above the lacustrine terrain and extensive aeolian sand in the lake basin (Fig. 7) imply that the dry side of the climatic continuum has been severe and long-lasting in western Inner Mongolia, even probably in all parts of western China.

6. Conclusions

Shallow groundwater is widely available in the arid area of Yabulai Mountains, western Inner Mongolia, and can meet the water demand of inhabitants with traditional life styles and adequate livestock grazing. The ions of the water samples taken from this region are considerably different although the lithology is relatively homogenous. This is theoretically caused by local factors, such as regolith, microclimate and weathering. The differences in ion chemistries, oxygen and tritium isotopes between water samples suggest that the groundwater originates mainly from quick infiltration of the small amount of local precipitation, and that the hydraulic relationship between various sampling sites is very weak. The high NO_3^- concentration in the water samples indicates that the shallow aquifer near settlements is already challenged by the problem of pollution related probably with the decomposition of household wastes. The water of deep aquifer with a higher TDS and an older age could be derived from local precipitation of former wetter epochs. From the geomorphology it is to suggest that the lakes in the endorheic depressions of the study area are mainly recharged by shallow groundwater. High salinity of the lake water is caused by long-term intensive evaporation. The palaeo-shorelines of Shugui Lake (Fig. 1) and their luminescence chronology indicate higher lake levels associated with wetter epochs in western Inner Mongolia during the middle Holocene and recent glacials.

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