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Assessment of the Hydrogeochemistry and Groundwater Quality of the Tarim River Basin in an Extreme Arid Region, NW China

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Abstract The concentrations of the major and trace elements in the groundwater of the Tarim River Basin (TRB), the largest inland river basin of China, were analyzed before and during rainy seasons to determine the hydrogeochemistry and to assess the groundwater quality for irrigation and drinking purposes. The groundwater within the TRB was slightly alkaline and characterized by high ionic concentrations. The groundwater in the northern sub-basin was fresh water with a Ca^{2+}–HCO_3^{-} water type, whereas the groundwater in the southern and central sub-basins was brackish with a Na^{+}–Cl^{-} water type. Evaporite dissolution and carbonate weathering were the primary and secondary sources of solutes in the groundwater within the basin, whereas silicate weathering played a minor role. The sodium adsorption ratio (SAR), water quality index (WQI), and sodium percentage (%Na) indicated that the groundwater in the northern sub-basin was suitable for irrigation and drinking, but that in the southern and central sub-basins was not suitable. The groundwater quality was slightly better in the wet season than in the dry season. The groundwater could be used for drinking after treatment for B^{3+}, F^{-}, and SO_4^{2-} and for irrigation after control of the sodium and salinity hazards. Considering the high corrosivity ratio of the groundwater in this area, noncorrosive pipes should be used for the groundwater supply. For sustainable development, integrated management of the surface water and the groundwater is needed in the future.

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Introduction

In China, particularly in the semi-arid and arid areas of NW China, groundwater is an essential and precious resource for life, agriculture, and ecology (Cui and Shao 2005; Wen et al. 2008; Xiao et al. 2012a). Groundwater shortages and poor water quality limits urban development in these areas (Qiu 2010). To effectively utilize and protect water resources, it is necessary to understand the hydrochemical characteristics and water quality of groundwater (Tizro and Voudouris 2008), which is one of the most important environmental, social, and political issues at the global level (Nickson et al. 2005; Arumugam and Elangovan 2009; Xiao et al. 2012a).

Located in the northern Qinghai–Tibetan Plateau and in the southern Xinjiang Uygur Autonomous Region, the Tarim River Basin is the largest inland river basin in China and one of the driest arid zones on the earth, with abundant natural resources, but fragile ecosystems (Feng et al. 2001). The TRB consists of 42 counties and 55 production and Construction Corps with a total population of 8.257×10^6, and it is one of the most important production locations for grain and cotton in China (Zhou et al. 2012). Increasing water utilization and rapid agricultural development over the last 30 years has led to significant environmental and hydrological degradation within the TRB (Feng et al. 2001, 2005; Xu et al. 2008). In this context, water quality and management for drinking and irrigation have become among the biggest concerns in this area. Zhang et al. (1995) and Xiao et al. (2012b) demonstrated the solute geochemistry of the surface waters within the TRB. Zhu and

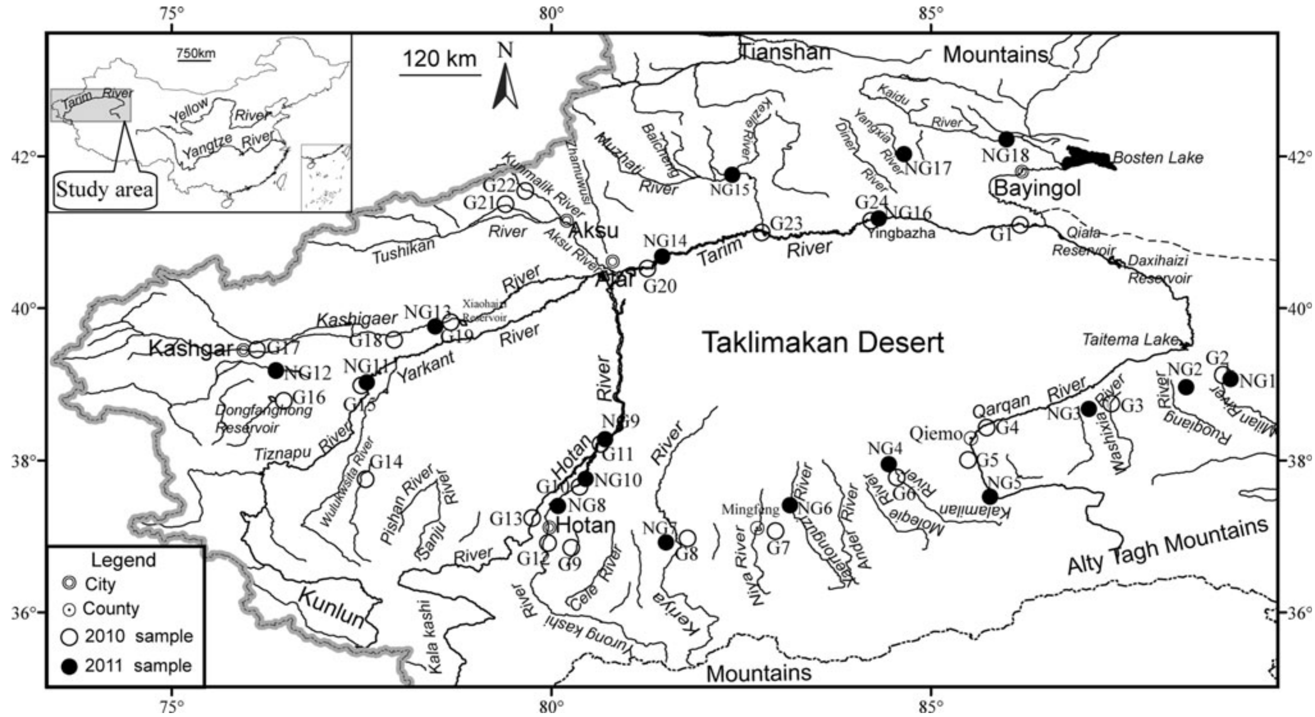

Fig. 1 Sampling sites within the TRB

Yang (2007) studied the major elements and their sources in the river water and groundwater in the southern Taklimakan. However, the water quality and hydrochemical characteristics of the groundwater throughout the basin have received little attention with limited available geochemistry data.

In the present study, the major ions and trace elements in 42 wells within the TRB were measured to identify in a preliminary way the hydrochemical processes and to assess the spatial patterns of the groundwater and its suitability for irrigation and drinking purposes within the TRB. This knowledge could lead to improved understanding of these hydro-chemical systems, promoting sustainable development of the water resources and effective management of groundwater resources in this area.

Site Description and Basin Geology

Located in an extreme arid area of NW China, the TRB is flanked by the Tianshan Mountains to the north and the Kunlun Mountains to the south (Fig. 1). The total basin area is 1.02×10^6 km^2, of which 47 % is mountainous region, 20 % is plain terrain, and 33 % is desert (Chen et al. 2011). The Taklimakan Desert is located at the center of the basin; it is the largest desert in China and one of the driest areas in the world. The Basin is 1,500 km long from east to west and $\sim$600 km wide from north to south. The altitude of the basin varies from 800 to 1,300 m above sea level (m.a.s.l.), and the western basin is higher than the eastern basin.

The TRB has an extreme arid desert climate with an average annual temperature of 10.6–11.5 °C (Chen et al. 2009). The multi-annual mean precipitation of the basin is 116.8 mm, and the annual potential evaporation varies from 2,500 to 3,000 mm. The precipitation increases moving from the west to the east across the plain area (Chen et al. 2009). The water in the TRB is supplied by ice, snow, and precipitation in the mountains. Glacial melt and snowmelt account for $\sim$40 % of the total runoff (Chen et al. 2007). The surface runoff varies seasonally: the period from June to September accounts for 73 % of the annual runoff volume, where as only 13 % of the runoff occurred between January and May (Feng et al. 2005).

The TRB is a Mesozoic–Cenozoic basin surrounded by a series of folded mountains, consisting of Archean and Proterozoic schist and gneiss, Paleozoic and Mesozoic sand stones, conglomerates and magmatic rocks ((XETCAS) 1965; Zhu et al. 1981). The Quaternary alluvial–diluvial plains at the northern foot of the Kunlun Mountains consist of loess, sand, gravel, and evaporites. A surficial and near surface accumulation of water-soluble minerals in the regolith is typical of most areas along the southern periphery of the Taklimakan Desert. The mobile dunes occupy 85 % of the Taklimakan Desert. Beneath these dunes, there are extensive evaporates, which include gypseous horizon, mirabilite, halite, and potassium salts (Zhu et al. 1981).

Materials and Methods

Twenty-four well samples (G1–G24) were collected from a range of locations on August 18–26, 2010, during the wet season of the TRB; 18 well samples (NG1–NG18) were collected on 18–26 May 2011, during the dry season of the TRB (Fig. 1). According to basin lithology and sampling locations, well waters were divided into six groups, namely Aksu Groundwater, Yarkant Groundwater, Hotan Groundwater, Southern Groundwater, Northern Groundwater, and Tarim Groundwater, marked as AG, YG, HG, SG, NG, and TG, respectively. Samples G21 and G22 belonged to AG; Samples from G14 to G19, and from NG11 to NG13 belonged to YG; Samples from G10 to G13, and from NG8 to NG10 belonged to HG; Samples from G2 to G9, and from NG1 to NG7 belonged to SG; Samples NG15, NG17, and NG18 belonged to NG; Samples G1, G20, G23, G24, NG14, and NG16 belonged to TG (Fig. 1). The groundwater samples were filtered in situ on collection through 0.22 μm Whatman® nylon filters. For cation analysis, a 60 mL aliquot was stored in a pre-cleaned high density polyethylene bottle and acidified to pH < 2 with 6 M ultrapure HNO_3. A 30 mL aliquot of the un-acidified sample was collected for anion analysis. The electric conductivity (EC), pH, and temperature were measured using portable Orion EC and pH meters at each site. All of the samples were stored at 4 °C until analysis. The samples were analyzed for cations (Ca^{2+}, K^+, Mg^{2+}, and Na^+) and Si using a Leeman Labs Profile ICP-OES and for trace elements (Fe, Mn, As, Zn, Pb, Cu, Cd, Cr, B, and Al) using a Leeman Labs Profile ICP-MS at the Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences. Repeated analyses demonstrated reproducibility within 2 %. A Dionex-600 ion chromatograph was used for F^-, Cl^-, NO_3^-, and SO_4^{2-} analysis at the Institute of Earth Environment, Chinese Academy of Sciences. The average replicated sample reproducibility was 0.5–1 % (2σ). Alkalinity was titrated by hydrochloric acid within 12 h, by Gran titration using 0.1 N HCl.

Sodium Adsorption Ratio (SAR) and Sodium Percentage (%Na) were used to determine the suitability of the groundwater for irrigation purpose in this study. SAR (Hem 1991) and %Na (Wilcox 1955) were calculated using the following equation:

$$\mathrm{SAR} = \mathrm{Na}^+/[(\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+})/2]^{0.5}$$

$$\%\mathrm{Na} = (\mathrm{Na}^+ + \mathrm{K}^+)/(\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}+\mathrm{K}^+ + \mathrm{Na}^+) \times 100$$

where all ionic concentrations are in meq/L.

The water quality index (WQI), a rating reflecting the composite influence of different water quality parameters, was used to obtain a more comprehensive picture of the groundwater quality for drinking purposes (Bordalo et al. 2006; Sahu and Sikdar 2008; Banoeng-Yakubo et al. 2009). Three steps were followed to compute WQI. In the first step, each parameter was assigned a weight (w_i) according to its relative importance in the overall drinking water quality. A maximum weight of 5 was assigned to parameters such as nitrate, arsenic, lead, chromium, cadmium and selenium due to their substantial importance in water quality assessment. Zinc was given the minimum weight of 1 as it plays an insignificant role in water quality assessment. Other parameters had a weight between 1 and 5 depending on their importance in water quality determination (Sahu and Sikdar 2008). In the second step, the relative weight (W_i) was computed using the following equation (Sahu and Sikdar 2008):

$$W_i = w_i / \sum w_i$$

where w_i was the weight of each parameter, and $\sum w_i$ was the sum of the weights of all of the parameters.

In the third step, a quality rating scale (q_i) for each parameter was assigned by dividing its concentration in each groundwater sample by its respective standard in the guidelines established in China; the result was then multiplied by 100:

$$q_i = (C_i/S_i) \times 100$$

where q_i was the quality rating, C_i was the concentration of each chemical parameter in each water sample in mg/L, and S_i was the Chinese drinking water standard for each chemical parameter in mg/L (Ministry of Health 2006).

To compute the WQI, the SI was first determined for each chemical parameter, which was then used to determine the WQI using the following equations:

$$SI_i = W_i \times q_i$$

$$WQI = \sum SI_i$$

where SI_i was the subindex of ith parameter, q_i was the rating based on the concentration of ith parameter, and n was the number of parameters.

Results

Quality of the Chemical Data

The accuracy of the measured data in this study was confirmed using the Normalized Inorganic Charge Balance (NICB%):

$$NICB\,\% = 100 \times (TZ^+ - TZ^-)/TZ^+$$

where TZ^+ and TZ^- are the sums of the meq/L concentrations of the cations and anions, respectively. If the NICB of the chemical dataset is >10 %, the analysis is questionable. The TZ^+ varied from 4.0 to 451 meq/L, with a

Table 1 Chemical composition of groundwater within the TRB

	2010				2011			
	Min.	Max.	Ave.	SD	Min.	Max.	Ave.	SD
pH	7.2	9.8	8.2	1.3	7.2	9.3	7.9	0.5
T (°C)	7.7	23.6	16.1	5.1	14.4	29.1	20.2	4.9
EC (μS/cm)	587	28,676	4,457	9,036	911	51,647	5,865	11,809
TDS (mg/L)	278	15,251	2,341	4,817	450	27,495	3,091	6,295
TH (mg/L)	38.2	3,035.6	705.2	1,161	98.4	6,839.8	897.0	1,532
K^+ (mg/L)	5.3	172.8	32.0	39.5	5.5	191.1	26.0	42.9
Na^+ (mg/L)	29.1	4,279.8	493.1	1,299	33.5	7,100.1	698.2	1,663
Ca^{2+} (mg/L)	6.1	427.4	89.8	141	15.3	813.3	148.7	188
Mg^{2+} (mg/L)	5.5	516.7	115.4	203	12.2	1,153.6	126.1	261
SiO_2 (mg/L)	3.4	14.7	10.4	3.2	1.5	9.8	6.6	1.9
F^- (mg/L)	0.9	2.4	1.7	0.8	0.4	5.5	2.1	1.1
Cl^- (mg/L)	26.4	6,032.1	725.6	1,932	40.1	10,506	1,000.8	2,471
NO_3^- (mg/L)	0	12.7	2.1	12.5	0	78.0	8.3	18.2
SO_4^{2-} (mg/L)	48.2	3,943.7	535.0	1,266	69.6	7,418.0	812.6	1,685
HCO_3^- (mg/L)	96.1	2,198.0	345.8	325	115.0	494.0	268.1	109

mean value of 42.6 meq/L and the TZ^- varied from 4.0 to 460 meq/L with a mean value of 43.2 meq/L. All of the NICB are <8 %, and most of them are <5 %, indicating the accuracy of our data.

Major Ion Chemistry

The summary statistics for the groundwater samples are listed in Table 1. The pH values in the groundwater ranged from 7.2 to 9.8, with a mean value of 8.1, indicating their alkaline nature. The total dissolved solids (TDS) value varied from 278 to 15,250 mg/L in 2010, with a mean value of 2,341 mg/L, and from 450 to 27,495 mg/L in 2011, with a mean value of 3,091 mg/L. These values were much higher than those other basins in (semi-) arid areas in central Asia near the TRB such as the Qinghai Lake Catchment (which ranged from 336 to 2,361 mg/L, with a mean value of 633 mg/L) (Jin et al. 2009; Xiao et al. 2012c), the Zhangye Basin (which ranged from 168 to 2,124 mg/L, with an average value of 647 mg/L) (Chang and Wang 2010) and the Heihe River Basin (which ranged from 330 to 4,861 mg/L, with an average value of 1,295 mg/L) (Zhu et al. 2010). TDS values in the groundwater in the northern basin indicated predominantly fresh water (TDS < 1,000 mg/L), with the remainder being brackish water (TDS > 1,000 mg/L). The EC varied from 0.59 to 51.64 mS/cm, with an average of 5.07 mS/cm, with most values within a range of 1–4 mS/cm.

The variations in the ion concentrations are illustrated in a Schoeller diagram (Fig. 2). The mean concentrations of Na^+, Ca^{2+}, Mg^{2+}, K^+, SiO_2, F^-, Cl^-, SO_4^{2-}, NO_3^-, and HCO_3^- were 538.1, 115.7, 120.1, 29.4, 8.7, 1.9, 846.4, 656.9, 4.8, and 311.7 mg/L, respectively. The relative abundance of major cations and anions were ranked in the order $Na^+ > Mg^{2+} > Ca^{2+} > K^+$ and $Cl^- > SO_4^{2-} > HCO_3^- > (F^- + NO_3^-)$, respectively (Fig. 2). Na^+ and Cl^- were, respectively, the dominant cation and anion, contributing 61 % of TZ^+ and 56 % of TZ^-, respectively. Generally speaking, the ion concentrations were slightly lower in the wet season than in the dry season (Table 1). The spatial variation of the ion concentrations were ranked in the order HG > YG > SG > TG > AG in the dry season (Fig. 3a), and TG > YG > HG > SG > NG in the wet season.

Ternary diagrams allow a rapid, visual classification of natural waters (Zhu et al. 2013). The groundwater could be divided into different types according to the ternary diagrams (Fig. 3). Na^+ and Cl^- were the dominant cation and anion, respectively, in most of HG, TG, and SG (Fig. 3). These samples belonged to the Na^+–Cl^+ water type, generally indicating the contribution of evaporite dissolution to the solutes. Other samples suggested a trend toward the center of the field, indicating their complicated sources. The concentrations of Ca^{2+}–(Mg^{2+}) and HCO_3^- were relatively high in NG and AG, which presumably inherited the chemistry of the underlying carbonate-rich sedimentary rocks. The water types of the groundwater in the sub-basins of the TRB were basically the same as those of the river waters (Xiao et al. 2012b).

The correlations between the ions in the groundwater were calculated using SPSS software and are listed in Table 2. Strong positive correlations with significant P levels < 0.01 were obtained for Ca^{2+}–Na^+, K^+–Na^+, Ca^{2+}–Cl^-, K^+–Cl^-, Na^+–Cl^-, Cl^-–SO_4^{2-}, Na^+–SO_4^{2-},

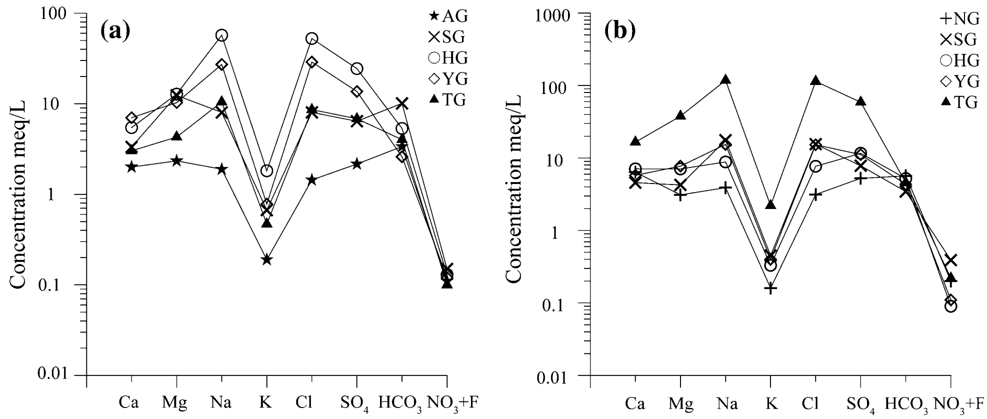

Fig. 2 Schoeller diagram showing the variation in the major ion concentrations in the groundwater samples in the wet season (**a**) and the dry season (**b**) within the TRB

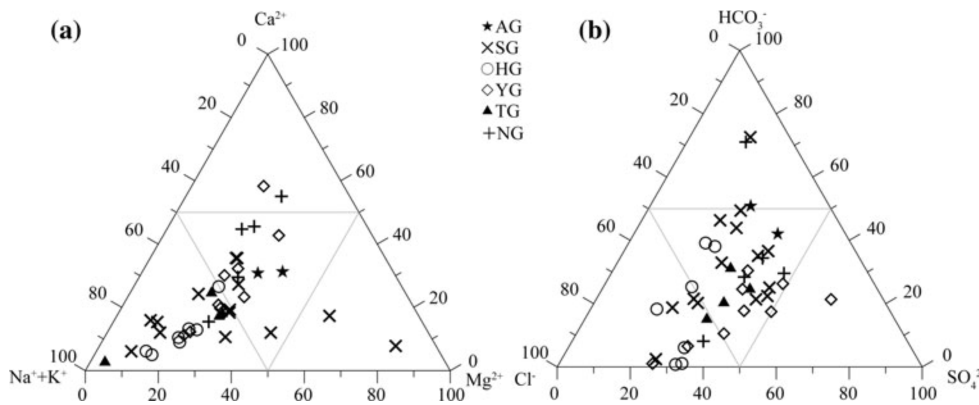

Fig. 3 Ternary diagrams for cations (**a**) and anions (**b**) in the groundwater within the TRB

Table 2 Correlation coefficients between the major ions in the groundwater

	TDS	Ca^{2+}	Mg^{2+}	K^+	Na^+	F^-	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^-
TDS	1	0.81	0.81	0.94	0.98	−0.09	0.98	0.98	0.10	0.01
Ca^{2+}		1	0.74	0.74	0.77	−0.21	0.83	0.76	−0.08	−0.07
Mg^{2+}			1	0.66	0.69	0.03	0.71	0.72	0.01	0.53
K^+				1	0.95	−0.13	0.95	0.94	−0.06	−0.13
Na^+					1	−0.13	0.99	0.99	−0.12	−0.17
F^-						1	−0.16	−0.06	0.11	0.25
Cl^-							1	0.98	−0.11	−0.17
SO_4^{2-}								1	−0.11	−0.11
NO_3^-									1	0.10
HCO_3^-										1

Correlation is significant at the 0.01 level (2-tailed)

K^+–SO_4^{2-}, and Ca^{2+}–SO_4^{2-}. TDS values depend mainly on the concentrations of K^+, Na^+, SO_4^{2-} and Cl^- (Table 2).

Trace Element Chemistry

The mean concentrations of Fe, Mn, Ba, As, Zn, Pb, Cu, Cd, Cr, B, and Al in the groundwater of the TRB were 233, 75.3, 36.6, 6.4, 10.4, 0.82, 0.55, 0.028, 2.8, 2,154, and 34.3 μg/L, respectively. The trace elements could be divided into high trace elements (> 10 μg/L; B, Fe, Mn, Ba, and Al), moderate trace elements (10–0.1 μg/L; Pb, As, Cu, Zn, and Cr) and low trace element (< 0.1 μg/L; Cd). The relative abundance of trace elements was ranked in the order B > Fe > Mn > Ba > Al > Zn > As > Cr > Pb > Cu > Cd. Spatial variation of Cu, Zn, Cd, and Ba was minor whereas the remaining trace elements was major (Fig. 4). Cr and Cd were relatively high in SG; Ba was high in NG; Mn was high in YG; Al, Cu, Pb, and B were high in HG; Fe, As, and Zn were high in TG (Fig. 4). The strong positive relationship between Al and Cu

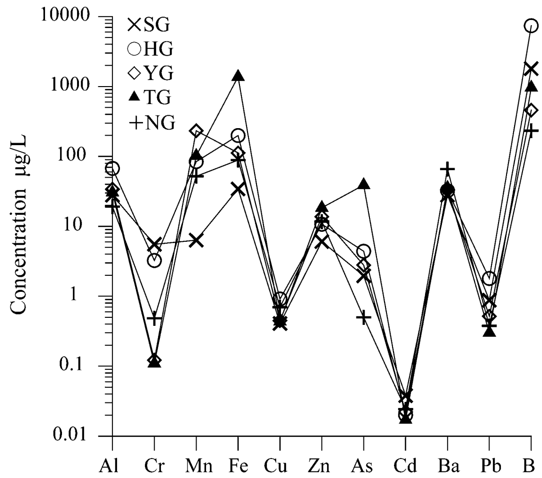

Fig. 4 Average concentrations of trace elements in the groundwater within the TRB

($R^2 = 0.82$), between Cd and Ba ($R^2 = 0.91$), and among Zn, Cr, and Fe ($R^2 = 0.85$, 0.98), indicated their similar sources. The concentration and distribution of trace elements in different sub-basins may be related to divers geology and/or human activities in these areas, which needs further study.

Discussion

Sources of the Major Components of Groundwater

The possible sources of Na^+ and K^+ in natural waters are atmospheric precipitation, evaporite dissolution and the weathering of Na-bearing silicate minerals. If halite dissolution was the source of the sodium, then the Na/Cl molar ratio would be approximately one, whereas a ratio >1 is typically interpreted as suggesting that the Na^+ was released from silicate or Na-bearing salts (Meybeck 1987). In our study, the Na/Cl molar ratio in the groundwater generally ranged from 0.7 to 2.4, with an average of 1.3. Meanwhile, the plot of ($Na^+ + K^+$) versus Cl^- showed an approximate 1:1 relationship (Fig. 5a), suggesting the evaporite influence on groundwater chemistry. Marine aerosols and atmospheric dust can also contribute Na^+ and Cl^- to groundwater. The Na/Cl molar ratios of the snow water and groundwater in this area were 1.1 and 1.3, respectively (Xiao et al. 2012b), which was different from the seawater (0.86) (Gaillardet et al. 1999). Moreover, being remote from ocean, the contribution of marine aerosols to Na^+ and Cl^- in this area was minor. Ca^{2+}, Mg^{2+}, and SO_4^{2-} may be from either the weathering of carbonates or the dissolution of evaporites. Under natural conditions, the (Ca + Mg)/HCO_3 equivalent ratio from carbonate weathering is 1. Figure 5b showed that samples in the northwestern basin were close to the 1:1 relationship line, indicating their source was carbonate weathering. The excess of ($Ca^{2+} + Mg^{2+}$) over HCO_3^- in most of the samples reflected extra sources of Ca^{2+} and Mg^{2+}; the excess was balanced by Cl^- and SO_4^{2-}, or an excess of alkalinity was balanced by Na^+ and K^+. The excess of $(Ca^{2+} + Mg^{2+})^*$ over HCO_3^- can be estimated by subtracting HCO_3^- from the total of ($Ca^{2+} + Mg^{2+}$). Similarly, the excess of $(Na^+ + K^+)^*$ over Cl^- can be estimated by subtracting Cl^- from the total ($Na^+ + K^+$). The $(Ca^{2+} + Mg^{2+})^* + (Na^+ + K^+)^*$ are possibly supplied by sulfate dissolution. The plot of $(Ca + Mg)^* + (Na + K)^*$ versus SO_4 in Fig. 5c showed that most of the samples were close to the 1:1 relationship line. In addition, SO_4^{2-} was strongly correlated with Cl^- (Fig. 5d), suggesting a common source for them. All of these indicated the contribution of the dissolution of sulfate minerals to the solutes in this area. Salinization was typical of the arid lands around the Taklimakan Desert. Halite, gypsum, and thenardite were the most common evaporites in this desert region. Several major composite sulfates of Ca, Mg, Na, and K (e.g., bloedite, eugsterite, and vanthoffite) were also widely distributed in this area (Zhu et al. 1981; Zhang et al. 1995). The weathering products of these salt minerals can contribute Ca^{2+}, Mg^{2+}, Na^+, K^+, SO_4^{2-}, and Cl^- to the groundwater, which supports the above arguments.

The (Ca + Mg)/(Na + K) ratio was used to evaluate the relative contribution of the different rocks (Sarin and Krishnasswami 1984; Ahmad et al. 1998; Han and Liu 2004; Si et al. 2009; Xiao et al. 2012c). In carbonate areas, this ratio was high. For example, the (Ca + Mg)/(Na + K) ratio was 10.0 in the Wujiang River and Yuanjiang Rivers (Han and Liu 2004), 6.0 in the Indus River (Ahmad et al. 1998), and varied between 5.2 and 11.5 in the Ganga–Brahmaputra Rivers (Sarin and Krishnasswami 1984). In evaporite areas, (Ca + Mg)/(Na + K) ratio was low. For example, the average (Ca + Mg)/(Na + K) ratio in the extreme arid Ejina Basin was only 0.6 (Si et al. 2009). The (Ca + Mg)/(Na + K) ratios of our samples varied from 0.04 to 4.0, with an average of 0.7 (Fig. 5e), which is essentially the same as that in the Ejina Basin (Si et al. 2009) and indicates the contribution of evaporite dissolution to the solutes. Fig. 5f showed that most of the ($Cl^- + SO_4^{2-}$) concentrations were much higher than the HCO_3^- concentrations. Furthermore, the average ratio of ($Cl^- + SO_4^{2-}$):HCO_3^-:SiO_2 was 122:16:1. There was also no positive correlation between Na^* (Na^* = Na–Cl) and SiO_2. These indicated that evaporite dissolution and carbonate weathering were the primary and secondary contributors of the major ions and that silicate weathering played a less important role in determining the concentrations of the major groundwater ions, which were the same as the river waters in this basin (Xiao et al. 2012b).

The concentrations of NH_4^+, NO_3^-, and $H_2PO_4^-$ may reflect human impact on water chemistry. NH_4^+ and

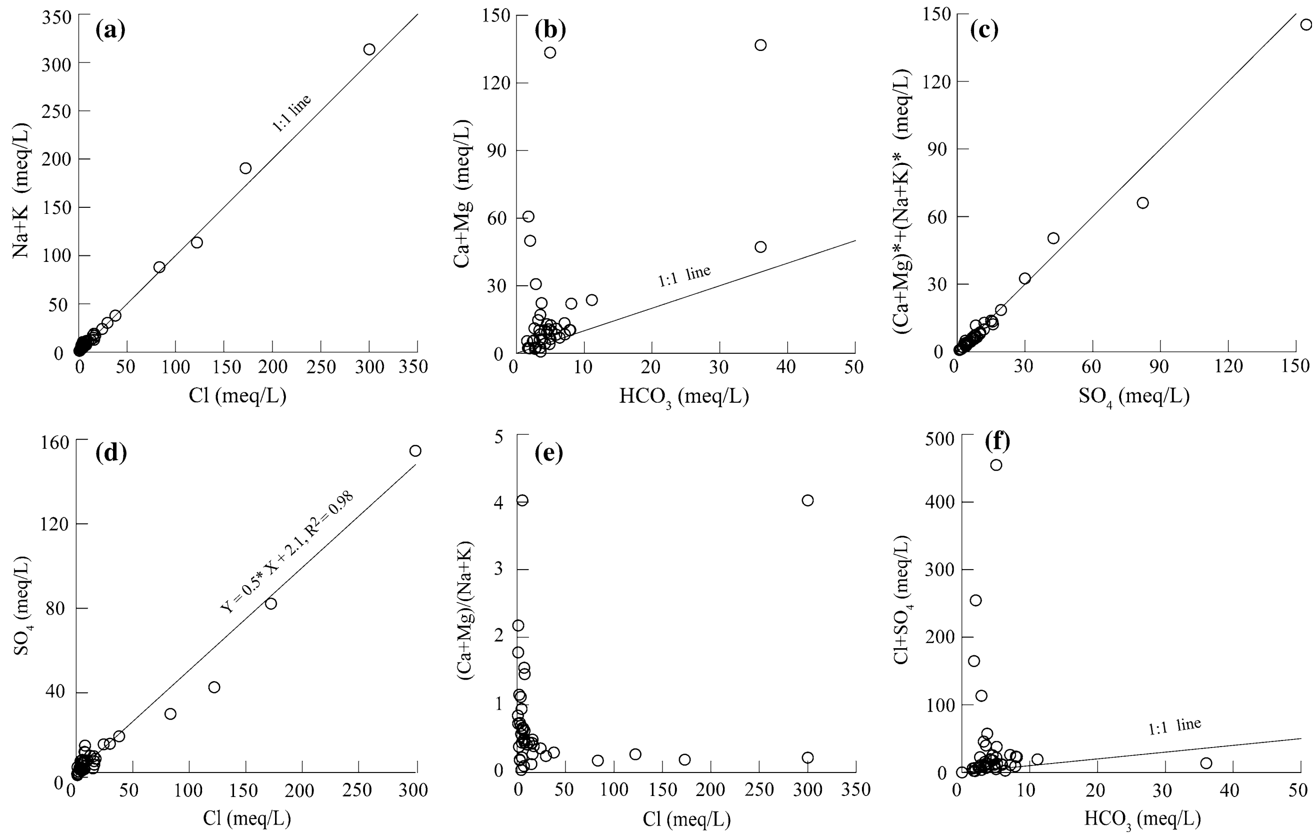

Fig. 5 Relationship between ions in the groundwater within the TRB

$H_2PO_4^-$ were not detected in any of these groundwater samples. However, the mean concentration of NO_3^- was 4.8 mg/L, higher than that of the surface water in this area (Zhu and Yang 2007; Xiao et al. 2012b). The concentration of NO_3^- in the G2 sample reached 78.0 mg/L, which exceeded the permissible drinking water standard of China (Ministry of Health 2006). Because high concentrations of NO_3^- in drinking water are toxic and may cause blue baby disease/methemoglobinemia and gastric carcinomas, G2 is not suitable for drinking. Sources of NO_3^- in groundwater are industrial, animal and human wastes, and fertilizers. G2 was located in an agricultural area, which may be influenced by agricultural activities. The concentrations of NO_3^- in all of the groundwater samples with the exception of G2 meet the permissible drinking water standard established by China in 2006.

Groundwater Quality Assessment

Groundwater for Irrigation Purposes

The groundwater within the TRB was primarily used for drinking and irrigation. Na^+ concentrations are widely used in assessing the suitability and classification of water for irrigation purposes because high concentrations of Na^+ can be adsorbed onto the soil cation exchange sites, causing soil aggregates to disperse, reducing soil permeability, and causing damage to sensitive crops (Oinam et al. 2012). The potential of irrigation water to cause these cation exchange reactions in the soil could be indicated by the SAR (Table 3; Richards 1954; Hem 1991).

The calculated SAR values of the groundwater ranged from 0.8 to 37.3, with an average value of 7.1. Only G9 in the southern sub-basin and G22 in the Aksu sub-basin were categorized as C2–S1, indicating medium salinity and low alkalinity hazards (Fig. 6a). Thirteen samples were categorized as C3–S1, showing a high salinity hazard and a low alkalinity hazard. Both C2–S1 and C3–S1 could be considered to have good quality and could be used for irrigating most of the soils and crops with little danger of exchangeable sodium (Raju et al. 2011). NG4 in the southern sub-basin was categorized as C3–S2, indicating a high salinity and a medium sodium type. G24 in the Tarim sub-basin was categorized as C3–S3, showing a high salinity hazard and a high alkalinity hazard. Both C3–S2 and C3–S3 could be considered to have moderate water quality and might be used on coarse textured or organic soils with good permeability (Rao et al. 2012). Fourteen

Table 3 Suitability of the groundwater for irrigation based on electrical conductivity (EC), sodium adsorption ratio (SAR) (Richards 1954) and percent sodium (%Na) (Wilcox 1955) and for drinking based on the water quality index (WQI) (Sahu and Sikdar 2008)

EC (μS/cm)	Water class	SAR	Water class	%Na	Water class	WQI	Water class
<250	Excellent	<10	Excellent	<20	Excellent	<50	Excellent
250–750	Good	10–18	Good	20–40	Good	50–100	Good
750–2,250	Permissible	18–26	Doubtful	40–60	Permissible	100–200	Poor
2,250–3,000	Doubtful	>26	Unsuitable	60–80	Doubtful	200–300	Very poor
>3,000	Unsuitable			>80	Unsuitable	>300	Unsuitable

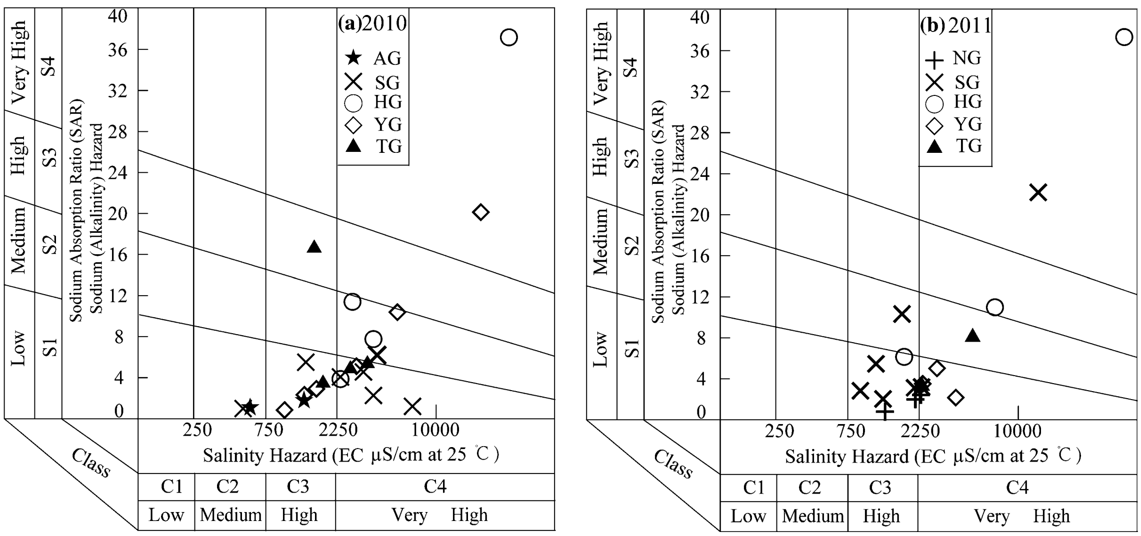

Fig. 6 Diagram for the classification of irrigation waters in 2010 (**a**) and 2011 (**b**) (after Richards 1954)

samples were categorized as C4–S1 with a very high salinity hazard and a low sodium hazard. Five samples were categorized as C4–S2 with a very high salinity hazard and a medium sodium hazard. NG10 in the Hotan sub-basin was categorized as C4–S3 with a very high salinity and high sodium hazard. Four samples were categorized as C4–S4 with a very high sodium hazard and a very salinity hazard. These types of groundwater with very high salinity (C4–S1–C4–S4) can be considered to have very poor quality, which cannot be used on soils with restricted drainage, and only appropriate for plants with good salt tolerance (Rao et al. 2012). The groundwater quality for each sample based on the SAR is shown in Table 4. Generally speaking, groundwater quality is better in the northern sub-basin than in the southern and central sub-basins, which may be related to their different geology. Carbonates dominated in the northern basin, whereas evaporites dominated in the southern and central basin. Evaporite dissolution could contribute more salts to groundwater and led to bad groundwater quality in southern and central sub-basin. At the same location, groundwater quality was slightly better in the wet season than that in the dry season, which might be related to the strong-dilution effect in the wet season.

Another index to determine the suitability of groundwater for irrigation purposes was %Na (Table 3; Wilcox 1955). The %Na values ranged from 11.1 to 93.3 %, with an average value of 51.9 %. Generally, the %Na should not exceed 60 % in irrigation water for better crop yields (Table 3; Rao et al. 2012). In our study, ~29 % of the samples had %Na greater than 60 %. The plot of %Na versus EC (Fig. 7) shows that groundwater in this area can be divided into five groups. 5 % of the groundwater samples were classified as excellent to good, 19 % as good to permissible, 7 % as permissible to doubtful, 32 % as doubtful to unsuitable and 37 % as unsuitable categories. The irrigation quality for each sample based on the %Na is shown in Table 4. The unsuitable samples were primarily in the lower reaches of Hotan, Yarkant, Tarim, and southern sub-basins (Fig. 7).

High concentrations of Na^+ in irrigation water tend to be absorbed by clays and to displace Ca^{2+} and Mg^{2+} by ion exchange, reducing the permeability and eventually resulting in soil with poor drainage. Thus, such soils are hard due to

Table 4 Groundwater quality classifications within the TRB

Site	Sample	SAR quality	%Na quality	WQI quality	Site	Sample	SAR quality	%Na quality	WQI quality
AG	G21	Excellent	Good	Good	SG	G2	Excellent	Excellent	Unsuitable
AG	G22	Excellent	Good	Excellent	SG	G3	Excellent	Good	Very poor
HG	G10	Excellent	Doubtful	Poor	SG	G4	Excellent	Permissible	Poor
HG	G11	Unsuitable	Doubtful	Unsuitable	SG	G5	Excellent	Permissible	Poor
HG	G12	Good	Unsuitable	Poor	SG	G6	Excellent	Unsuitable	Poor
HG	G13	Excellent	Permissible	Poor	SG	G7	Excellent	Doubtful	Good
HG	NG8	Excellent	Doubtful	Good	SG	G8	Excellent	Permissible	Poor
HG	NG9	Unsuitable	Doubtful	Unsuitable	SG	G9	Excellent	Permissible	Excellent
HG	NG10	Good	Doubtful	Poor	SG	NG1	Excellent	Permissible	Good
YG	G14	Excellent	Permissible	Good	SG	NG2	Doubtful	Doubtful	Very poor
YG	G15	Good	Doubtful	Very poor	SG	NG3	Excellent	Permissible	Good
YG	G16	Excellent	Permissible	Poor	SG	NG4	Good	Unsuitable	Good
YG	G17	Excellent	Good	Good	SG	NG5	Excellent	Permissible	Excellent
YG	G18	Doubtful	Doubtful	Unsuitable	SG	NG6	Excellent	Doubtful	Excellent
YG	G19	Excellent	Permissible	Good	SG	NG7	Excellent	Permissible	Poor
YG	NG11	Excellent	Permissible	Good	TG	G1	Excellent	Permissible	Poor
YG	NG12	Excellent	Permissible	Good	TG	G20	Excellent	Permissible	Good
YG	NG13	Excellent	Good	Poor	TG	G23	Excellent	Permissible	Poor
NG	NG15	Excellent	Good	Good	TG	G24	Good	Unsuitable	Good
NG	NG17	Excellent	Good	Good	TG	NG14	Excellent	Permissible	Poor
NG	NG18	Excellent	Excellent	Excellent	TG	NG16	Excellent	Permissible	Poor

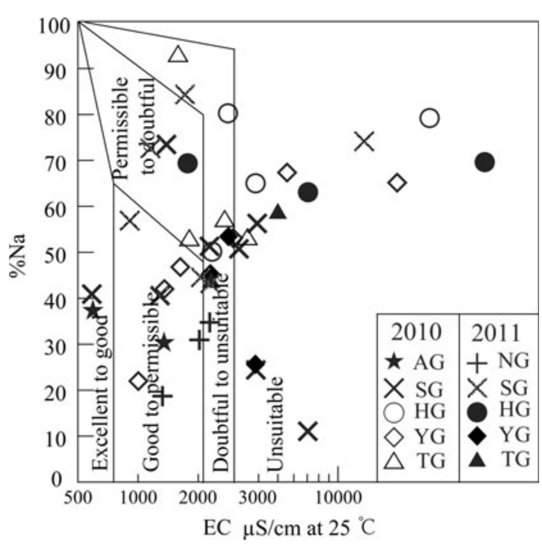

Fig. 7 Rating of the groundwater samples based on electrical conductivity and percent sodium (%Na) (after Wilcox 1955)

the lack of air and water circulation under dry climatic conditions. The groundwater samples classified as excellent to good, good to permissible, permissible to doubtful, doubtful to unsuitable and unsuitable were considered broadly to have excellent, good, moderate, poor, and very poor water quality for irrigation, respectively (Fig. 7). Groundwater samples with poor and very poor water quality were primarily collected from the southern and central sub-basins, whereas samples with excellent, good and moderate water qualities were mainly from the northern and western sub-basins. Sodium control and soil management measures would be required to reduce the salinity and sodium hazards with poor groundwater quality.

Groundwater for Drinking Purposes

Fluoride is essential to prevent dental caries, but excess intake could cause dental/skeleton fluorosis and further lead to cancer and osteosclerosis. According to the Ministry of Health of China (Ministry of Health 2006), the fluoride concentration limit in drinking water is 1.0 mg/L. Fluoride concentrations in this study varied from 0.4 to 5.5 mg/L, with an average of 1.9 mg/L. Approximately 95 % of the samples exceed this standard. High boron concentrations in drinking water are considered to have risks for human health, especially for fertility and pregnancy (Dotsika et al. 2006). The boron concentration limit in drinking water is 0.5 mg/L in China (Ministry of Health 2006). Boron concentrations in this study varied from 0.1 to 14.7 mg/L, with an average of 2.2 mg/L. Approximately 56 % of the samples exceeded the permissible drinking water standard of boron in China (Ministry of Health 2006). Sulfate is likely to react with human organs if it exceeds the maximum allowable limit, and it has a laxative effect on the human system in

Table 5 Chemical summary of the groundwater within the TRB and Chinese State Standards (CSS) for drinking water

Parameters	CSS	Weight (w_i)	Relative weight (W_i)	Parameters (mg/L)	CSS	Weight (w_i)	Relative weight (W_i)
pH	6.5–8.5	4	0.055	Cd	0.005	5	0.068
TH (mg/L)	450	2	0.027	Cr	0.05	5	0.068
TDS (mg/L)	1,000	4	0.055	Na	200	2	0.027
Ca (mg/L)	75*	2	0.027	B	0.5	3	0.041
Mg (mg/L)	30*	2	0.027	Ba	0.7	2	0.027
Fe (mg/L)	0.3	4	0.055	Al	0.2	2	0.027
Mn (mg/L)	0.1	4	0.055	Cl	250	3	0.041
As (mg/L)	0.01	5	0.068	F	1.0	4	0.055
Zn (mg/L)	1.0	1	0.014	SO_4	250	4	0.055
Pb (mg/L)	0.01	5	0.068	NO_3	20	5	0.068
Cu (mg/L)	1.0	2	0.027	HCO_3	120*	3	0.041
						$\sum w_i = 73$	

* Ca, Mg and HCO_3 standards are World Health Organization (WHO) standards (World Health Organization 2011)

combination with excess magnesium in groundwater (Arumugam and Elangovan 2009). Approximately 54 % of the samples exceeded the permissible drinking water standard of sulfate in China (Ministry of Health 2006). Other elements, such as Al, Cr, Mn, Fe, Cu, Zn, As, Cd, Ba, and Pb, were within the permissible drinking water standards in China (Ministry of Health 2006).

WQI was used to assess the suitability of the groundwater for human consumption (Table 3; Bordalo et al. 2006; Sahu and Sikdar 2008; Banoeng-Yakubo et al. 2009). In this study, 22 parameters were chosen and the $\sum w_i$ was 73 (Table 5). The calculated relative weight (W_i) values of each parameter are also given in Table 5. The computed WQI values were classified into five categories (Table 3). In this study, the calculated WQI values ranged from 34.7 to 940, with an average of 168. Therefore, the groundwater quality could be categorized into five groups (Table 4). Only 12.2 % groundwater samples were classified as having ''excellent'' water quality. Approximately 36.6, 34.1, and 7.3 % samples were classified as having ''good'', ''poor'', and ''very poor'' water quality, respectively. Approximately 9.8 % of the samples were classified as ''unsuitable for drinking''. Generally speaking, groundwater quality of the northern basin was better than the central and southern basins. Similarly, groundwater quality in the wet season was slightly better than in the dry season.

Another very important parameter for the evaluation of water quality is the corrosivity ratio (CR) (Raju et al. 2011), which evaluates the quality with respect to the variations in chloride and sulfate concentrations. The CR was calculated as follows:

$$CR = \left(Cl^- + SO_4^{2-}\right)/HCO_3^-(\text{Alkalinity})$$
$$(\ddot{O}\text{zcanand etal. 2007}).$$

The primary effect of corrosion is loss in the hydraulic capacity of pipes. The CR in the groundwater ranged from 0.4 to 126, with an average value of 11.8. The samples with a CR < 1 were considered to be safe, whereas >1 was considered to be unsafe. Approximately 93 % of the samples had a CR > 1, indicating that they were unsafe for metallic pipes.

Groundwater Quality Management for Sustainable Development

Although the TRB is rich in natural resources, the natural environment in the basin is extremely vulnerable because of limited water resources. The increase in population and agricultural production in recent decades have aggravated the significant environmental and hydrological degradation of the TRB (Feng et al. 2001); for instance, the lower Tarim River nearly dried up in 1972 (Feng et al. 2005). Therefore, the use and protection of groundwater resources has reasonably become a key issue in this area. Our results showed that the groundwater in this area, especially in the southern and central basins, had a very high salinity hazard and a high sodium hazard and was unsuitable for irrigation. Thus, the relative control of sodium and salinity hazards is required before irrigation. In addition, most samples exceeded the permissible drinking water standard for B^{3+}, F^-, and ${SO_4}^{2-}$ in China. Thus, treatment of the B^{3+}, F^-, and ${SO_4}^{2-}$ is required for drinking in this area. In the areas with CR values >1, noncorrosive pipes, viz., polyvinyl chloride, should be used for the water supply instead of metal pipes. Surface water and groundwater exchanged reciprocally and frequently on the mountain pediment alluvial–proluvial fan of the basin, and 90 % of the groundwater on the plain was from the surface water. Excessive usage of surface water may result in the deterioration of the groundwater quality. Thus, integrated management of the surface water and groundwater is also solution to water quality issues in this area, for example, establishing a reasonable water allocation program and transfer mechanism, introducing a water market adjustment mechanism and strengthening the centralization of the basin management. In addition, strict water use permission and water quality supervision systems of surface and groundwater should be established to ensure the quality and supply of water resources.

Conclusions

The major ions and trace elements in 42 wells within the TRB were measured to determine the hydrogeochemistry and to assess the groundwater quality for irrigation and drinking purposes. The groundwater within the TRB was characterized by slight alkalinity and high ion concentrations. TDS values in the TRB were higher than in the neighboring basins. The groundwater was brackish in the southern and central sub-basins, classified as the Na^+–Cl^- water type. Evaporite dissolution contributed most of the solutes. SAR and Na % revealed that high sodium and salinity hazards were the primary problem for irrigation and that these hazards must be relatively controlled before irrigation. For human health, the groundwater could be used for drinking after treatment for B^{3+}, F^-, and SO_4^{2-}. The groundwater with poor drinking water quality was primarily from the central and southern basins. The groundwater quality in the wet season was slightly better than in the dry season. Due to the high CR of the groundwater, noncorrosive pipes (polyvinyl chloride) should be used for water supply instead of metal pipes. For sustainable development, the integrated management of surface water and groundwater for drinking and irrigation is needed in this area. Suggestions derived from this study can also be applicable to other similar areas in the world.

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