

Variation of groundwater hydrochemical characteristics in the plain area of the Tarim Basin, Xinjiang Region, China

Qiao Li · Jinlong Zhou · Yinzhu Zhou ·
Chunyan Bai · Hongfei Tao · Ruiliang Jia ·
Yuanyuan Ji · Guangyan Yang

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Abstract Groundwater hydrochemistry could reveal the interaction mechanism between groundwater and the environment, which provides a scientific basis for environmental resources management. In this study, Shukaliyefu's classification method and Piper diagram were adopted to determine the hydrochemical types of groundwater in the Tarim Basin of Xinjiang, China. The method of "one vote veto" was applied to evaluate the quality of groundwater. Phreeqc software was used to calculate the saturation indices of calcite and fluorite in groundwater. By comparing groundwater quality data of 2003 and 2011, we characterized the variations in hydrochemical types and water quality types, salinization of groundwater and fluoride geochemistry of the plain area of the Tarim Basin. Results show that the primary anion in phreatic water in the plain area of the Tarim Basin changed from HCO_3^- to SO_4^{2-} or Cl^- . On the contrary, the primary anion in confined water changed from SO_4^{2-} or Cl^- to HCO_3^- . In 2003, 63.1 % of the sampling points in the study area exceeded the Class III water quality standard of China. In 2011, the proportion increased to 82.5 %. In addition, severe groundwater salinization was found at 19.7 % of the sampling points. Some of the deep groundwater samples

were salinized as well. In the Aksu area at the north-west part of the Tarim Basin, F^- concentration exceeding the standard limit (1 mg/L) was found to be 55.0 % of the groundwater samples tested. Based on these findings, it is concluded that the phreatic water in the study area was severely influenced by the industrial wastewater and domestic sewage related to human activities, while the confined water was less affected. The general quality of groundwater was in an aggravation trend, and the groundwater salinization was in a severe condition in this area. The Ca^{2+} – Na^+ ionic exchange, the unsaturated fluorite and oversaturated calcite in the aquifer of the Aksu area are proposed to cause F^- enrichment in groundwater of this area.

Keywords Plain area of Tarim Basin · Groundwater hydrochemical type · Variation of groundwater quality types · Groundwater salinization · High fluoride groundwater

Introduction

Groundwater is an important component of water resources. In the cycling process of natural system, there is extremely complex material, energy and information exchange in the lithosphere, biosphere and atmosphere. Groundwater hydrochemical research is an essential part of quality evaluation of groundwater resources. It is significant for the utilization and management of regional groundwater resources as well as for the protection of ecological environment. The hydrochemical characteristics are ceaselessly changing on temporal and spatial scales. By studying the temporal variation characteristics of groundwater hydrochemistry, the interaction mechanism between

Q. Li · J. Zhou (✉) · Y. Zhou · C. Bai · H. Tao · R. Jia · Y. Ji
College of Water Conservancy and Civil Engineering,
Xinjiang Agricultural University, Ürümqi 830052, China
e-mail: zjzhoujl@163.com

J. Zhou · G. Yang
School of Environmental Science, China University of
Geosciences, Wuhan 430074, China

Y. Zhou
School of Water Resources and Environment,
China University of Geosciences, Beijing 100083, China

groundwater and the environment can be revealed, providing a scientific basis for environmental resource management (Zhang et al. 2006).

The plain area of the Tarim Basin is located in the southern part of the Xinjiang Uyghur Autonomous Region, China. It is one of the China's major cotton-producing areas. The area has abundant groundwater resources, with an average annual recharge of 22.0 billion m³. The exploitable amount of groundwater is 7.1 billion m³. However, the actual exploitation amount of groundwater in 2010 was 4.2 billion m³, which only accounted for 18.9 % of the recharge amount (Xu et al. 2002). The potential for groundwater exploitation is enormous in the plain area of Tarim Basin. At reasonable utilization, the problem of water shortage in south Xinjiang could be effectively relieved, and this is also conducive to the melioration of saline-alkali land. In recent years, the highly intensive and non-judicious human activities, together with the climatic drought, have caused the deterioration of groundwater quality, salinization of groundwater and the aggravation of land salinization, which has become the bottleneck of regional ecological environment and economic and social development. The most obvious non-judicious human activities in Tarim Basin are excessive fertilizer use and flood irrigation (Li et al. 2013). The Tarim Basin has seen intensive confrontation between environmental protection and economic development over the past five decades (Wu 2012).

Xu et al. (2012) applied a comprehensive quantitative approach including statistical, principal component and gray relation analyses to assess the groundwater chemistry based on monitored data from 840 samples collected from the lower reaches of Tarim River from 2000 to 2009. Field studies were carried out in Tarim Basin for analysis of snowmelt model for flood forecast for a river in arid zone (de la Paix et al. 2012). The changes in annual runoff of the three original rivers and the mainstream of Tarim River were analyzed by the non-parametric tests based on the hydrologic data during the period of 50 years (Zhou et al. 2012). Combining the ecological quantity analysis with GIS technology, based on the land use data and remote sense images, the changes in land use and land cover and the driving force were analyzed in the mainstream of the Tarim River from 1973 to 2005 (Zhao et al. 2013).

From October to December 2011 during the period of the Xinjiang Groundwater Utilization and Protection Planning Project, groundwater sampling was conducted at 57 representative monitoring points in the plain area of the Tarim Basin. These were the same groundwater sampling points as in the Xinjiang Groundwater Resource Investigation and Evaluation Project led by the Ministry of Water Resources in 2003.

The main purpose of this study was to characterize the spatial variation in groundwater hydrochemistry from the changes in groundwater hydrochemical types, water quality types, groundwater salinization, fluoride geochemistry, and to provide a scientific basis for ameliorating the current deterioration of groundwater in this area.

Study area

Location and climate

There are five administrative districts (prefectures) and 42 counties (cities) under respective jurisdictions in the research area, and they include Bayingol Mongolian Autonomous Prefecture (hereinafter referred as Bayingol), Aksu Prefecture, Kizilsu Kirghiz Autonomous Prefecture (referred as Kizilsu), Kashi and Hotan (Xu et al. 2002). The geographic locations of these districts are shown in Fig. 1.

The Tarim Basin is located at the center of the Eurasian Continent, and is the biggest inland basin of China. The Basin lies between the Tianshan Mountains and the Kunlun Mountains. It is bounded in the west by the eastern foot of the Pamirs, in the east by the Lop Nur depression, in the north by the southern foot of the Tianshan Mountains, and in the south by the northern foot of the Kunlun Mountains. Including the surrounding mountains, the Basin covers a total area of 105×10^4 km², which accounts for 63 % of the total area of Xinjiang; the plain area of Basin (the area without desert and mountain area in Fig. 1) occupies 53×10^4 km². At the basin center, there is the Taklamakan Desert, which covers 33.76×10^4 km², and is also known as the “Sea of Death”. The piedmont plain and oasis only occupy 19.24×10^4 km² (Zhang et al. 2006). The climate of Tarim Basin is of typical continental temperate, which is characterized by arid climate all the year around with rare rain, hot summers and freezing winters. The average annual temperature is 10.5–12.2 °C, with a maximum of 42.2 °C and a minimum value of −30.9 °C. Because the basin is surrounded by mountains and plateaus, the oceanic moist air cannot enter this area. The duration of sunlight is long, so this area enjoys abundant sunshine and heat resources. Generally, the annual precipitation is 50–70 mm in the north, 15–30 mm in the south, and only 10 mm in the central desert area and Ruopqiang and Qiemo area in the southeast. At the same time, the evaporation amount is as high as 2,200 mm, which is 22 times that of the precipitation.

Hydrogeological setting

As the Tarim Basin is an enclosed arid inland basin surrounded by mountains, the hydrographic net of the basin is

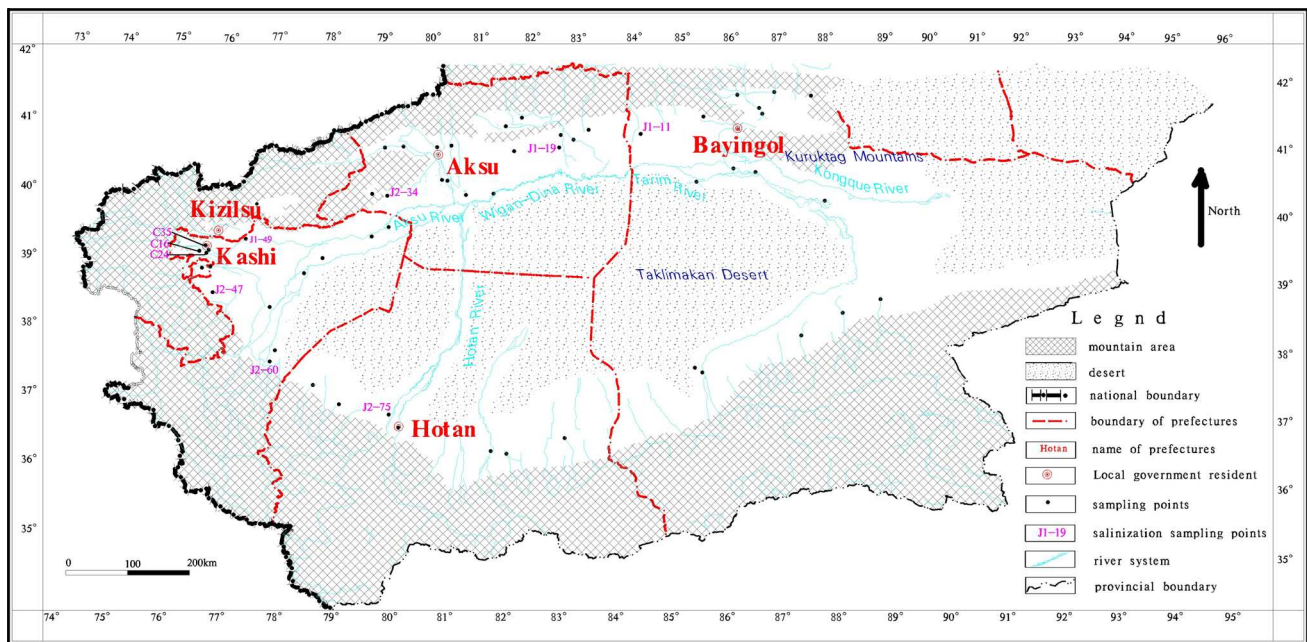


Fig. 1 Geographical location of the Tarim Basin and groundwater sampling points

formed by the Kongque River, the Weigan River—Dina River, the Aksu River, the Yarkant—Kashi River, the Tarim River, the Hotan-Keriya River, the Cherchen River, etc. The alluvial fans of various sizes formed by the rivers overlap with each other, and form the piedmont sloping plain. The recharge, runoff and discharge of the groundwater in the basin area are in a self-contained system. The surrounding mountain area is the source region of water resources, and the piedmont alluvial-proluvial plain is the recharge-runoff region of groundwater. The Taklimakan Desert in the central region of the basin is the groundwater discharge region, while the Lop Nur Lake basin in the east is the runoff confluence center.

The dominant recharge source of groundwater in the basin is the infiltrated surface water, while the basin's hydrographic net controls the distribution of groundwater. The alluvial-proluvial plain surrounding the basin slopes towards the center. In other words, the piedmont region is higher in elevation while the land close to the desert is lower. The slope of the region is gradually reduced from piedmont to fine-grained soil plain area. The alluvial plains of Kongque River and Tarim River are relatively flat. In general, the land is higher at the west end and inclines towards the east with a gradient of 1–3 %. Furthermore, the Quaternary loose deposit of large thickness has provided a favorable aquifer for groundwater storage. In particular, the Quaternary sediment thickness is 1,000–1,500 m in the middle and upper alluvial-proluvial plains of The Aksu River and Weigan-Dina River as well as the Hotan-Yutian Region (Fig. 1). Quaternary sediment

in other parts of the piedmont alluvial-proluvial plain is 500–1,000 m thick. However, the Quaternary sediment thickness is relatively small in the alluvial plains of Tarim River and Kongque River as well as the piedmont alluvial-proluvial plain of Kuruktag Mountains. For alluvial-proluvial plain of Kuruktag Mountains, the thickness is <100 m.

In the piedmont clinoplain areas surrounding the basin, the particle size of the Quaternary sediments becomes finer from the piedmont area to the front edge of alluvial-proluvial plain. The lithology of the alluvial-proluvial plain is as follows: gravel-cobble and sand gravel for the upper layer; sand gravel and coarse sand in the middle; and fine-grained sand, silt, sandy loam and loam at the bottom. The lithology of Quaternary sediments in Kongque River and Tarim River alluvial plains is of fine sand, silt, sandy loam and loam (Liu et al. 2008).

There are plentiful phreatic and confined water reserves in the study area. The single-structure phreatic areas are mainly distributed in the upper layers of the alluvial-proluvial sloping plain of northern and western margins, as well as the alluvial-proluvial sloping plain of southern margin. The phreatic-confined water areas of double-layered structure are mainly distributed in the middle and lower layers of alluvial-proluvial sloping plain of northern and western margins, as well as alluvial plains of Kongque River and Tarim River.

Under the influence of geomorphic feature and land-form, stratigraphic lithology and recharge and runoff conditions, the phreatic water table depth is characterized by a

Table 1 Assessment indicators of groundwater quality in Xinjiang in 2003 and 2011

Prefecture	Samples ID	Year	pH	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	TDS (mg/L)	Total hardness (as CaCO ₃) (mg/L)	NH ₄ ⁺ (mg/L)	NO ₂ ⁻ (as N) (mg/L)	NO ₃ ⁻ (as N) (mg/L)	F ⁻ (mg/L)
Aksu	J2-39	2003	7.90	257.37	220.94	791.95	330.26	0.03			1.52
	J2-39	2011	7.83	207.87	216.19	740.00	265.80				2.53
	J1-30	2003	7.70	136.13	205.57	584.47	231.18	0.12			
	J1-30	2011	7.91	149.09	166.80	570.00	132.90				2.33
	J1-25	2003	7.90	77.99	60.52	298.17	133.11	0.03			
	J1-25	2011	8.04	73.11	61.16	290.00	132.90				1.96
	J2-38	2003	8.00	41.12	91.26	298.19	150.12	0.06			
	XJ-87	2011	7.41	207.87	447.26	1,340.00	817.80				2.97
	J2-34	2003	7.70	808.26	749.27	2,533.24	780.62				1.50
	J2-34	2011	7.71	809.98	817.65	2,690.00	792.20				1.30
	J2-33	2003	7.50	568.62	528.33	1,859.86	625.50	0.03			
	XJ-80	2011	7.30	797.80	1005.71	2,996.34	833.10				1.25
	J1-29	2003	7.90	21.98	36.50	201.19	135.11	0.03			
	XJ-85	2011	7.94	15.77	27.48	162.39	92.00	<0.04	<0.012	1.45	1.01
	J1-21	2003	7.70	18.43	64.36	273.54	217.17				0.80
	J1-21	2011	7.52	17.92	89.94	352.23	265.80				0.70
	J1-28	2003	7.50	99.26	135.44	531.14	376.30	0.03			2.05
	J1-28	2011	7.96	41.57	64.43	242.07	143.10				1.73
	J1-26	2003	7.50	74.44	136.41	627.54	434.35	0.03			1.28
	J1-26	2011	7.32	71.68	131.81	623.92	429.30				0.59
	J1-27	2003	7.60	42.54	100.86	411.52	275.22	0.03			1.06
	J1-27	2011	7.67	37.27	75.23	321.51	224.90	<0.04	<0.012	1.60	0.21
	J1-32	2003	7.70	265.88	420.74	1,376.80	270.22				
	J1-32	2011	7.43	629.35	813.57	2,616.31	1,058.00				1.15
	S1-10	2003	7.50	75.86	108.55	437.73	288.23				
	S1-10	2011	7.85	43.01	61.16	255.95	158.40	<0.04	<0.012	1.17	0.76
	S2-38	2003	7.70	65.94	76.85	314.77	180.14				1.65
	S2-38	2011	7.76	152.68	264.92	853.68	468.20				5.28
	S2-60	2003	7.40	93.59	100.86	423.58	225.18				0.58
	S2-60	2011	7.21	316.83	593.62	1,874.35	838.20				0.53
	J1-19	2003	7.70	53.17	64.36	510.00	125.00				1.65
	J1-19	2011	7.81	237.98	299.59	895.02	403.80				0.67
	J2-23	2003				0.00					
	XJ-89	2011	7.55	116.12	162.22	621.11	327.10	<0.04	<0.012	1.23	0.53

Table 1 continued

Prefecture	Samples ID	Year	pH	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	TDS (mg/L)	Total hardness (as CaCO ₃) (mg/L)	NH ₄ ⁺ (mg/L)	NO ₂ ⁻ (as N) (mg/L)	NO ₃ ⁻ (as N) (mg/L)	F ⁻ (mg/L)
Bayingol	J2-87	2003	7.70	170.16	315.08	825.48	428.34	<0.02			
	J2-87	2011	7.84	164.15	330.33	838.85	419.10				
	J2-78	2003				0.00		<0.02			
	J2-78	2011	7.93	279.55	346.03	1,040.77	400.70				
	J2-80	2003	7.80	184.34	192.12	801.70	375.30				
	J2-80	2011	7.80	149.81	179.89	764.79	255.60				
	J2-82	2003	7.60	255.24	391.92	1,100.39	558.45	<0.02			
	J2-82	2011	7.68	243.71	481.76	1,215.64	544.80				
	J1-75	2003	7.70	172.29	232.47	737.87	342.27	<0.02			
	J1-75	2011	7.88	178.48	254.46	792.55	351.6	<0.04	<0.0122	0.57	0.82
	S1-1	2003				0.00		0.18			
	XJ-62	2011	8.09	55.19	126.25	447.16	166.60				
	J2-6	2003	7.20			860.00	275.00	<0.02			0.24
	J2-6	2011	7.71	15.05	38.60	257.00	214.70				
	J1-11	2003	8.60	90.75	118.15	427.24	33.03	0.05			
	J1-11	2011	8.62	156.98	132.14	600.13	30.70	0.42	<0.012	0.48	1.73
	J1-10	2003	7.70	113.44	234.39	638.39	350.28				0.25
	J1-10	2011	7.41	163.43	479.47	1,134.42	664.40				0.59
	HS33	2003				0.00		<0.02			
	HS33	2011	7.85	29.39	138.35	428.34	218.80				
	J1-5	2003	7.60	482.12	512.00	1,610.68	241.19	<0.02			
	XJ-58	2011	7.73	1,035.06	974.97	3,203.35	819.80				
	J1-1	2003	8.00			350.00	157.00	0.11			0.40
	XJ-61	2011	8.09	36.56	49.71	229.62	115.50				
	S1-94	2003	7.50	381.44	435.15	1,416.92	595.48				
	S1-94	2011	7.65	416.46	476.86	1,609.11	569.40				
	S1-91	2003	7.20	833.08	795.38	2,699.73	1,336.07				
	S1-91	2011	7.36	964.09	1,319.86	3,778.01	1,611.00				
	S2-8	2003	7.20	411.22	374.63	1,446.49	765.61	0.15			
	S2-8	2011	7.25	1,569.79	1,618.98	5,342.86	1,850.20				
	J1-76	2003	7.40	1,737.05	1,536.96	5,187.73	1,901.52				
	J1-76	2011	7.83	867.33	875.23	2,767.42	1,172.50				

Table 1 continued

Prefecture	Samples ID	Year	pH	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	TDS (mg/L)	Total hardness (as CaCO ₃) (mg/L)	NH ₄ ⁺ (mg/L)	NO ₂ ⁻ (as N) (mg/L)	NO ₃ ⁻ (as N) (mg/L)	F ⁻ (mg/L)
Hotan	J2-77	2003	7.60	131.16	140.25	660.17	303.24	0.01			
	J2-77	2011	7.71	123.29	169.42	731.83	304.60	<0.04	<0.012	4.05	0.89
	J2-75	2003	7.60	170.16	91.26	611.65	295.24	0.01			
	J2-75	2011	7.64	173.47	149.47	710.43	325.10	<0.04	<0.012	1.73	0.70
	J1-61	2003	7.20	197.10	405.37	1,114.09	640.51				0.22
	J1-61	2011	7.78	136.19	258.38	711.37	340.40				
	J2-69	2003	7.20			1,050.00	433.00	0.01			0.64
	J2-69	2011	7.23	261.63	491.74	1,445.64	743.20				
	J1-67	2003				1,500.00	651.00	0.01			0.30
	J1-67	2011	7.42	555.52	891.25	2,464.17	1,047.80				
	J1-65	2003	7.50	99.26	336.21	723.96	482.39	0.01			
	J1-65	2011	7.81	78.85	310.71	665.63	396.60	<0.04	<0.012	0.70	0.38
	J1-68	2003	7.60	93.59	348.70	740.40	450.36				0.46
	J1-68	2011	7.73	93.18	308.75	705.95	390.50				
Kashi	J1-49	2003	8.00	108.48	192.12	560.00	160.13	0.15			
	J1-49	2011	8.13	132.61	247.91	708.94	207.50	0.51	<0.012	3.75	0.57
	J2-46	2003	7.70	53.17	192.12	623.13	350.28	0.53			
	J2-46	2011	8.01	21.50	105.31	322.76	199.30				
	J2-47	2003	7.80	65.23	254.56	597.86	370.30	0.01			
	J2-47	2011	7.79	129.02	427.14	999.33	565.30				
	J1-51	2003	7.80	227.59	280.50	814.06	243.19	0.17			
	J1-51	2011	8.13	136.19	178.25	595,060.00	97.10	0.21	<0.012	4.90	0.52
	J2-42	2003				0.00		0.55			
	J2-42	2011	7.89	98.92	250.2	707.47	382.3				
	S1-72	2003	7.30	246.73	382.32	1,178.08	623.50				0.90
	S1-72	2011	7.78	1,612.8	1,229.42	4,745.48	1,183.7				
	S1-51	2003	7.50	202.07	309.31	1,032.00	485.39				
	S1-51	2011	7.56	612.86	1,147.99	3,117.06	1,456.7				
	J1-42	2003	7.40	327.56	268.97	1,072.01	606.48	0.55			
	J1-42	2011	7.75	759.81	1,172.51	3,141.2	1,395.3				
	J1-55	2003				0.00		0.06			
	J1-55	2011	7.62	157.7	307.11	963.92	499.9				
	J2-60	2003	7.60	250.28	305.47	921.33	380.30	0.01			
	J2-60	2011	7.93	283.14	326.41	1,021.06	419.1				

Table 1 continued

Prefecture	Samples ID	Year	pH	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	TDS (mg/L)	Total hardness (as CaCO ₃) (mg/L)	NH ₄ ⁺ (mg/L)	NO ₂ ⁻ (as N) (mg/L)	NO ₃ ⁻ (as N) (mg/L)	F ⁻ (mg/L)
Kizilsu	J2-61	2003	7.50	154.56	264.17	778.64	480.38				0.50
	J2-61	2011	7.55	315.39	761.56	1,934.08	896.5				
	C1	2003	7.70	112.12	417.97	850.00	536.76				
	C1	2011	7.79	104.00	492.25	970.00	575.12				
	C24	2003	7.70	65.40	386.01	740.00	579.50				
	C24	2011	7.65	62.25	437.56	840.00	560.25				
	C35	2003	7.70	65.40	341.75	670.00	439.96				
	C35	2011	7.60	65.92	408.92	790.00	421.43				
	C16	2003	7.70	41.62	295.04	550.00	404.77				
	C16	2011	7.57	71.74	416.59	790.00	496.36				
	C43	2003	7.70	67.95	388.47	740.00	541.78				
	C43	2011	7.74	65.92	404.26	780.00	545.38				
	J1-44	2003	7.40	182.92	206.53	827.59	415.33	0.01			0.90
	J1-44	2011	7.73	193.54	226	893.36	428.3				

zonal pattern distribution. In general, the water table depth is >50 m in the piedmont zone, 10–50 m in the middle layer of alluvial–proluvial plain, and <10 m in the lower layer of the alluvial–proluvial plain as well as the alluvial plans of the Tarim River and the Kongque River. The areas where the water table depth is over 50 m are distributed along the piedmont region in zonal patterns (Liu et al. 2008).

Materials and methods

Sampling point selection

To eliminate the effect of spatial difference, the groundwater sampling points in this study were the same points as used by the 2003 Xinjiang Groundwater Resource Investigation and Evaluation Project funded by the Ministry of Water Resources in China. We collected two series of ground water samples at April 24th–May 21st 2003 and November 7th–27th 2011. However, due to the overexploitation and other human and natural causes, groundwater levels have declined and five sampling wells were already dried up. In this study, there were a total of 57 groundwater sampling points in the region, 52 of which were in the original locations and five were set up near the original locations; samples from 52 sampling points were for complete analyses (analyzed elements are K⁺, Na⁺, Ca²⁺, Mg²⁺, Cl⁻, SO₄²⁻, HCO₃⁻, CO₃²⁻, pH, TDS, total hardness, NH₄⁺, NO₂⁻, NO₃⁻, COD_{Mn} and F⁻) and five points were for simple analyses (K⁺, Na⁺, Ca²⁺, Mg²⁺, Cl⁻, SO₄²⁻, HCO₃⁻, CO₃²⁻, pH, TDS and total hardness). Groundwater samples are from local main production layers (either confined or unconfined aquifers), with the depth of the wells ranging between 7 and 300 m (Table 1). Types of aquifers that these wells are tapping into are shown in Table 2.

Sample collection and preservation

A total of 114 groundwater samples were collected in 2003 and 2011. The weather was sunny during the sample collection. The groundwater level was measured using a tape during sampling. Groundwater was pumped for approximately 10 min to eliminate the interference of stagnant water in wells. Groundwater temperature was determined in the field using a mercury thermometer. Samples collected were stored at 4 °C and were transported back to the laboratory for immediate analyses to preclude any deterioration of quality. The sampling containers were 550 mL water bottles, which were rinsed 3–5 times with the groundwater before each sampling. MapGIS was used to draw the distribution diagram of sampling points, which is shown in Fig. 1.

Table 2 Types of aquifer where the wells were drilled

Area	Aquifer type	Depth
North Aksu Prefecture	Unconfined aquifer	10–90
South Aksu Prefecture	Confined aquifer	100–249
Southeast of Bayingol	Unconfined aquifer	7–85
Northwest of Bayingol	Confined aquifer	100–300
Hotan	Unconfined aquifer	50–95
Middle and East of Kashi	Unconfined aquifer	7–96
West Kashi	Confined aquifer	100–245
Kizilsu	Confined aquifer	108–180

Table 3 Groundwater quality standard (GB/T14848-93)

Indicator	I	II	III	IV	V
pH	6.5–8.5			5.5–6.5, 8.5–9	<5.5, >9
Cl [−] (mg/L)	≤50	≤150	≤250	≤350	>350
SO ₄ ^{2−} (mg/L)	≤50	≤150	≤250	≤350	>350
F [−] (mg/L)	≤1.0	≤1.0	≤1.0	≤2.0	>2.0
TDS (mg/L)	≤300	≤500	≤1,000	≤2,000	>2,000
COD _{Mn} (mg/L)	≤1.0	≤2.0	≤3.0	≤10.0	>10.0
NH ₄ ⁺ (mg/L)	≤0.02	≤0.02	≤0.2	≤0.5	>0.5
Total hardness CaCO ₃ (mg/L)	≤150	≤300	≤450	≤550	>550

Analytical procedures

For quality assurance, all sample analyses were carried out in duplicate. Sample collection, handling and analysis were undertaken in a clean environment. The water sample test was completed by the Laboratory of the Second Hydrogeological Brigade of Xinjiang Bureau of Geology and Mineral Exploration, according to Methods for Examination of Drinking Natural Mineral Water GB/T8538-2008 and Standard Examination Method for Drinking Water GB/T5750.1-5750.13-2006. The test items include total dissolved solids (TDS), pH, total hardness (as CaCO₃), K⁺, Na⁺, Ca²⁺, Mg²⁺, Cl[−], SO₄^{2−}, HCO₃[−], CO₃^{2−}, COD_{Mn}, NH₄⁺, NO₃[−], NO₂[−] and F[−]. TDS, pH and total hardness were measured using 180 °C dry weight, PHS-3 B and Chrome black indicator titration, respectively. Concentrations of K⁺, Na⁺ and Ca²⁺ were quantified using flame atomic spectrophotometry. Concentrations of Mg²⁺ and SO₄^{2−} were analyzed using EDTA-2Na titrations. Concentrations of F[−] and NO₂[−] were measured using an ion selective electrode method and diazamine coincidence spectrophotometry. Concentrations of Cl[−] and NO₃[−] were determined using ion chromatography. Furthermore, concentrations of HCO₃[−] and CO₃^{2−} were analyzed with potentiometric titration. The above analyses were added

with 10 % repeat samples at the time of the test, i.e., every 10 samples were added with 1 repeat sample to be tested repeatedly, with an error of <5 %. All the analytical results of samples are in line with the quality requirements, with 100 % pass rate for the error of <5 %.

Water quality evaluation methods

The method of “one-vote veto” was applied to evaluate the groundwater quality. In other words, if one fails, all will fail. The Groundwater Quality Standard (GB/T14848-93) (Table 3) was also adopted as the evaluation basis. The following eight indicators were selected as the evaluation indices, and they are Cl[−], SO₄^{2−}, F[−], pH, TDS, COD_{Mn}, ammonia–nitrogen and total hardness. As stated earlier, the quality evaluations of the Tarim Basin groundwater were conducted in 2003 and 2011, respectively, to interpret the temporal variation in groundwater quality. Shukaliefu’s classification method and a Piper diagram were adopted to determine the hydrochemical type of groundwater (Zhou et al. 2010).

Geochemical modeling (PHREEQC)

To study the occurrence of F[−], the program PHREEQC was used to calculate the saturation indices of calcite and fluorite in groundwater (Hu et al. 2009).

Statistical analyses

Microsoft Excel was applied on a one-way ANOVA to interpret the influence of groundwater quality variation in different prefectures (Lin et al. 2012). The *F* test (*P* < 0.05) was used to analyze if there is a significant difference in groundwater quality between different regions.

Results and discussion

Variation in groundwater hydrochemical characteristics

The hydrochemical condition of the study area is complex. Due to the combined effect of lixiviation–evaporation and evaporation concentration, an obvious horizontal distribution regularity of hydrochemical characteristics was found in the groundwater flow direction (Song et al. 2011).

Two sets of groundwater samples were collected at April 24th–May 21st 2003 and November 7th–27th 2011. Phreatic water in the upper layer of the alluvial–proluvial plain was found to be dominated by HCO₃·SO₄[−] Na·Mg, and SO₄·Cl[−] Na·Ca in the lower layer. The hydrochemical type variation was relatively simple in spatial distribution

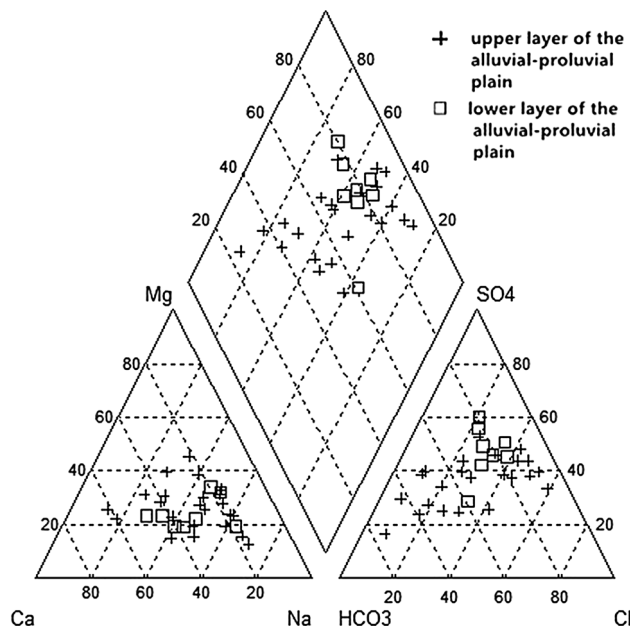


Fig. 2 Piper diagram of phreatic water of the Tarim Basin in 2011

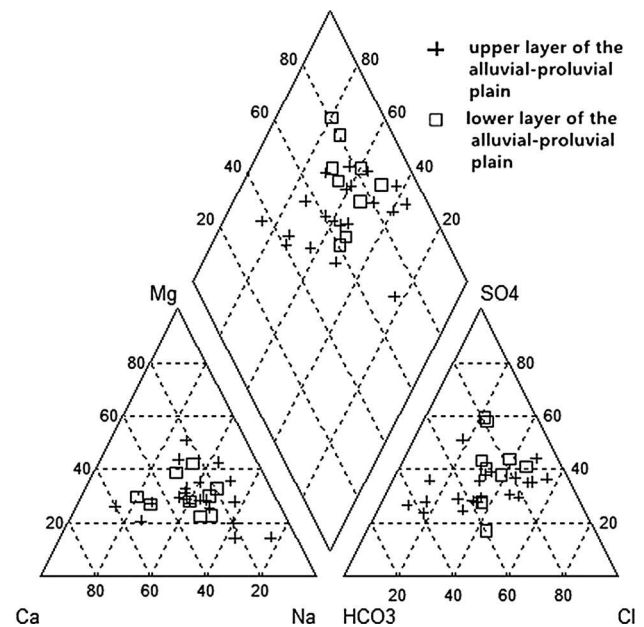


Fig. 3 Piper diagram of phreatic water of the Tarim Basin in 2003

(Fig. 2) and no major changes were found. The surface water studies by Zhang et al. (2008) showed that the major pollutants of surface water are SO_4^{2-} and Cl^- in the Tarim Basin. Therefore, the groundwater hydrochemical type was clearly affected by surface water. The $\text{SO}_4^{2-} + \text{Cl}^-$ content exceeds 50 % at most sampling sites. In 2003, the major anions of phreatic water were $\text{HCO}_3^- \cdot \text{SO}_4^{2-}$ in the upper layer of the alluvial-proluvial plain and $\text{HCO}_3^- \cdot \text{Cl}^-$ in the lower layer. In 2011, $\text{SO}_4^{2-} \cdot \text{Cl}^-$, $\text{Cl}^- \cdot \text{SO}_4^{2-}$ and other types gradually appeared (Fig. 3).

For confined water in the middle and upper layers of the alluvial-proluvial plains on the northern and western margins of the Tarim Basin, the variation in hydrochemical type was relatively large compared to that in phreatic water (Fig. 4). The primary anions were $\text{HCO}_3^- \cdot \text{SO}_4^{2-}$, $\text{Cl}^- \cdot \text{SO}_4^{2-}$, and a small amount of $\text{SO}_4^{2-} \cdot \text{HCO}_3^-$. The primary cations were Na-Ca, Na-Mg, with a small amount of Ca-Mg. For confined water, the primary anions were $\text{SO}_4^{2-} \cdot \text{Cl}^-$ and $\text{Cl}^- \cdot \text{SO}_4^{2-}$ and the primary cations were of Na-Ca and Na-Mg in 2003 (Fig. 5). In 2011, the confined water in this area was dominated by HCO_3^- . It indicated that confined water was less affected by the Cl^- and SO_4^{2-} released by the domestic and industrial wastewater than phreatic water (Adhikary et al. 2009).

Variation in groundwater quality

Characteristics of groundwater temporal variation

Through groundwater quality evaluation, the variation in different water quality types and the proportion of

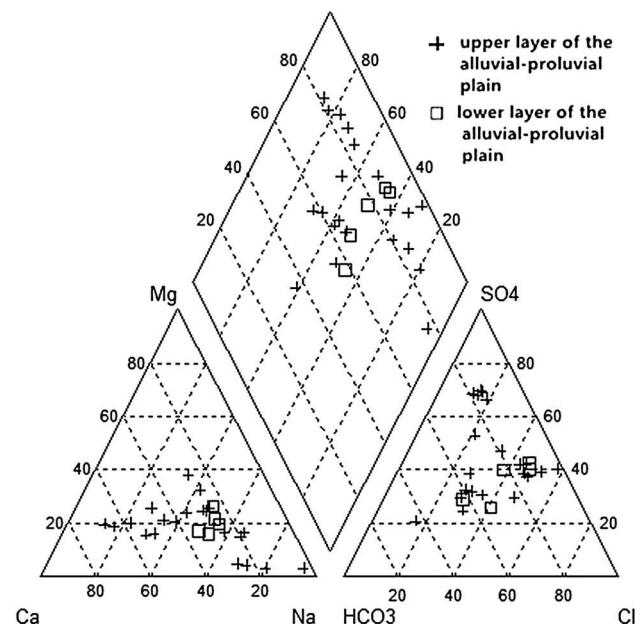


Fig. 4 Piper diagram of confined water of the Tarim Basin in 2011

evaluation items for each water quality type were determined. This is a significant feature in identifying the major pollutants in each area as well as the analysis of the causes of such pollution (Mamatha and Sudhakar 2010). The assessment indicators of groundwater quality in the Tarim Basin in 2003 and 2011 are shown in Table 1. The proportions of indices for each water quality type in Tarim

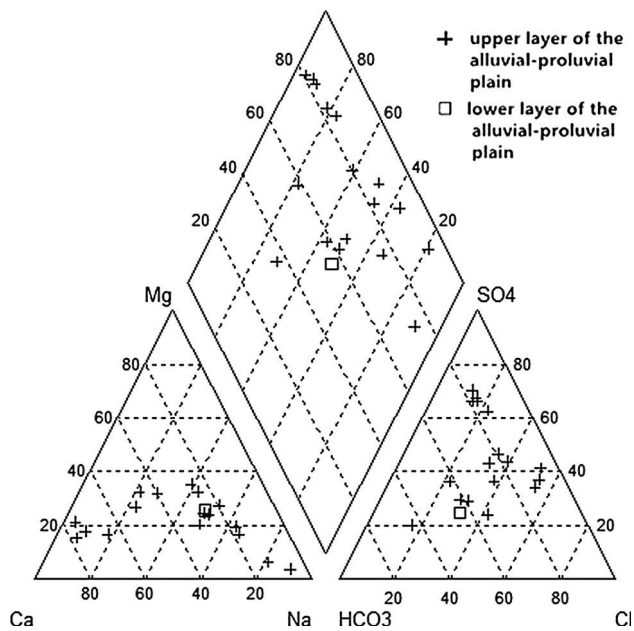


Fig. 5 Piper diagram of confined water of the Tarim Basin in 2003

Basin are shown in Table 4. According to the analyses, the tendency of groundwater quality variation in Tarim Basin was as follows:

- (1) The degradation in water quality was particularly evident in the Hotan and Kashi Regions. Samples of class I and II water quality, according to Chinese water standard of groundwater quality standard GB/T14848-93, were recorded there in 2003, but the quality of all samples had deteriorated to class V in 2011.
- (2) The overall quality of groundwater was in an obvious downward trend. In 2003, the groundwater quality at 63.1 % of sampling points exceeded the class III standard. This proportion had increased to 82.5 % in 2011. It is thus clear that the quality of groundwater in the basin is relatively poor and has been getting worse over the past 8 years.
- (3) The number of sites displaying evaluation indices of poor-quality water (classes IV and V) increased year by year to a different extent. In Table 4, it can be seen that the proportions of each evaluation item of classes IV and V for different water quality types had increased over the last 8 years to a different extent. The sum of proportions of SO_4^{2-} content and permanganate indices of classes IV and V water samples exceeded 50 %.

Characteristics of groundwater spatial variation

As shown in Table 5, groundwater spatial variation was observed. Most of the concentration of ions (except for F^-

and Ca^{2+}) in Bayingol located to the east of the Basin are at a maximum, while the ion concentrations in Kizilsu located in the west were at a minimum in 2003. The concentration of most ions (except for F^- and Cl^-) in Kashi is at a maximum, and in Kizilsu at a minimum in 2011. $\text{K}^+ + \text{Na}^+$, HCO_3^- concentrations and total hardness of groundwater in different prefectures have passed the test of 0.05 level of significance, which were statistically significant in 2003, while not in 2011. Besides, the maximum F^- concentration occurred in Aksu Region both in 2003 and 2011.

Groundwater salinization

According to Xinjiang Water Resource Communiques (2005 and 2010), the exploitation quantity of groundwater in 5 prefectures in the Tarim Basin in 2005 and 2010 was 1.68×10^9 and $4.18 \times 10^9 \text{ m}^3$, respectively (see Table 6). Due to the highly intensive and continuous exploitation, the normal groundwater recharge was disrupted. This had caused the phreatic water with a relatively high TDS level, as well as shallow confined water to recharge the exploited layer in the form of leakage recharge, which led to groundwater salinization marked by increased contents of SO_4^{2-} and Cl^- . Groundwater became gradually salinized and TDS rose distinctly. According to the 2003 and 2011 monitoring data, 34, out of 57, groundwater samples showed an increased TDS, which accounted for 59.6 %; 26 samples showed an increased Cl^- content which accounted for 45.6 %. For SO_4^{2-} , 33 samples showed an increased concentration, which accounted for 57.9 %. Overall, the salinization of groundwater in the plain area of the Tarim Basin has the following features:

- (1) Of 57 sampling points in the study area, 11 points showed severe groundwater salinization (the increased extent of the TDS, Cl^- , and SO_4^{2-} concentrations was over 10 %, and reached or exceeded the class III water quality standard). These points comprised 19.3 % of the total number of wells, and were mainly located in Kashi Region.
- (2) The comparative analyses, based on the sample number and location of sampling points, suggested that the distribution of salinization in the study area was sporadic (Fig. 1). Most salinization points were distributed around the centers of counties or cities. It indicated that the SO_4^{2-} and Cl^- contents of groundwater were affected by urban domestic and industrial wastewater.
- (3) It should be noted that the deep groundwater (well depth >100 m) in the Tarim Basin was obviously salinized. According to Table 7, it is clear that the

Table 4 Proportions of evaluation indexes in different water quality levels in the Tarim Basin in 2003 and 2011

Prefecture	Evaluation indicator	Year	I	II	III	IV	V	Total	IV–V subtotal	Wells involved in statistics
Aksu	pH	2003	100.0	0.0	0.0	0.0	0.0	100	0.0	16
		2011	100.0	0.0	0.0	0.0	0.0	100	0.0	17
	TDS	2003	25.0	25.0	31.3	12.5	6.3	100	18.8	16
		2011	23.5	11.8	35.3	11.8	17.6	100	29.4	17
	Total hardness	2003	18.8	50.0	18.8	0.0	12.5	100	12.5	16
		2011	23.5	23.5	17.6	5.9	29.4	100	35.3	17
	NH ₄ ⁺	2003	0.0	0.0	100.0	0.0	0.0	100	0.0	9
		2011	0.0	0.0	100.0	0.0	0.0	100	0.0	4
	COD _{Mn}	2003	91.7	8.3	0.0	0.0	0.0	100	0.0	12
		2011	0.0	41.2	5.9	52.9	0.0	100	52.9	17
	F [−]	2003	22.2	0.0	0.0	66.7	11.1	100	77.8	9
		2011	41.2	0.0	0.0	35.3	23.5	100	58.8	17
	Cl [−]	2003	25.0	50.0	0.0	12.5	12.5	100	25.0	16
		2011	29.4	23.5	23.5	5.9	17.6	100	23.5	17
	SO ₄ ^{2−}	2003	6.3	62.5	12.5	0.0	18.8	100	18.8	16
		2011	5.9	35.3	17.6	11.8	29.4	100	41.2	17
Bayingolin	pH	2003	92.3	0.0	0.0	7.7	0.0	100	7.7	13
		2011	93.8	0.0	0.0	6.3	0.0	100	6.3	16
	TDS	2003	0.0	15.4	38.5	38.5	7.7	100	46.2	13
		2011	12.5	12.5	25.0	25.0	25.0	100	50.0	16
	Total hardness	2003	7.7	23.1	30.8	0.0	38.5	100	38.5	13
		2011	12.5	25.0	18.8	6.3	37.5	100	43.8	16
	NH ₄ ⁺	2003	72.7	0.0	27.3	0.0	0.0	100	0.0	11
		2011	0.0	0.0	50.0	50.0	0.0	100	50.0	2
	COD _{Mn}	2003	90.9	9.1	0.0	0.0	0.0	100	0.0	11
		2011	0.0	18.8	6.3	56.3	18.8	100	75.0	16
	F [−]	2003	100.0	0.0	0.0	0.0	0.0	100	0.0	3
		2011	66.7	0.0	0.0	33.3	0.0	100	33.3	3
	Cl [−]	2003	9.1	18.2	27.3	9.1	36.4	100	45.5	11
		2011	18.8	12.5	31.3	6.3	31.3	100	37.5	16
	SO ₄ ^{2−}	2003	0.0	9.1	27.3	9.1	54.5	100	63.6	11
		2011	12.5	18.8	6.3	18.8	43.8	100	62.5	16
Hotan	pH	2003	100.0	0.0	0.0	0.0	0.0	100	0.0	7
		2011	100.0	0.0	0.0	0.0	0.0	100	0.0	7
	TDS	2003	0.0	0.0	57.1	42.9	0.0	100	42.9	7
		2011	0.0	0.0	71.4	14.3	14.3	100	28.6	7
	Total hardness	2003	0.0	14.3	28.6	28.6	28.6	100	57.1	7
		2011	0.0	0.0	71.4	0.0	28.6	100	28.6	7
	NH ₄ ⁺	2003	100.0	0.0	0.0	0.0	0.0	100	0.0	5
		2011	0.0	0.0	100.0	0.0	0.0	100	0.0	3
	COD _{Mn}	2003	100.0	0.0	0.0	0.0	0.0	100	0.0	5
		2011	0.0	28.6	28.6	28.6	14.3	100	42.9	7
	F [−]	2003	100.0	0.0	0.0	0.0	0.0	100	0.0	4
		2011	100.0	0.0	0.0	0.0	0.0	100	0.0	3
	Cl [−]	2003	0.0	60.0	40.0	0.0	0.0	100	0.0	5
		2011	0.0	57.1	14.3	14.3	14.3	100	28.6	7
	SO ₄ ^{2−}	2003	0.0	40.0	0.0	40.0	20.0	100	60.0	5
		2011	0.0	14.3	14.3	42.9	28.6	100	71.4	7

Table 4 continued

Prefecture	Evaluation indicator	Year	I	II	III	IV	V	Total	IV–V subtotal	Wells involved in statistics
Kashi	pH	2003	100.0	0.0	0.0	0.0	0.0	100	0.0	14
		2011	100.0	0.0	0.0	0.0	0.0	100	0.0	16
	TDS	2003	0.0	0.0	78.6	21.4	0.0	100	21.4	14
		2011	0.0	6.3	62.5	12.5	18.8	100	31.3	16
	Total hardness	2003	0.0	14.3	42.9	21.4	21.4	100	42.9	14
		2011	6.3	12.5	18.8	18.8	43.8	100	62.5	16
	NH ₄ ⁺	2003	37.5	0.0	25.0	0.0	37.5	100	37.5	8
		2011	0.0	0.0	0.0	50.0	50.0	100	100.0	2
	COD _{Mn}	2003	100.0	0.0	0.0	0.0	0.0	100	0.0	7
		2011	0.0	27.3	27.3	45.5	0.0	100	45.5	11
	F [−]	2003	100.0	0.0	0.0	0.0	0.0	100	0.0	2
		2011	100.0	0.0	0.0	0.0	0.0	100	0.0	2
	Cl [−]	2003	7.7	46.2	30.8	15.4	0.0	100	15.4	13
		2011	6.3	56.3	6.3	12.5	18.8	100	31.3	16
	SO ₄ ^{2−}	2003	0.0	0.0	7.7	61.5	30.8	100	92.3	13
		2011	0.0	6.3	12.5	18.8	62.5	100	81.3	16
Total	pH	2003	98.0	0.0	0.0	2.0	0.0	100	0.0	51
		2011	98.0	2.0	0.0	0.0	0.0	100	0.0	57
	TDS	2003	8.0	12.0	50.0	24.0	6.0	100	30.0	51
		2011	10.5	8.8	45.6	15.8	19.3	100	35.1	57
	Total hardness	2003	7.8	27.5	27.5	11.7	25.5	100	37.2	51
		2011	12.3	17.5	26.3	8.8	35.1	100	43.9	57
	NH ₄ ⁺	2003	44.1	0.0	47.1	0.0	8.8	100	8.8	34
		2011	72.7	0.0	0.0	18.2	9.1	100	27.3	11
	COD _{Mn}	2003	94.4	5.6	0.0	0.0	0.0	100	0.0	36
		2011	0.0	28.9	15.4	46.1	9.6	100	55.7	52
	F [−]	2003	63.1	0.0	0.0	31.6	5.3	100	36.9	19
		2011	56.0	0.0	0.0	28.0	16.0	100	44.0	25
	Cl [−]	2003	12.8	42.5	21.3	10.6	12.8	100	23.4	47
		2011	15.8	33.3	21.1	8.8	21.0	100	29.8	57
	SO ₄ ^{2−}	2003	2.1	27.7	17.0	29.8	23.4	100	53.2	47
		2011	5.3	19.3	14.0	19.3	42.1	100	61.4	57

There was only one comparison point in Kizilsu, and the indexes of COD_{Mn} and F[−] changed from I into III. Therefore, they are not listed in the table

distribution of salinization coefficients [Cl[−]/(HCO₃[−] + CO₃^{2−})] in this area shows the following pattern: the salinization coefficient of deep groundwater at some sampling points is >2 in the Aksu and Kashi areas, between 1 and 2 in the Baying and Kashi area, and <1 in Hotan area.

Fluoride geochemistry in the study area

The Aksu area is a typical high fluoride groundwater area in the Tarim Basin. Of the 57 sampling points, groundwater samples from the Aksu area had an average F[−]

concentration of 1.38 mg/L, which is 2.6 times the average value (0.53 mg/L) for the other four regions (autonomous prefectures). For the other four regions, only one sampling point in the Kashi area had F[−] concentration exceeding the class III standard limit (1.0 mg/L) according to the Groundwater Quality Standard (GB/T14848-93). There were 12 out of 22 groundwater samples (accounting for 54.5 % of the total samples) in the Aksu area that had F[−] concentration exceeding the standard limit with the range of 0.13–5.28 mg/L.

According to the study of Li et al. (2013), the fluoride distribution was characterized by the distinctive features in Tarim basin. The F[−] concentration of the groundwater in

Table 5 Variability of Groundwater in plain area in the Tarim Basin

	Ca ²⁺	Mg ²⁺	K ⁺ +Na ⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	Total hardness (as CaCO ₃)	TDS	F ⁻
2003									
Aksu, mean (mg/L)	60.72	35.61	141.54	168.79	193.80	202.43	298.61	1,147.37	1.34
Bayingol, mean (mg/L)	94.73	95.52	313.72	439.19	467.11	249.29	629.78	1,689.26	0.25
Hotan, mean (mg/L)	91.38	50.08	106.63	138.25	264.36	238.71	434.35	385.03	0.34
Kashi, mean (mg/L)	120.14	39.64	96.04	124.10	338.86	170.33	463.22	1,529.71	0.70
Kizilsu, mean (mg/L)	89.56	40.84	63.70	76.15	204.88	141.99	415.33	355.76	0.90
<i>F</i> value	3.77	3.53*	3.53*	3.52	3.11	1.76*	2.26*	2.93	3.69
2011									
Aksu, mean (mg/L)	86.31	53.14	214.65	230.94	311.69	253.82	434.32	1,030.34	1.50
Bayingol, mean (mg/L)	115.25	72.88	336.90	395.31	488.93	235.91	587.84	1,530.11	1.05
Hotan, mean (mg/L)	115.74	52.92	189.06	203.16	368.53	256.71	506.89	1,060.33	0.66
Kashi, mean (mg/L)	139.38	76.72	350.81	387.27	559.44	284.95	663.88	1,659.76	0.55
Kizilsu, mean (mg/L)	81.47	38.83	171.88	199.12	221.68	232.12	363.30	830.01	0.67
<i>F</i> value	1.01	0.58	0.83	0.79	1.22	0.19	0.79	1.05	0.99

* Past 0.05 significance test

Table 6 Statistics of exploitation quantity of groundwater in the five prefectures in the Tarim Basin in 2005 and 2010

Name of prefecture and city	Exploitation quantity (10 ⁶ m ³)		
	2005	2010	Variation amount
Bayingolin	498.20	900.94	402.74
Aksu	312.97	704.89	391.92
Kizilsu	56.92	100.48	43.56
Kashi	629.75	2,095.06	1,465.31
Hotan	181.90	374.05	192.15
Total	1,679.74	4,175.42	2,495.68

Qiman Township of Kuqa County was the highest (5.28 mg/L), and decreased from the eastern and western regions of the Aksu area to the central regions. In the vertical direction, the F⁻ concentration of shallow groundwater is higher than that of deep groundwater.

The amount of fluoride ion released to groundwater is controlled by the degree of saturation of fluorite and calcite and the concentrations of Ca²⁺, HCO₃⁻ and Na⁺ in groundwater. Based on the chemical or Phreeqc analyses, F⁻ enrichment in groundwater in the Aksu area is mainly controlled by two hydrochemical processes, which are the Ca²⁺–Na⁺ exchange and unsaturated fluorine with over-saturated calcite.

Ca²⁺–Na⁺ exchange

According to Shukaliefu's classification method, most groundwater in the Aksu area is dominated by HCO₃–Na

Table 7 Salinization coefficient of deep groundwater samples in salinization sampling points in the Tarim Basin

Prefecture	Sampling well number	Cl ⁻ (mg/L)	HCO ₃ ⁻ (mg/L)	CO ₃ ²⁻ (mg/L)	Salinization coefficient
Aksu	J2-34	809.98	224.15	0	3.6
	J1-19	237.98	112.08	0	2.1
Bayingolin	J1-11	156.98	130.76	6.12	1.1
Hotan	J2-75	173.47	246.57	0	0.7
Kashi	J1-49	132.61	128.27	0	1.0
	J2-47	129.02	261.51	0	0.5
	J2-60	283.14	124.53	0	2.3
	C24	62.25	149.55	0	0.4
	C35	65.92	112.16	0	0.6
	C16	71.74	112.08	0	0.6

and Cl–Na. This is because the Ca²⁺–Na⁺ exchange occurring on the surface of aquifer sediments has caused the elevation of Na⁺ concentration and the decline of Ca²⁺ concentration in groundwater. High concentration of HCO₃⁻ in the groundwater of the study area is mainly caused by hydrolysis of aluminosilicate. A high concentration of HCO₃⁻ could suppress the concentration of Ca²⁺ in groundwater, which leads to F⁻ enrichment (Zeng and Liu 1996). In groundwater, there is the following equilibrium:



When groundwater is alkaline or weakly alkaline, the concentration of OH⁻ will increase, and the equilibrium (1)

moves to the left. This also causes equilibrium (2) to shift to the left, which increases the concentration of F^- in groundwater. Alkaline and weakly alkaline water is favorable for the dissolution of fluorine-containing minerals (mainly CaF_2); as the pH value increases, F^- concentration increases. Thus, fluoride enrichment is likely to occur in alkaline and weakly alkaline waters. Groundwater pH values in plain area of Aksu Prefecture are between 7.21 and 8.24, which provide favorable conditions for fluoride enrichment.

Unsaturated fluorite and oversaturated calcite

PHREEQC software was used to calculate the saturation indices of fluorite and calcite for the 22 groundwater samples in the Aksu area. The saturation indices for fluorite and calcite in the groundwater samples in the Aksu area are shown in Fig. 6. Most groundwater samples in the Aksu area were oversaturated or saturated with respect to calcite, while only one sample was in relation to fluorite (Fig. 6). The rest of the samples were all unsaturated with respect to fluorite. The ± 0.2 deviation (calculation errors, test errors and program analysis errors) represented the range for saturation (dashed in the Fig. 4) (Mamatha and Sudhakar 2010; Dragon 2012; Jia et al. 2012). Because the groundwater was unsaturated with respect to fluorite, F^- concentration was controlled by the dissolution of fluoride. On the other hand, the calcite was oversaturated, and Ca^{2+} content was controlled by precipitation of calcite. Therefore, a low Ca^{2+} concentration would lead to high fluoride groundwater.

Conclusions

- (1) Analysis of variation in groundwater hydrochemical type in the research area from 2003 to 2011 showed that shallow groundwater was greatly affected by the SO_4^{2-} and Cl^- in urban domestic wastewater. The major pollutants in urban domestic wastewater are SO_4^{2-} and Cl^- . Because the phreatic water in Tarim Basin is mostly pore phreatic water in loose rock mass, the surface water and groundwater can easily exchange. An analysis of groundwater salinization showed that the salinization points were mostly distributed around the center of each county (city). Based on these two points, prevention and treatment measures against groundwater pollution by urban wastewater should be taken.
- (2) This study revealed that shallow groundwater salinization was very severe in the study area, and some other areas also show the problem of deep groundwater salinization. Therefore, it is imperative to

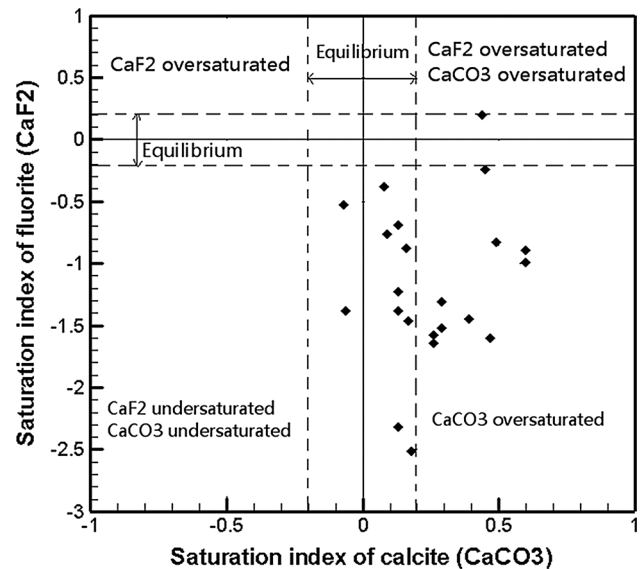


Fig. 6 Plot of calcite saturation index versus fluorite saturation index for groundwater samples from the Aksu Prefecture

conduct multi-level water-seal and exploitation measures for groundwater. In the meantime, over-exploitation of deep groundwater should be prevented to avoid the leakage recharge of shallow confined water and phreatic water with high TDS level.

- (3) The comparative analysis of groundwater quality type in the plain areas of the Tarim Basin during 2003–2011 showed that the general water quality has deteriorated. It was mainly associated with the increased concentration of various ions in the groundwater as a result of aggressive agricultural activities in the irrigation area, dense population in urban areas and the pollution by three industrial wastes (waste water, waste gas, solid waste discharge by industrial activities).
- (4) High fluoride groundwater occurred widely in the Aksu area. There are various artificial defluoridation methods in usage, which can mainly be divided into three categories: coagulation sedimentation (medication), filter layer adsorption method and electrochemical method. The first and second methods are suitable for area with groundwater of high fluoride content, while the other indexes are relatively low or meet the drinking water standard area. The third method suits for area with groundwater of high fluoride content; other indicators are relatively high and do not accord with the standard of drinking water. Because distribution of high fluoride water in Aksu is very wide, and many areas have no replaceable low-fluoride aquifers, the first or second method can be employed.

- (5) Groundwater quality monitoring is a long term and systematic endeavor. More importantly, it is the basis for acquiring first-hand information of groundwater quality. At present, there is no complete system of groundwater quality monitoring in the plain areas of the Tarim Basin. So it is difficult to track the variation of groundwater quality in this area. Hence, the groundwater quality monitoring should be strengthened to achieve stratified (phreatic water, shallow confined water and deep confined water) and regular water quality monitoring intervals (1–2 times per year).

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