ECOHYDROLOGY
Ecohydrol. **6**, 1009–1020 (2013)

DOI: 10.1002/eco.1415

The effects of oasis ecosystem hydrological processes on soil salinization in the lower reaches of the Tarim River, China

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ABSTRACT

On the basis of the characteristics of the oasis hydrological recycling processes in the lower reaches of the Tarim River, the impacts of surface water and groundwater on soil salt content were analyzed to determine how these processes affect soil salinization. The results showed that the relationship between surface water quality and soil salt content in the 0–50 cm layer of soil was significantly positive, with soil salt content declining as groundwater depths increased. However, there was no clear correlation between surface water and salt content in the 50–100 cm layer of soil. When the groundwater depth was <6 m, the soil salt content showed a high-surface concentration, exhibiting a 'T' distribution and decreased with increasing soil depth in the order of 0–20 cm > 20–50 cm > 50–100 cm. However, with increasing groundwater depth (>6 m), soil salt loads were reduced and showed a 'rhombus' distribution, mainly accumulating in the middle layer in the order of 20–50 cm > 0–20 cm > 50–100 cm. When groundwater depth was greater than 6 m, the hardness, total dissolved solids (TDS), and conductance of the groundwater underwent a radical change. Thus, the critical threshold groundwater depth for condensing salt content in groundwater and changing soil salt load distributions was deemed to be 6 m. Salt accumulation in the 0–50 cm layer of soil was determined by the TDS volume in the groundwater when groundwater depth was shallow, which accounted for more than 90% of salt accumulation. However, salt accumulation was determined by the volume of TDS in irrigation water when groundwater depth increased. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS oasis ecosystem; soil salinization; hydrological recycle; Tarim River

Received 2 September 2011; Revised 24 June 2013; Accepted 27 June 2013

INTRODUCTION

Soil salinization is a growing worldwide environmental problem, especially in arid and semi-arid regions (Wang *et al*., 2008). It describes a soil degradation process that results from salinity caused by factors such as prevailing climate, geology, and soil texture as well as from human activities such as irrigation (Wei and Xu, 2005). On a global scale, it is estimated that 30% of all land is affected by salinity, most of which occurs in arid and semi-arid areas (Wang, 1993). Nearly, 50% of the irrigated land in these regions has some degree of soil salinization, and about 10 million ha of irrigated land is abandoned every year because of soil salinization and alkalization (O'Hara, 1997; Sazabolcs, 1987). In China, 17 million ha of irrigated land is salinized, accounting for one third of the country's irrigated land (Shi, 2004). Therefore, soil salinization is an important issue that must be investigated, addressed, and rectified to improve the environment and to maintain sustainable development, especially in arid regions (Zhou *et al*., 2003).

Soil salinization has attracted the attention of numerous researchers over the past few decades. Many previous studies have focused on the distribution (Mo *et al*., 2004; Liu *et al*., 2005a, b), causes (Eiichi *et al*., 1996; Chen *et al*., 1997; Liu *et al*., 2002; Tikhonravova, 2007), harm to soil (Lv *et al*., 2002; Li *et al*., 2003a; Wang, 2004; Gabbasoya and Suleimanov, 2007; Ma *et al*., 2008), and preventive measures (Sembiring *et al*., 1995; Mao, 1998; Li *et al*., 2001; Barrett, 2002; Li *et al*., 2003b; Wang *et al*., 2005) of soil salinization. Particularly, since the 1990s, the monitoring and forecasting of soil salinization on a regional scale has made significant progress with the application of 3S technology (Mougenot *et al*., 1993; Qi *et al*., 1997; Luo and Chen, 2001; Dehaan and Laylor, 2003; Mettemieht and Zinck, 2003; Howari, 2004; Weng and Gong, 2006).

Oases are an intrazonal landscape found in arid and semi-arid regions of the world. Although oases account for only 4–5% of the total area of these regions, more than 90% of the population and more than 95% of social wealth are concentrated within these zones (Han, 2001). Oases are

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found in the deserts of the drought prone areas of Northwest China (Pan and Chao, 2003), including the lower reaches of the Tarim River, which is China's longest inland river. The lower reaches of the Tarim River are a low-land flat region, which naturally accumulates salts transported from the upper river. Because of many years of inefficient irrigation and farming methods, soil salinization in the lower river oases is extreme. As a result of this soil salinity, the oases' ecological environment and sustainable agricultural development are severely affected.

Although soil salinization in the Tarim River Basin has attracted the attention of many scientific experts and researchers, most recent studies have focused on describing soil salinization spatial distribution, causes, and prevention methods (Liu and Tian, 2005; Feng *et al*., 2007; Fu *et al*., 2007). Few studies have yet to be carried out on the relationship between soil salinization and regional ecological environment and processes. Likewise, the qualitative and quantitative effects of surface water and groundwater on soil salinization in the ecohydrological cycle are also not well known. In this paper, the effects of surface water and groundwater on soil salinization were quantified based on the analysis of hydrological processes of the Tikanlik oasis ecosystem in the lower Tarim River. The objective of this study was to determine the optimal groundwater depth for sustainable development of oases, establish reference points for the rational utilization and improvement of land suffering from soil salinization, and accelerate the sustainable development of oasis systems in arid regions.

MATERIALS AND METHODS

Study area

The Tikanlik oasis (40°32′30″–40°45′30″E and 87°18′45″–89°48′47″N) is situated at the lower reaches of the Tarim River (Figure 1) in the Xinjiang Uygur Autonomous Region. The oasis stretches from Yuli County in the north to Ruoqiang County in the south, and the land is generally flat, with elevation decreasing from north to south. The region has an extreme desert climate. Annual precipitation varies between 17.4 and 42.0 mm, but the total annual potential evaporation ranges between 2500 and 3000 mm. Solar radiation measures from 5692 to 6360 MJ/m^2 annually, with cumulative daylight hours ranging from 2780 to 2980. Annual accumulative temperature $\geq$ 10 °C varies between 4100 and 4300 °C, with the average diurnal temperature ranging from 13 to 17 °C. Strong winds are common in the region.

The Tikanlik oasis is located in one of China's most arid zones. The soil there is either alkalized desert soil or salinized meadow soil. Shallow groundwater is mainly supplied from agricultural irrigation seepage. The dominant desert vegetation is characterized by drought-resistance, salt-tolerance, high-osmotic pressure, and small and thick leaves.

Upland cotton (*Gossypium hirsutum*) is the dominant crop in the region. From a total area of 1140.37 km^2, about 95% of arable land requires irrigation because of the prevalence of drought. The peak irrigation period for cotton crops is from June to August, when agricultural fields are irrigated with locally practiced watering rates via drip

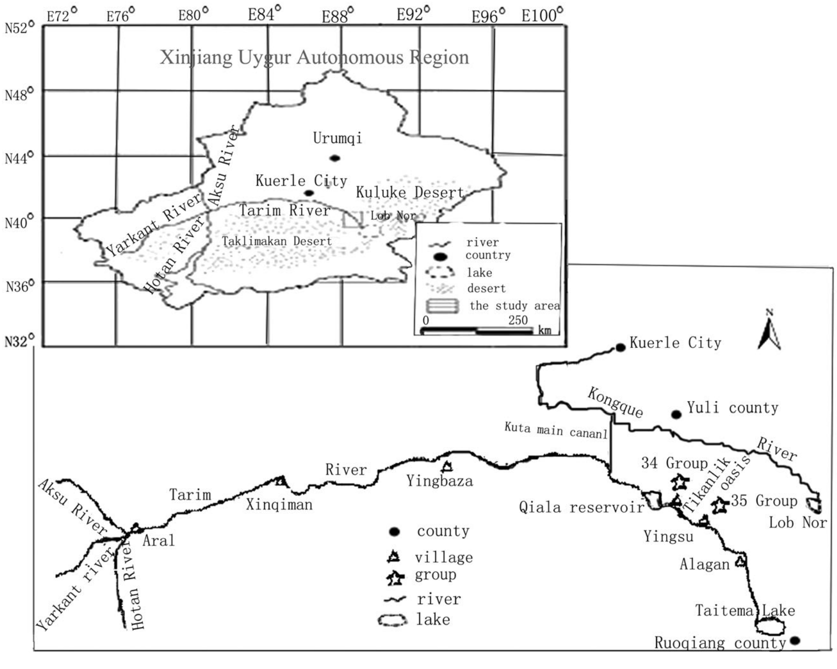

Figure 1. Sketch map of the study area.

irrigation and flood methods. Irrigation water comes mainly from the Tarim River, so large amounts of water from the upper river are diverted to irrigated lands, with the drainage water discharged back to the river. This process results in a continuous decrease in river water quality and higher salt loads to the downstream irrigated areas. Continued diversion of huge amounts of water in the upper river combined with low-irrigation efficiency has resulted in a rise in the groundwater table and an increase in soil and groundwater salinity in the oasis' irrigated areas. Hence, the salinity of the applied irrigation water as well as the depth and salinity of the groundwater are major sources of soil salinization in the affected region.

Measurements of groundwater depth and quality on a regional scale

We conducted measurements at 68 monitoring wells that were more or less evenly distributed across the area (Figure 2). Groundwater depth and quality measurements were conducted monthly in 2007, and a total of 816 groundwater samples were collected. Once obtained, the samples were immediately airproofed and then taken to the laboratory for analysis within 48 h. Total dissolved solids (TDS) in the groundwater were measured by weight, whereas concentrations of Cl^- were measured by using the standard colorimetric method with a microflux autoanalyser, SO_4^{2-} by volume, Ca^{2+} and Mg^{2+} by atomic absorption spectroscopy (Varian), and Na^+ and K^+ by flame emission spectroscopy (Varian). Additionally, pH was measured by a PHS-2C acidity meter, alkalinity, CO_3^{2-}, and HCO_3^- by the acid titration method, hardness by the Ethylenediaminetetraacetic acid volumetric method, and electrical conductivity (EC) using a DDS-307 conductivity meter.

Measurements of surface water (irrigation water) quality on a regional scale

The agricultural irrigation water used in the study area is mainly sourced from the Tarim River through the Qiala reservoir. An irrigation water sample was collected monthly from Qiala reservoir in 2007 and analyzed following the groundwater quality index measurements that previously mentioned.

Measurement of soil salinity on a regional scale

Close to each groundwater monitoring well, soil profiles were set for soil salinity by the gravimetric method. At each site, samples within the profile of 0–20, 20–50, and 50–100 cm were collected monthly, labeled, and stored in an aluminum box. Three soil samples were measured in each layer, and the average of the three samples was considered to be the representative moisture of this layer. A total of 7344 soil samples were collected at the same time as the groundwater investigation.

Measurement of salinity of groundwater, irrigation water, and soil on a field scale

Three farm fields were selected for observations of groundwater and irrigation water salinity and their influence on the soil salinization. These fields were located in the northern, western, and southern parts of Tikanlik and exemplified the region's agricultural land use systems with cotton. The fields were irrigated via drip irrigation during the growing season, with an irrigation depth of 50 cm and via flood in winter and spring to leach the soil salinity. Prior to sowing, the field soil moisture capacity in the 50–100 cm layer of soil reached 90%. In each field, a well was

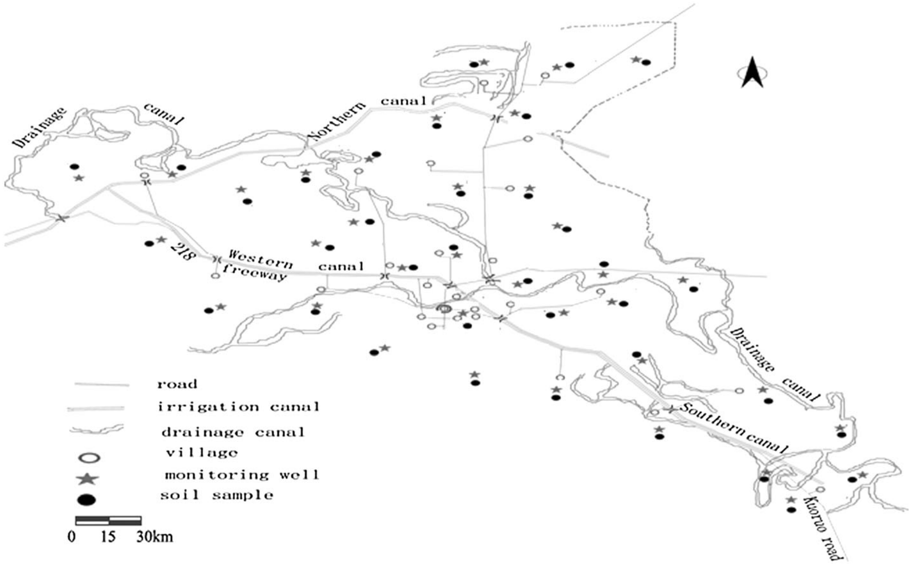

Figure 2. Groundwater monitoring wells distribution in the study area.

established to monitor groundwater depth and quality, and a soil profile was created to a depth of 100 cm to observe soil salinity.

The groundwater and soil observations at the selected sites were conducted in March and October. The March measurements provided background salinity levels in the fields and groundwater depths. Salt accumulation in the soil was assessed during the intensive irrigation in the growing seasons and outside the growing period. Soil salinity was measured during October in the 0–50 cm layer because drip irrigation only seeped to this soil depth. Compared with the groundwater depth measured in the three fields in March (2.12 m, 4.76 m, and 6.09 m, respectively), there was an average increase of 0.4 m in groundwater depths in October. There were six irrigation periods through the growing period, with an average irrigation rate of 600 m^3/hm^2. Irrigation water samples were collected to analyze the TDS in each irrigation period, with the average TDS considered to be the representative TDS of the irrigation water.

Statistical analysis

The relationship between surface water, groundwater, and soil salt content was analyzed by correlation analysis, and the relationship between the groundwater chemicals were analyzed by partial correlation analysis. The relationship between soil salt content and TDS was analyzed by curve estimation. All statistical analyses were performed using SPSS 13.0 (SPSS Inc., Chicago, Illinois, USA), giving a significant level of $p < 0.05$. Figures created using SigmaPlot 9.0 (Jandel Corporation, Las Vegas, NV, USA). Contour analyses were performed by Surfer 8.0 (Golden Software, Inc., Denver CO, USA).

RESULTS

Hydrological recycle process in oasis

An oasis is part of a mountain-oasis-desert system. Oases are formed between mountains and deserts, and their hydrological processes are closely related to those of both mountains and deserts (Xu *et al.*, 2005). Run-off from mountain watersheds converts into groundwater and surface water, which can also mutually exchange to a certain extent. When run-off arrives at an oasis, the oasis ecosystem becomes the major area in which water resources are developed, utilized, and depleted. The basic hydrological processes in the oasis ecosystem are presented in Figure 3.

Water resources in oases mainly include surface water (e.g. natural rainfall and irrigation water) and groundwater. The lower reaches of the Tarim River features a typical continental climate of extreme dryness and strong evaporation. Long-term average annual precipitation (50 mm) is exceeded many times over by the annual potential evaporation and does not have a significant influence on either surface water or groundwater. Therefore, water recycling in the study area is achieved via the mutual recycling processes of groundwater and irrigation water.

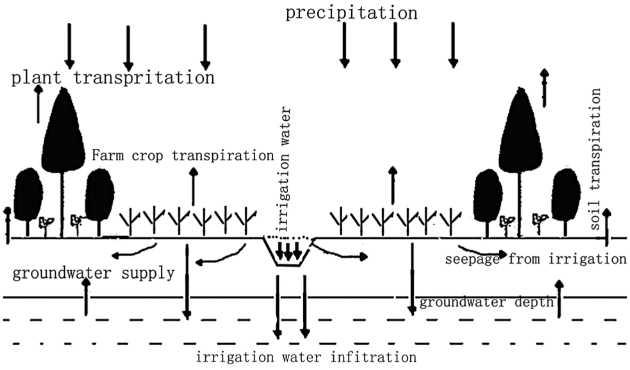

Figure 3. Hydrological recycle in oasis ecosystem.

Irrigation of the area's water-intensive crops and seepage from the canal network are the primary groundwater sources. The groundwater then contributes to the soil water of the unsaturated zone through capillarity, and vegetation absorbs the soil water through their root systems. With vegetation continuing the transpiration, groundwater constantly contributes to the soil water. Simultaneously, it accompanies the phreatic evaporation of bare soil and the evaporation of channels and waters. Subsequent run-off, together with surface water, converts to groundwater and soil water, which maintain the natural vegetation in the desert. With constant evaporation and leakage, the water finally forms a lake or disappears in the desert.

Surface water characteristic and its relationship with soil salinization

Change of annual irrigation water quality. The irrigation water in the study area is primarily sourced from the Tarim River via the Qiala reservoir. Results from the annual irrigation water quality analysis found that the primary hydrochemical types of the irrigation water in the oasis were SO_4, Cl, HCO_3-Na, Mg, and Ca. Both CO_3^{2-} and K^+ had very low concentrations in the irrigation water. For the relationships between TDS and EC, the concentrations of HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Na^+ showed significant positive correlations (Table I). The value of TDS slowly decreased in January, but began to increase in March and peaked in April. Subsequently, it decreased after April and increased again in June, before demonstrating a second peak in July. After July, it slowly decreased again and reached a minimum value in October before once again increasing. The average value of TDS was 2–3 g $.L^{-1}$, the maximum value presented in April was 4.14 $g.L^{-1}$, and the minimum value presented in October was 1.58 $g.L^{-1}$. The magnitude of change between the maximum and minimum values was 364.31% (Figure 4a). The annual changes of EC, HCO_3^-, Cl^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and Na^+

Table I. Correlation analysis of irrigation water quality.

		EC	pH	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+
TDS	P.	0.9849	−0.113		0.8909	0.9944	0.879	0.8586	0.9827	0.998	
	Sig.	0.0000	0.7262		0.0001	0	0.0001	0.0003	0.0000	0.0000	

TDS, Total dissolved solids

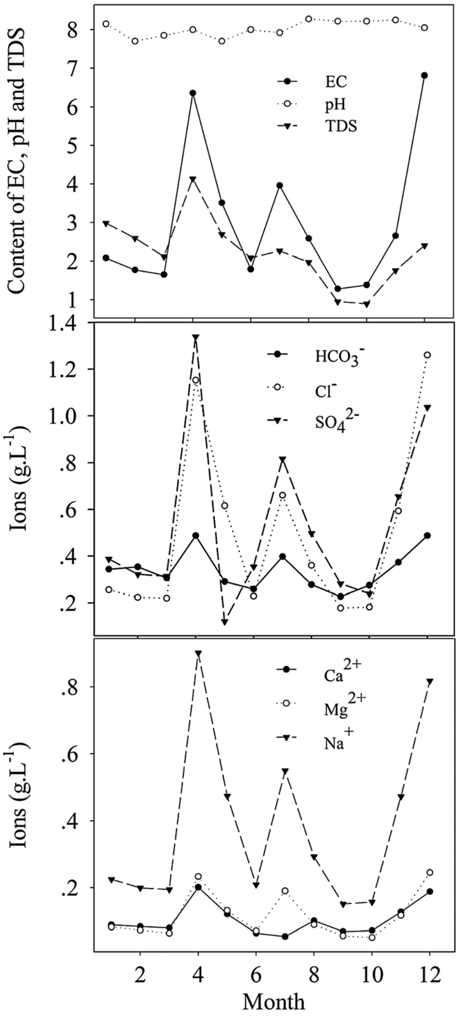

Figure 4. Annual variations in surface water chemistry.

showed a basically consistent and similar decrease in TDS, the biggest changes being 393.48%, 114.98%, 608.43%, 907.44%, 272.22%, 380.39%, and 497.35%, respectively (Figure 4a, b, and c). There was no significant correlation between TDS and pH ($P > 0.05$), and the pH showed stable alkalescency (Figure 4a). The maximum and the minimum pH values were observed in August and February respectively, and the magnitude of changes between them was 8.24%.

Relationship between total dissolved solids of irrigation water and soil salinity. Changes in TDS are representative of general water chemistry variation (Chen *et al.*, 2007). The correlation relationship among TDS of the irrigation water and soil salinity within the 0–20 cm, 20–50 cm, and 50–100 cm soil layers decreased with increasing soil depth. The TDS of the irrigation water mainly affected soil salinity within the 0–50 cm soil layer, and the relationship between TDS and soil salinity in the 0–50 cm soil layer showed a significantly positive correlation ($P < 0.05$). The correlation was not statistically significant when soil depths were greater than 50 cm (Table II).

Groundwater depth and salinity distribution

Because of the essential contribution of groundwater to soil salinization, it was important to identify the areas in the study region where groundwater was particularly shallow or saline. The results from contour analysis with surfer 8.0 revealed that groundwater depth distribution changed with irrigation intensity because water from irrigation and seepage from the principal canal network are the primary sources of the groundwater in the Tikanlik oasis. Before cropping in March, groundwater depths were deeper because of scant irrigation (Figure 5a). The average groundwater depth was 4.52 m, and the minimum and maximum values were 2.12 and 8.92 m, respectively. In contrast, groundwater depths become shallower during the intensive irrigation cropping period (July) (Figure 5b). During that time, the average groundwater depth was 3.58 m, a reduction of 0.94 m compared with before cropping.

Interestingly, there was strong similarity between the spatial patterns of groundwater depths during the intensive and non-intensive irrigation periods, with groundwater depths shallower in the oasis' north and mid-west and deeper in the south, even in March when very little irrigation occurs. This is consistent with the distribution of arable land and irrigation networks in the region, with arable land mainly situated in the northern and mid-western areas of Tikanlik. Corresponding to the distribution of arable land, there are three main arterial canals, specifically the western, northern, and southern canals, which form the irrigation network in the Tikanlik oasis. The northern and western canals are the primary irrigation canals, and the southern canal is the subsidiary canal.

Similar to the spatial distribution pattern of the groundwater depth, average groundwater salinity was more pronounced in the northern and mid-western parts of the region ($P < 0.05$, Figure 6). Figures 5 and 6 show that the majority of these areas

Table II. Relationship between total dissolved solids in surface water and soil salt content.

		TDS in surface water	Soil salt content in 0–20 cmlayer	Soil salt content in 20–50 cm layer	Soil salt content in 50–100 cm layer
TDS in surface water	P.	1	0.9869	0.9990	−0.5216
	Sig.		0.0030	0.0273	0.6506
Soil salt content in 0–20 cm	P.	0.9869	1	0.9929	−0.3773
	Sig.	0.0030		0.0756	0.7536
Soil salt content in 20–50 cm	P.	0.9990	0.9929	1	−0.4845
	Sig.	0.0273	0.0756		0.6779
Soil salt content in 50–100 cm	P.	−0.5216	−0.3773	−0.4845	1
	Sig.	0.6506	0.7536	0.6779	

TDS, Total dissolved solids

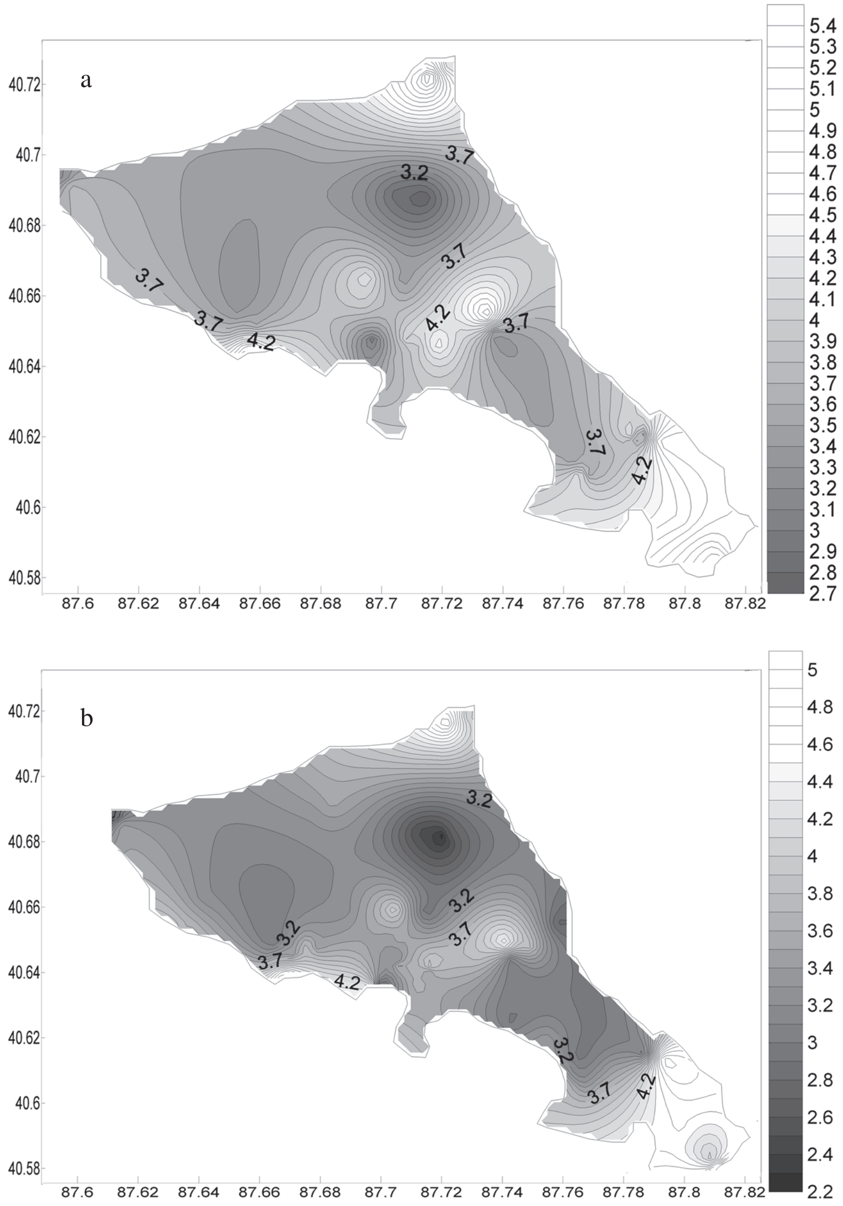

Figure 5. Groundwater depth distribution in the study area. (a) groundwater depth distribution before cropping and (b) groundwater depth distribution during the intensive irrigation.

Table III. Partial correlation analysis of groundwater chemical compositions.

	alkalinity	Hardness	PH	pC	TDS	Total salt	HCO_3^-	Cl^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+
alkalinity	1.0000												
Hardness	−0.2228	1.0000											
pH	−0.3517	−0.4398	1.0000										
EC	0.0710	0.7124*	−0.3541	1.0000									
TDS	−0.0079	0.9581**	−0.5097	0.8537**	1.0000								
Total salt	0.0455	0.9234**	−0.5077	0.9020**	0.9939**	1.0000							
HCO_3^-	1.0000**	−0.2237	−0.3506	0.0696	−0.0090	0.0443	1.0000						
Cl^-	−0.0362	0.9510**	−0.4882	0.8824**	0.9969**	0.9956**	−0.0374	1.0000					
SO_4^{2-}	0.0912	0.9074**	−0.5194	0.9010**	0.9895**	0.9980**	0.0900	0.9885**	1.0000				
Ca^{2+}	−0.2211	0.7755*	−0.2294	0.9410**	0.8412**	0.8678**	−0.2223	0.8706**	0.8576**	1.0000			
Mg^{2+}	−0.1751	0.9209**	−0.4740	0.4161	0.8217*	0.7569*	−0.1756	0.7936*	0.7407*	0.4680	1.0000		
Na^+	0.1199	0.8775**	−0.5158	0.9292**	0.9771**	0.9943**	0.1186	0.9815**	0.9959**	0.8664**	0.6934	1.0000	
K^+	0.0899	0.6650	−0.3237	0.8963**	0.8013*	0.8392**	0.0889	0.8079*	0.8573**	0.8971**	0.3772	0.8585**	1.0000

TDS, Total dissolved solids; EC, Electrical conductivity
*, **Correlation is significant at the 0.05 level and 0.01level, respectively

experienced shallower groundwater depths (2.5–4.5 m) and had salinity ranging between 2.50 and 4.80 g.L^{-1}.

Groundwater characteristics and their relationship with soil salinization

Correlation analysis of the chemical composition of groundwater. Because the chemical characteristics of groundwater change with depth, partial correlation analysis was used to analyze the relationships among the chemical compositions of groundwater in the oasis, controlling for groundwater depth (Table III). Results showed that although the correlation between total alkalinity and HCO_3^- was significant, it was not notable with other chemical compositions. This suggests that groundwater alkalinity mainly resulted from bicarbonate. Strong positive correlations were also observed between hardness and Mg^{2+} and Ca^{2+}. Thus, groundwater hardness in the oasis resulted primarily from high concentrations of Mg^{2+} and Ca^{2+}. The average pH value changed in the range from 7 to 8, which was relatively stable and related to the lack of CO_3^{2-} and HCO_3^- in the groundwater. There were significant correlations between EC and all measured ions, with the exception of HCO_3^- and Mg^{2+} because of their very low concentrations in the groundwater. The relationships among TDS and Cl^-, SO_4^{2-}, Ca^{2+}, and Na^+ showed a significantly positive correlation. This suggests that the chemical composition of the groundwater mainly consisted of Cl, SO_4-Na, and Ca. The correlations among total salt content of groundwater and Cl^-, SO_4^{2-}, and Na^+ were the highest, followed by Ca^{2+}, suggesting that the primary salts in groundwater were Na_2SO_4 and NaCl, followed by $CaCl_2$ and $CaSO_4$.

Relationship between groundwater chemical characteristics and groundwater depth. All measured chemical characteristics changed with groundwater depth (Figure 7). Alkalinity, hardness, EC, TDS, and total salt showed only small changes when groundwater depths were less than 6 m; however, alkalinity, hardness, TDS, and total salt increased rapidly when groundwater depths exceeded 6 m, the magnitude of the increase increasing with groundwater depth. Similarly, the pH fluctuated unsteadily when groundwater depths were less than 6 m, but decreased sharply when depths were greater than 6 m. From these findings, we can see that groundwater quality changed markedly when groundwater depths exceeded 6 m, especially TDS and total salt, which both increased significantly at depths greater than 6 m. This suggests that 6 m was groundwater's critical threshold depth for higher salinity accumulation.

Effects of groundwater characteristics on soil salinity. Because of the region's lower surface relief, the soil in the Tikanlik oasis has higher accumulated salinity from the upper river water of the Tarim River. In our study, and as shown in Figure 8, soil salinity was closely related to

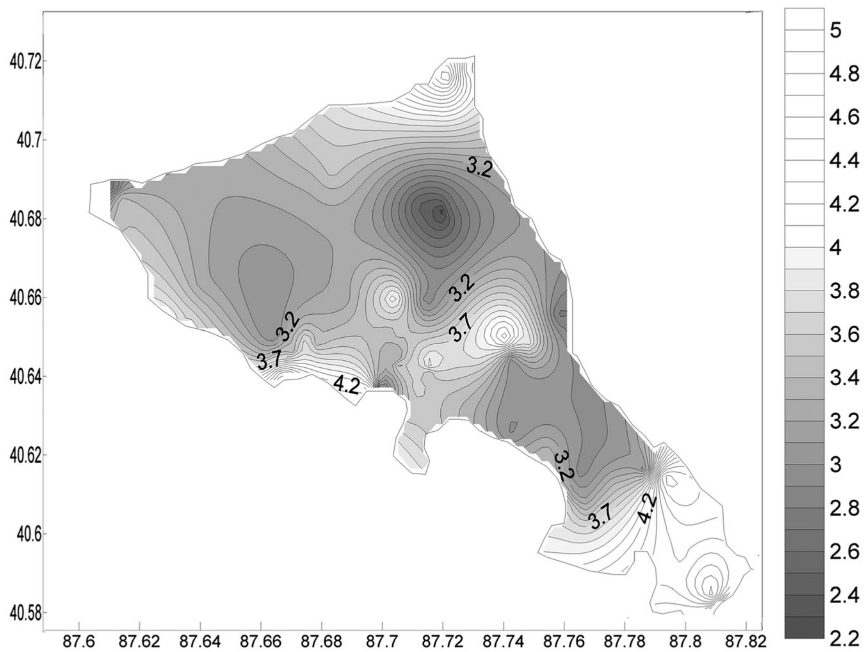

Figure 6. Annual average total dissolved solids in groundwater distribution in the study area.

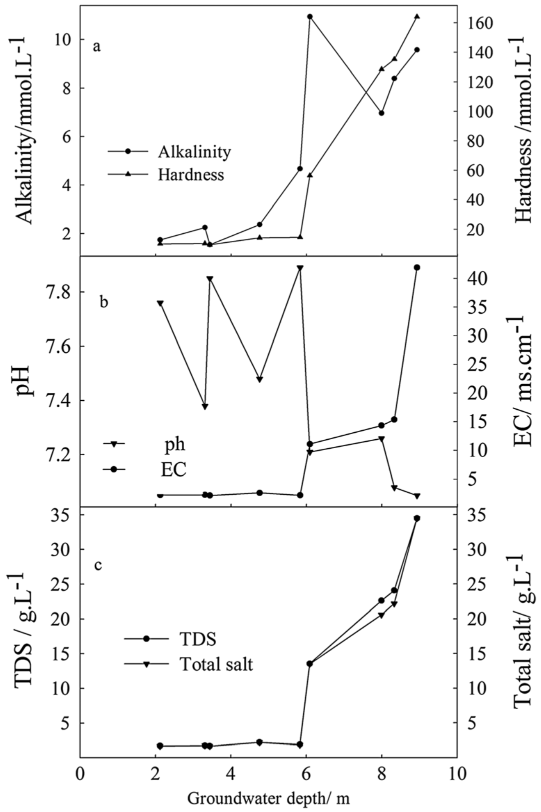

Figure 7. Change in groundwater chemical composition with groundwater depth increased in the study area.

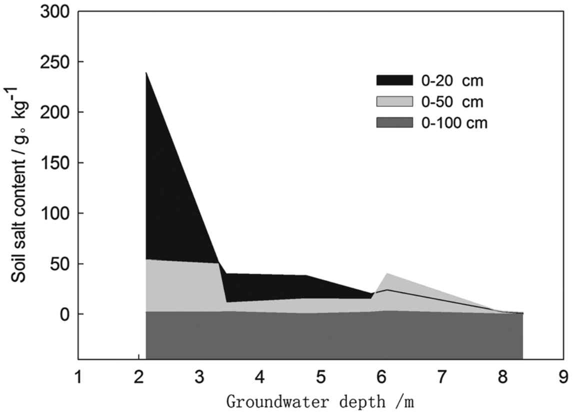

Figure 8. Relationship between soil salt content and groundwater depth in the study area.

groundwater depth, such that groundwater depth increased as soil salt content decreased. The magnitude of decrease in salt content in the 0–20 cm soil layer was the largest, followed by the 20–50 cm soil layer, and finally by the 50–100 cm soil layer. The correlation coefficients between groundwater depth and total salt in the 0–20 cm, 20–50 cm, and 50–100 cm soil layers was 0.7439, 0.7401, and 0.6374, respectively ($P < 0.05$). When groundwater depth changed in a range from 2–6 m, total salt in the oasis soil was high. The results showed that higher soil salinity content tended to accumulate on the surface layer and then decreased with deeper soil profile depths, i.e. total salt was much higher in the 0–20 cm soil layer than in the 20–50 cm soil layer. This suggests that total soil salt showed a 'T' distribution, which changed in the order 0–20 cm > 20–50 cm > 50–100 cm when groundwater depths were less than 6 m.

However, total salt in the oasis soil sharply decreased when groundwater depths exceeded 6 m. For example, total salt content in the 0–20 cm soil layer decreased rapidly from 239.12 g.L^{-1} at a groundwater depth of 2.12 m to 24.26 g.L^{-1} at a groundwater depth of 6.09 m and continued to decrease to 0.19 g.L^{-1} when the groundwater depth increased to 8.33 m. In contrast, total salt in the 20–50 cm soil layer increased as groundwater depth increased. This demonstrated that total salt in the soil showed a 'rhombus' distribution, which changed in the order 20–50 cm > 0–20 cm > 50–100 cm when groundwater depths were greater than 6 m.

The change in groundwater salinity was the result of soluble salts exchanged between soil and groundwater as groundwater depths changed. Figure 9 illustrates the relationship between the TDS in groundwater and soil total salt. The TDS in the groundwater showed an exponential relationship with total salt content in the 0–20 cm, 20–50 cm, and 50–100 cm soil layers ($P < 0.05$).

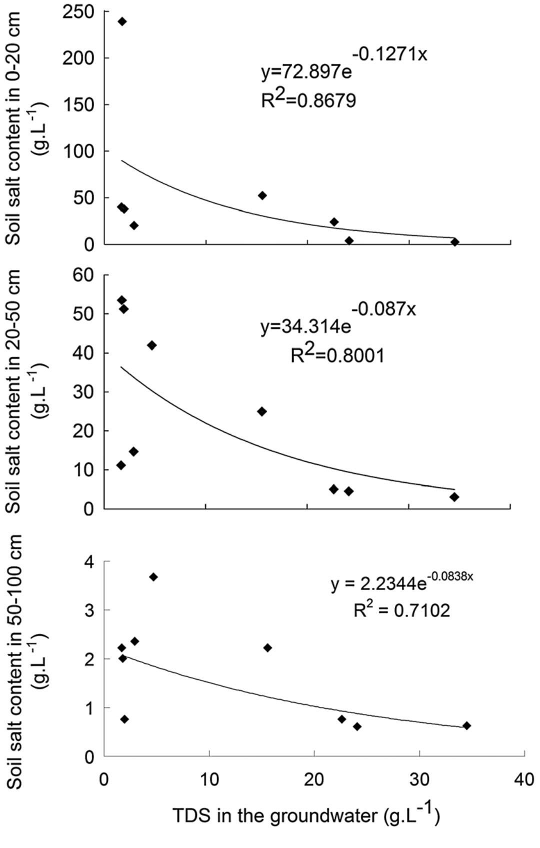

Figure 9. Relationship between total dissolved solids in groundwater and soil salt content in the study area.

Salt contribution from irrigation and groundwater

Because the quantity of salt added to the water is dependent on the amount and salt concentration of the water, the water-salt balance can be calculated by the input of salt to the soil profile from irrigation and groundwater (Ibrakhimov *et al*., 2007). In this paper, we used the soil water-salt balance model (Li and Li, 1998), which only considered water-salt movement in a vertical direction, to quantify the salt loads in soil that originated from irrigation water and groundwater. The formula can be expressed as follows:

$$\Delta S = S_r + S_i + S_g + S_s + S_f - S_c - S_p - S_d \tag{1}$$

$$\Delta S = S_2 - S_1 \tag{2}$$

where ΔS is the soil load change at a certain depth in a certain period, S_1 is the soil salt load at the start, S_2 is the soil salt load at the end, S_r is the salt load originating from precipitation, S_i is the salt load originating from irrigation, S_g is the salt load originating from groundwater, S_s is the salt load originating from the dissolving, absorption, and conversion processes, S_f is the salt load originating from fertilizer, S_c is the salt load entrained by crop absorption, S_p is the salt load entrained by the deposition, absorption, and conversion processes, and S_d is the salt load entrained by groundwater drainage or seepage.

In the study area, S_r can be ignored because of the very low-annual precipitation (<50 mm), S_c can be ignored because the ash content absorbed by cotton is less than 5% of biomass, S_d can be ignored because drip irrigation has little effect on surface run-off and seepage, and S_p, S_f, and S_s can be also ignored because of their very limited impact. Therefore, the soil salt-water balance model can be simplified as follows:

$$\Delta S = S_2 - S_1 = S_i + S_g \tag{3}$$

According to the simplified salt-water model, the increased volume of soil salt loads originated in irrigation and groundwater contributions. Field irrigation is primarily supplied by the Tarim River through the Qiala reservoir, so average annual TDS in the water of the Qiala reservoir was considered representative of the irrigation water, i.e. the volume of TDS was 2.24 g.L^{-1}. Because drip irrigation only infiltrated to a soil depth of 50 cm, we assumed that all salt loads originating from irrigation resided in the plough horizon, if the water-salt horizontal direction of movement was ignored. The increased volume of salt loads in the soil was the difference between salt loads in the soil before sowing and after harvesting.

The water-salt balance of soil in the cotton fields at different groundwater depths is presented in Table IV. The results show that salt loads from the water were closely related to groundwater depth. When groundwater depth was relatively shallow (2.12 m), large amounts of salt were added to the 0–50 cm soil layer from the water, of which the increased volume of salt loads

Table IV. Balance of soil salt in 0–50 cm layer of cotton fields.

Groundwater depth (m)	Before breeding (kg. hm^{-2})	After harvest (kg. hm^{-2})	Total salt accumulation (kg. hm^{-2})	Slat originated from surface water (kg. hm^{-2})	Slat originated from groundwater (kg. hm^{-2})
−2.12	37835.2	121176	83340.8	8046	75294.8
−4.76	26554	59336.8	32782.8	8046	24736.8
−6.09	15395.2	30600	15204.8	8046	7158.8

in the 0–20 cm layer explained more than two thirds of the total increased salt loads in the 0–50 cm layer. However, as groundwater depths increased, salt loads that had accumulated in the 20–50 cm layer likewise gradually increased. The added salt loads in the 20–50 cm layer were larger than those in 0–20 cm layer when groundwater depth increased to 6.09 m.

Differences were observed in the salt contribution originating from irrigation water and groundwater at different groundwater depths. When the groundwater depth was 2.12 m, the salt contribution from the irrigation water only explained 9.65% of the total added salt loads in the soil. The salt contribution increased to 24.54% when groundwater depth increased to 4.76 m and more than doubled to 52.92% when groundwater depth increased to 6.09 m. In contrast, the salt contribution of the groundwater explained more than 90% of the total added salt loads in the soil when groundwater depth was 2.12 m. As groundwater depths increased, the salts originating from the groundwater gradually decreased because of weaker capillarity. When groundwater depth increased to 6.09 m, salts originating from groundwater only accounted for 47.08% of all increased salt loads in the soil.

DISCUSSION

Studies on hydrological processes are important for understanding the principle sources of secondary soil salinization, which are a major cause of degradation in irrigated lands worldwide (Jalali, 2007). Because of the scarcity of rainfall in arid zones, hydrological processes in oasis ecosystems are mainly related to irrigation and groundwater (Ye *et al.*, 2007). Therefore, among the major sources of secondary soil salinization in oasis ecosystems are the salinity of applied irrigation water and the groundwater (Ibrakhimov *et al.*, 2007).

Our analyses showed that the quality of irrigation water sourced from the Tarim River demonstrated regular annual changes. Peak TDS in irrigation water was observed in April, June, and November, which is consistent with the growing period of local crops and the irrigation methods used in the upper river (Li *et al.*, 2005). April marked the beginning of the growing season in the oasis, when large amounts of river water were diverted for irrigation to flush salts from the soil before planting. At the same time, drainage water in the upper river discharged back to the river, resulting in a continuous decrease in river water quality and higher salt loads in the downstream irrigated areas. June marked the peak period for cotton irrigation. In this period, greatly increased irrigation and high rates of evaporation were the principle causes of TDS increases in river water. Irrigation gradually decreased until November, when huge amounts of river water were used to flood the fields for salinity mitigation post-harvesting, after which the drainage water was discharged back to the river once again, causing the volume of the TDS in the river water to increase.

Irrigation water quality is closely related to total salt content of the soil (Ma *et al.*, 2008). Correlation analysis showed that there was a significant positive correlation between the TDS in irrigation water and total salt in the 0–50 cm layer of soil, (especially the 0–20 cm soil layer), but there was no significant correlation in the 50–100 cm layer of soil. This suggests that salt loads originating from irrigation were mainly accumulated in the plough horizon (0–50 cm soil layer), which is consistent with the previous research (Liu and Tian, 2005).

Salinization from groundwater occurs when groundwater depth reaches a certain threshold, above which it rises by capillarity (Hillel, 2000). Moreover, the magnitude and distribution of salts in groundwater, as well as, the chemical characteristics of the water, affect the extent of soil salinization (Wang *et al.*, 2008). In the studied oasis, the groundwater was relatively deep, with the shallowest average groundwater depth located at 2.12 m below the surface. Different groundwater types were chemically dominated by Cl, SO_4- Na, and Ca, and the main salts found in the groundwater were Na_2SO_4 and NaCl.

Our analysis showed that the relationship between groundwater chemical compositions and groundwater depth was significant. When groundwater depth was less than 6 m, the volume of alkalinity, hardness, EC, TDS, total salt, and pH in groundwater did not fluctuate significantly over the year. However, the EC, TDS, total salt content, and all other measured chemicals in the groundwater increased sharply when groundwater depth was greater than 6 m. This suggests that, in the Tikanlik oasis, 6 m was the threshold level, below which groundwater quality sharply decreased, and large salt loads were accumulated.

Analyses of the relationship between groundwater depth and soil salt content indicated that the soil salt content was high with high-surface concentration and decreased with increasing soil depth in the order 0–20 cm > 20–50 cm > 50–100 cm, giving a 'T' distribution when groundwater depth was relatively shallow. However, soil salt loads decreased as groundwater depths increased. This displayed a 'rhombus' distribution, which was mainly accumulated in the middle layer in the order 20–50 cm > 0–20 cm > 50–100 cm, as groundwater depth increased. These results are consistent with research on the influence of intermittent water deliveries on the hydrochemistry of soil in the lower Tarim River (Chen *et al*., 2007). Additionally, Ye *et al*. (2007) concluded that the critical phreatic water depth is 5 m, below which the evaporation of phreatic water ceases and groundwater cannot effectively uprise into the soil. Likewise, when groundwater depth goes beyond the critical phreatic water depth, the salts in groundwater cannot move up to the surface soil via capillarity. Therefore, in the present study, 6 m was the critical groundwater level below which salt accumulation processes in the surface soil ceased.

Although many water-salt balance models have been proposed, few can be widely applied for the quantification of salt loads originating from groundwater and irrigation water because of the complexity of the salt-water movement, and the large number of parameters which are difficult to determine (Lin and Dilbar, 2007). Consequently, quantitative research on soil salinization in hydrological processes has been rather limited to date. In this paper, for quantification of salt loads originating from the groundwater and irrigation water, we assumed that the amount of salinity from irrigation water totally resided within the 0–50 cm soil column and ignored the horizontal motion of salt-water movement. Therefore, salt accumulation in soil (i.e. the difference between soil salt content before cropping and after harvesting) was the contribution from groundwater and irrigation water. Calculation results showed that the salinity of the applied irrigation water, as well as, the depth and salinity of the groundwater, jointly determined soil salt accumulation. When the groundwater depth was shallow (2.12 m), more than 90% of soil salt accumulation was estimated in the 0–5 cm soil column as a result of groundwater contribution, which was the decisive factor for soil salt accumulation. However, for the proportion of salts supplied by irrigation in the 0–50 cm layer, soil salt accumulation increased as groundwater depth increased. Salt loads from the irrigation water accounted for 52.92% of total soil salt accumulation in the 0–50 cm soil column when groundwater depth increased to 6.09 m.

CONCLUSIONS

The following conclusions may be drawn from our study:

1. Salt loads originating from the irrigation water were mainly accumulated in the plough horizon in the study area. Results from an analysis of the water-salt processes in the lower Tarim River oasis showed that the TDS in irrigation water and soil salt loads in the 0–20 and 20–50 cm layers were significantly positively correlated, with correlation coefficients of 0.9869 ($P < 0.01$) and 0.9990 ($P < 0.05$), respectively. However, there was no statistically significant correlation between the TDS in irrigation water and the 50–100 cm layer soil total salt, which may be related to the irrigation methods used in the study area.
2. Groundwater quality was closely related to groundwater depths in the lower Tarim River oasis. When groundwater depths were less than 6 m, the pH, alkalinity, hardness, EC, TDS, and total salt in groundwater showed little change. However, when groundwater depths exceeded 6 m, the chemical composition of the groundwater exhibited a marked change and the volume of EC, TDS, and total salt in groundwater increased rapidly. Therefore, it was concluded that 6 m was the threshold below, which groundwater quality sharply decreased, and large salt loads were accumulated in Tikanlik oasis groundwater.
3. The distribution and volume of soil salt was affected by groundwater depth in the Tikanlik oasis. When groundwater depth was relatively shallow, soil salt loads were high and showed a 'T' distribution, which suggested that a higher salinity content tended to accumulate on the surface layer in the order 0–20 > 20–50 > 50–100 cm . As groundwater depth increased, soil salt loads decreased and showed a 'rhombus' distribution, which was accumulated mainly in the middle layer in the order 20–50 > 0–20 > 50–100 cm . We found that the change in the distribution of soil salt loads occurred at the 6 m groundwater depth because of weak capillarity, i.e. the salinity originating from the groundwater could not move to the surface soil via capillarity with water because the groundwater was too deep. This suggested that 6 m was also the critical threshold level, below which salt accumulation in the surface soil stopped.
4. The salt accumulated in soil from irrigation water and groundwater changed with groundwater depth. Using the simplified water-salt balance model, we demonstrated that the salt loads brought indirectly by groundwater through capillarity accounted for more than 90% of the soil salt accumulation in the 0–50 cm soil layer when groundwater depth was shallow (2.12 m). However, the soil salt content in the 0–50 cm layer contributed by groundwater decreased as groundwater depths increased. In contrast, the salt accumulated in the 0–50 cm soil layer brought directly by irrigation water continued to increase as groundwater depths increased. This suggested that, in the Tikanlik oasis, salt accumulation in the 0–50 cm soil layer was determined by the volume of TDS in groundwater when the groundwater depth was shallow, but was determined by the volume of TDS in irrigation water when groundwater depths increased.

ACKNOWLEDGEMENTS

The research in this study was supported by the National Natural Science Foundation of China (Grant No. 41271006, 91025025 and 40901061), Projects of West Light Foundation of the Chinese Academy of Sciences (No. XBBS201008) and China Scholarship Council.

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