

The spatio-temporal variability of groundwater depth in a typical desert-oasis ecotone

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Eight groundwater observation wells were installed along the river plain, where the landscapes varied from floodplain, to oasis farmland, to desert-oasis ecotone to desert, in a typical desert-oasis ecotone in northwestern China. Ten years of data were used to analyze temporal and spatial changes in the groundwater depth. The results indicated that in the last decade: (1) the groundwater depths in the floodplain (GW1) and the desert (GW8) were basically stable; (2) the groundwater depths in the oasis farmland (GW2, GW3, GW4) increased dramatically: the annual fluctuations were 1.43, 1.01 and 0.79 m respectively, with the groundwater depths increasing by 0.13–0.18 m every year; (3) the groundwater depths in the desert-oasis ecotone (GW5, GW6, GW7) also increased dramatically: the annual fluctuations were 1.10, 1.06 and 1.05 m respectively, and the depths increased by 0.10–0.15 m every year; (4) the influence distance between the river and both the farmland and the desert-oasis ecotone was about 1000–2000 m in the study area. These results show that the natural seasonal fluctuation influence on groundwater depths was not significant, but the human-induced fluctuations such as intensive irrigation caused a significant increase in groundwater depth in both the farmland and the desert-oasis ecotone, seriously affecting sustainable agriculture development and the environment, in the oasis.

1. Introduction

Groundwater, which contains by far the largest volume of unfrozen fresh water on Earth, is a very important natural resource. It smooths out variations in water quality and prevents a portion of stored water from being susceptible to sudden disasters. It also allows long dry periods to be bridged and generally reduces the risk of temporary water shortages. Because of its stable quantity and high quality, groundwater is the major source of drinking water for nearly half the world's population, sustaining streams, lakes, wetlands, and aquatic communities, and also supporting economic development and agricultural irrigation worldwide

(Alley *et al.* 2002; WWAP 2009). In arid regions, especially, groundwater resolves spatial and temporal disconnects between water supply and demand, and allows us to plant crops and develop agriculture.

Despite its importance to our life and production, groundwater is vulnerable to climate change and intensive human activities (Taniguchi and Holman 2010; Green *et al.* 2011). Siebert (2010) studied groundwater irrigation worldwide and found that groundwater depths increased dramatically as the utilization ratio of groundwater rose. Scanlon *et al.* (2012) pointed out that groundwater would be unable to support irrigation in the southern High Plains within the next 30 years, at the current extrapolated depletion rate. Water

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deficit is becoming a serious problem, and groundwater has become an increasingly important source of irrigation water (Oki and Kanae 2006). In the Heihe River Basin in northwest China, the dynamics of the rivers have changed; they are now dominated by artificial, rather than natural, water regulation, while at the same time, the overexploitation of artificial oases has led to the disappearance of natural ones. The consumption of groundwater has increased greatly because of rapid agricultural development. Farmlands, urban areas, water bodies and vegetation have all experienced dramatic changes. Agricultural development has caused water use patterns, irrigation water reuse rates and the seasonality of water resource availability in these areas to change dramatically (Cheng *et al.* 2014).

As a consequence, a series of ecological problems have arisen, including vegetation degradation, soil salinization, desertification, serious drops in groundwater levels and frequent sandstorms (Gao *et al.* 2004; Li and Zhao 2004). In order to restore the deteriorated ecological environment, an ecological water conveyance project (EWCP) was implemented in 2000. Recently, some studies have begun to show that the degradation of the ecological environment in the lower reaches of the river has been controlled since the implementation of the artificial water-transfer project (Liu and Zhao 2010; Ao *et al.* 2012). However, as large amounts of surface water of the Heihe River have been transferred from the upper-middle reaches to the lower reaches, the available surface water for irrigation in the middle reaches has sharply decreased from $9.20 \times 10^8 \text{ m}^3/\text{a}$ in 1990s to $7.26 \times 10^8 \text{ m}^3/\text{a}$ in 2000s (Chen 2006). In response to this situation, groundwater has become an increasingly important water resource for irrigation in the area, and there is tremendous pressure to exploit it, with the exploitation amount rising dramatically year after year.

A desert-oasis ecotone is typically located between an oasis and the desert, as a narrow belt between them. The ecotone plays a prominent ecological role that far exceeds its physical extent, such as ensuring oasis ecological security, maintaining internal oasis stability, and controlling the flux of energy and nutrients, as well as being a biotic exchange between desert and oasis (Wang *et al.* 2007). Despite its important role for the oasis environment, an ecotone is very sensitive to human activities such as groundwater exploitation (Jiang and Liu 2009; Zhao *et al.* 2009; Liu and Zhao 2010; Ao *et al.* 2012). These special ecosystems, populated mainly with natural vegetation in the desert itself, artificial sand-fixing vegetation in the desert-oasis ecotone, and agricultural crops in the oasis, are internally controlled, and interact with shallow groundwater because of the scarce precipitation in these arid

areas. The ecological carrying capacity of water resources in this area is quite limited and the ecosystems are very fragile. As the most reliable water resource, groundwater has the capacity to balance large swings in precipitation during droughts; it is also helpful when surface-water resources reach the limits of irrigation in the oasis. Despite its critical value, the quantity and quality of groundwater in these areas have been rapidly deteriorating because of the intense and large-scale overexploitation of groundwater resources in recent decades. Therefore, groundwater assessment is becoming more and more important. Studying the dynamics of the changes in groundwater depth is an important method for thoroughly understanding the impact of human activities on the trends of, and variations in, groundwater depth (Zhang *et al.* 2009; Zhang and Yan 2010). Monitoring and evaluation of the changes in groundwater in this sensitive area, however, is lagging far behind what is necessary.

This study reports about the changes in groundwater depths in the midstream area of the Heihe River Basin, northwest China – an area representative of oasis-desert ecotones in arid regions. This area can be seen as a natural laboratory for research into desert-oasis ecotone dynamics. We assessed the temporal and spatial changes in groundwater depth for the various landscapes in this study area – floodplain, oasis farmland, desert-oasis ecotone and desert – to answer the following questions: (i) How did the level of groundwater change in various landscapes? (ii) What are the reasons for these changes? (iii) How does groundwater respond to different exploitation intensities in different landscapes? Answers to these questions will contribute to our understanding of the dynamics of groundwater in desert-oasis ecotone regions.

2. Field site and methods

2.1 Field site

The study area, covering the Pingchuan marginal oasis ($39^\circ 21' \text{N}$ and $100^\circ 21' \text{E}$, at 1367 m above mean sea level a.m.s.l.), Linze County in Gansu Province, is located in a typical oasis-desert ecotone at the southern edge of the Badain Jaran Desert. The area has a typical temperate desert climate: dry and hot in summer, cold in winter, very little precipitation and high evaporation, strong winds and frequent drifting sands. The annual mean air temperature is 7.6° , with an absolute maximum of 39.1° in summer and an absolute minimum of 27° in winter. The annual mean precipitation is 117 mm, which occurs mostly during July and August. Because of sparse rainfall and high variability, little perennial runoff originates from this area. The annual mean potential evaporation is 2390 mm.

The frost-free season is about 165 days. The mean annual wind velocity is 3.2 ms^{-1} and the prevailing wind direction is northwest. Gales with wind velocity above 17 ms^{-1} occur mainly in spring for about 15 days per year. The main soil types are Arip-samment and Calciorthids, with loose structure and low organic matter, and are very susceptible to wind erosion. The landscapes in the study area change along the river from floodplain, to oasis farmland, to desert-oasis ecotone to desert. The groundwater depths vary over the different landscapes, ranging from 0.8 to 12 m.

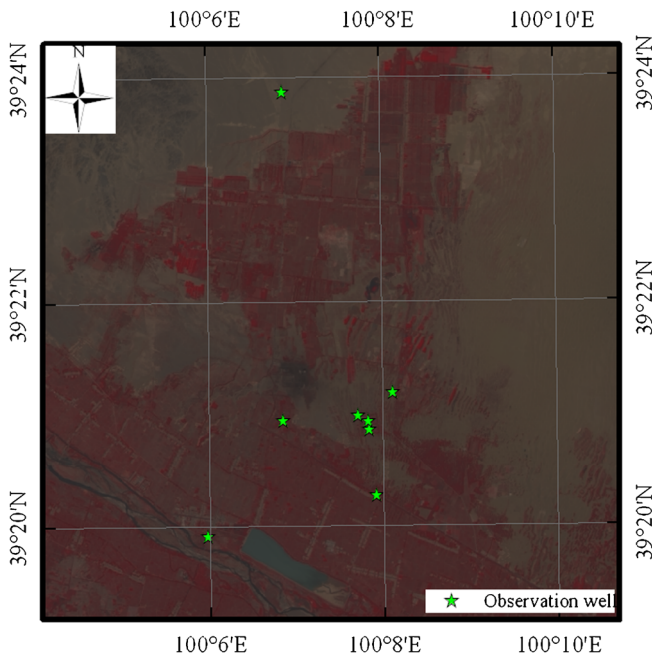


Figure 1. Location of the eight observation wells in the study area.

2.2 Locations of groundwater depth monitoring wells

Taking into consideration the characteristics of the various landscapes in the desert-oasis ecotone, eight groundwater observation wells were installed along the river plain, at the edge of Linze Oasis, to form a groundwater depth observation transect to represent the main landscapes in the study area: floodplain, farmland, farmland shelter-belt and desert. The eight wells were identified with Arabic numbers, 1–8. The characteristics of each observation well are described in figure 1 and table 1. The groundwater depth in each well was measured every 10 days from 2002 to 2011.

2.3 Methods

SPSSV15 and Origin 8 were used to estimate the groundwater depth variation for the eight observation wells. Linear regression analysis was performed to show the trends of groundwater changes. Mean value, range and coefficient of variation were chosen to show the statistical characteristics of groundwater depth.

3. Results

3.1 Seasonal variations in groundwater depth

The groundwater depth of the floodplain remained basically at 0.8 m throughout the year. The range of groundwater depth between the different months varied less than 0.09 m (figure 2, GW1). From figure 2 (GW2, GW3, GW4), we can see that the groundwater depths for farmland were different in

Table 1. General information for the eight groundwater observation wells.

Well	Altitude (m)	Location	Depth of well (m)	Landscape type	Dominant vegetation	Soil type	Distance from river (m)
GW1	1380	39°19'55.0"N; 100°05'59"E	15	Floodplain	<i>Tamarix chinensis</i> Lour.	Bog soil	320
GW2	1399	39°20'16.7"N; 100°07'55.1"E	15	Oasis farmland	<i>Zea mays</i> L. <i>Gossypium</i> spp.	Irrigation-silting soil	1000–2000
GW3	1400	39°20'51.5"N; 100°07'50.5"E	15				
GW4	1393	39°21'11.5"N; 100°08'07.1"E	15				
GW5	1401	39°20'59.2"N; 100°07'42.7"E	15	Desert-oasis ecotone	<i>Populus gansuensis</i> <i>Elaeagnus angustifolia</i> L. <i>Haloxylon ammodendron</i>	Aeolian sandy soil	2000–3000
GW6	1398	39°20'56.4"N; 100°07'49.7"E	15				
GW7	1398	39°20'57.0"N; 100°06'51.4"E	15				
GW8	1404	39°23'52.5"N; 100°06'52.4"E	18	Desert	<i>Nitraria schoberi</i> L.	Aeolian sandy soil	7500

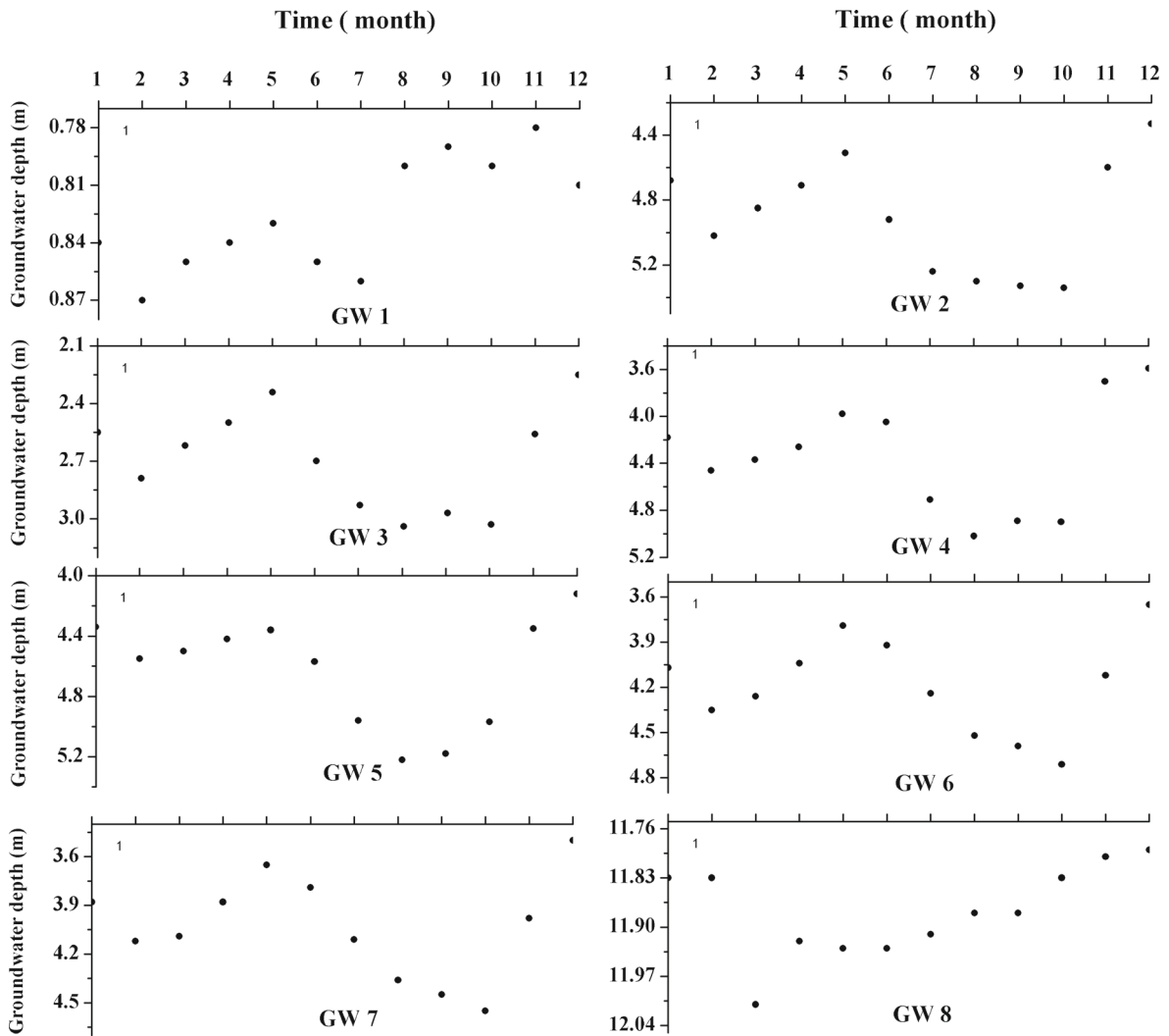


Figure 2. Seasonal variations in groundwater depth.

different observation wells; the values ranged from 2.0 to 5.3 m. The groundwater depth fluctuations for all farmlands followed the same pattern, with twin peaks, and the annual fluctuation ranges were 1.4, 1.0 and 0.8 m, respectively. From figure 2 (GW5, GW6, GW7), we can see that the groundwater depths for the desert-oasis ecotone ranged from 3.5 to 5.2 m. The groundwater depth fluctuations for the farmland shelter-belts followed the same pattern of twin peaks line that was observed in farmland, and the annual fluctuation range was 1.1 m. From figure 2 (GW8), we can see that the groundwater depth for the desert was 11.8 m, and the variation in groundwater depth among the different months was about 0.1 m.

3.2 Inter-annual changes in groundwater depth

It can be seen from figure 3 that the trends in groundwater depth were different for different landscapes. The groundwater depth for the floodplain

was basically stable, fluctuating around 0.1 m (figure 3: GW1). The groundwater depths for farmland showed significant increasing trends; the annual increase rates were 0.13, 0.18 and 0.18 m, respectively (figure 3: GW2, GW3, GW4). As for the groundwater depths for the desert-oasis ecotone, there were also significant increasing trends, and the annual increase rates were 0.10, 0.15 and 0.15 m, respectively (figure 3: GW5, GW6, GW7). The groundwater depths for the desert decreased with time; the annual decrease rate was 0.18 m (figure 3: GW8).

3.3 Spatial variability of groundwater depth

The groundwater depths changed along the latitudinal direction and increased from south to north (figure 4a). Along the longitudinal direction, the groundwater depths showed no significant linear trend (figure 4b).

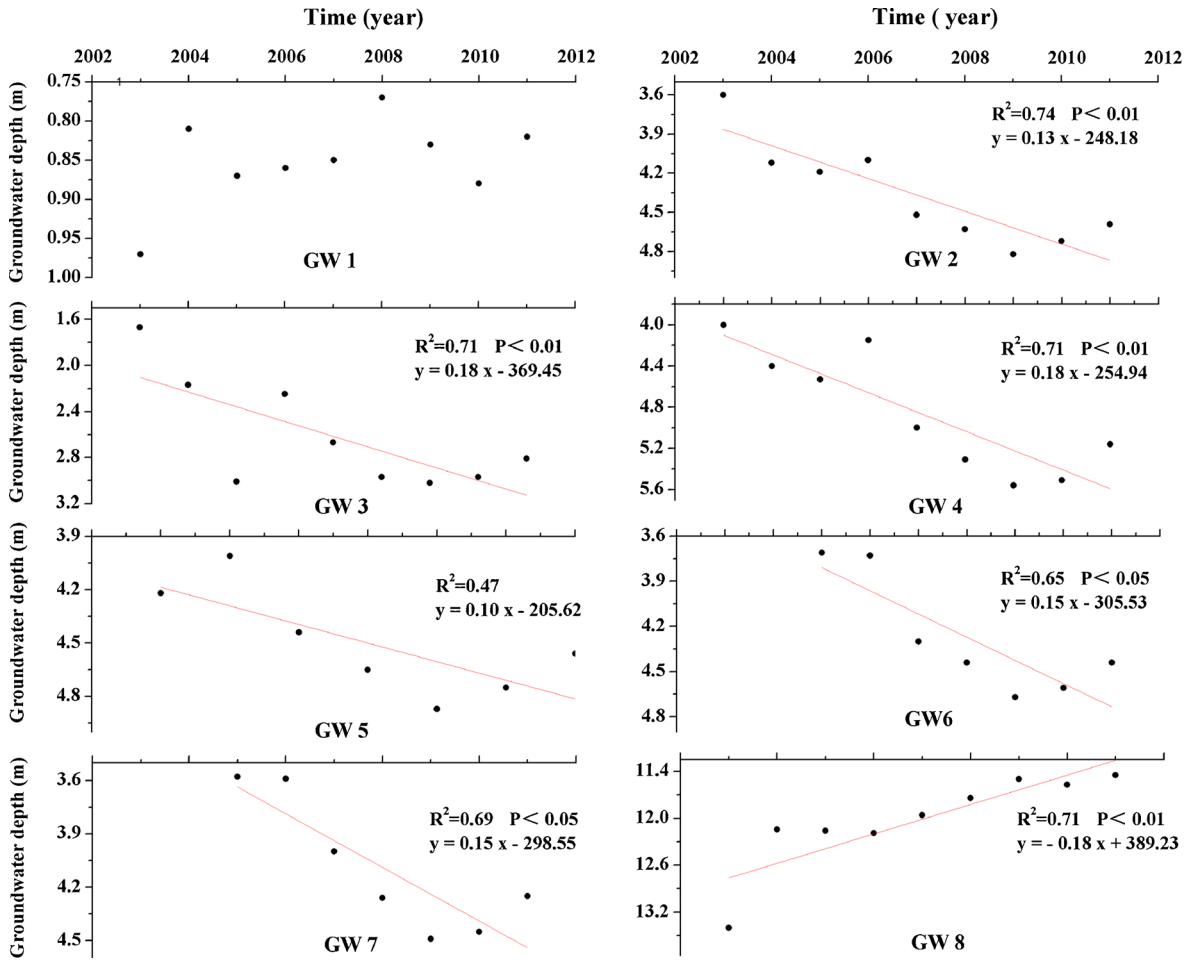


Figure 3. Inter-annual changes in groundwater depths (x represents the year, y represents the groundwater depth of the year).

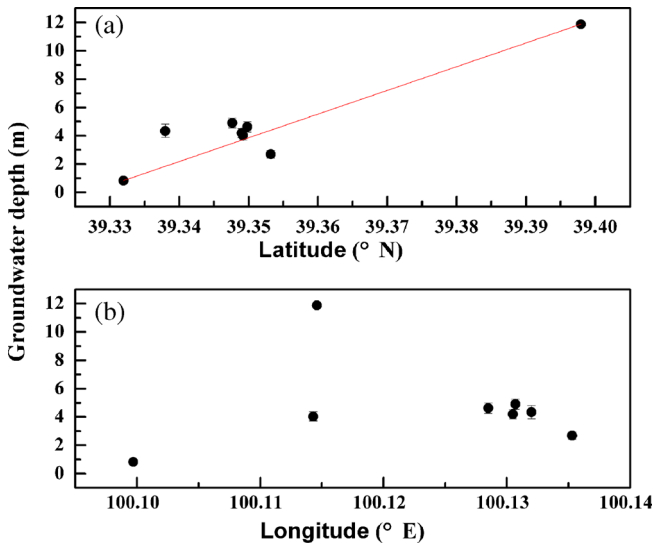


Figure 4. Changes of groundwater depth from (a) south to north and from (b) west to east.

It can be seen from table 2 that groundwater depths (minimum, maximum and mean value) all increased, from floodplain, to farmland, to desert-

oasis ecotone to desert. But the values of range and CV in the farmland and desert-oasis ecotone were higher than in the floodplain or the desert (table 2).

4. Discussion

Ashland *et al.* (2005) identified the annual fluctuations of groundwater into two types: natural seasonal fluctuation and human-induced fluctuation. In this study area, the natural seasonal fluctuations of groundwater depths are controlled mostly by the late winter or early spring snowmelt recharge from Qilian Mountain. The human-induced fluctuations are mainly caused by the abstraction of groundwater in the summer irrigation season and by infiltration of excess farmland irrigation water after the irrigation season. The former is characterized by peak groundwater depths that typically occur in the non-irrigation season, whereas the latter is characterized by a bimodal curve where the peak groundwater depths occasionally occur in the

Table 2. Statistical characteristics of groundwater levels in the observation wells.

Landscape Well	Floodplain GW1	Oasis farmland			Desert-oasis ecotone			Desert GW8
		GW2	GW3	GW4	GW5	GW6	GW7	
Minimum/m	0.78	3.59	4.33 3.39	2.25	4.12	3.65 3.76	3.50	11.79
Maximum/m	0.86	5.02	5.34 4.47	3.04	5.22	4.71 4.83	4.55	11.99
Mean±SD/m	0.83±0.03	4.34±0.47	4.90±0.35 3.98±0.36	2.68±0.27	4.630±0.36	4.19±0.32 4.28±0.33	4.03±0.32	11.89±0.06
Range/m	0.09	1.43	1.01 1.08	0.79	1.10	1.06 1.07	1.05	0.22
CV	0.04	0.11	0.07 0.09	0.09	0.08	0.08 0.07	0.08	0.01
Distance/m	320		1000–2000			2000–3000		7500

(SD=standard deviation, CV=coefficient of variation).

Table 3. Changes in irrigation area and in amount of groundwater used for irrigation, 1998–2011. (Ratio 1 = ratio of groundwater irrigation area to total irrigation area; Ratio 2 = ratio of groundwater to total water used for irrigation).

Period	Cumulative number of irrigation wells	Surface-water irrigation area (104 ha)	Groundwater irrigation area (104 ha)	Ratio 1 (%)	Surface-water used for irrigation (107 m ³ /a)	Groundwater used for irrigation (107 m ³ /a)	Ratio 2 (%)
1998	93	0.60	0.08	12	5.06	0.11	2
2001	280	0.62	0.15	19	4.22	0.50	11
2006	351	0.62	1.19	66	4.59	2.08	27
2011	354	0.62	1.38	69	4.33	1.68	28

later fall after the farmland irrigation season, or in winter.

In floodplains, the groundwater depth is affected mainly by the amount of river inflow (Allen *et al.* 2004). Interchanges between groundwater and surface water are very common because of the short distance between the floodplain and the Heihe River. Due to the relatively stable river flow, the annual fluctuations were very small in the floodplain, and were attributed to natural seasonal fluctuations. The variation in groundwater depth among the different months was only 0.09 m (figure 2). From figure 3, we can see that groundwater depth in the floodplain showed no significant trend, remaining basically stable.

Farmland irrigation consumes 90% of the water resources worldwide (Shiklomanov 2000; Jury and Vaux 2005). In the most recent decade, as the quantity of surface water has decreased, groundwater has become the main irrigation water resource. Worldwide, 40% of the freshwater used for irrigation is groundwater, and in USA, the ratio has reached 60% (Siebert 2010). The Heihe River is the second largest inland river in China, and the major water consumption area in its basin is in the middle reach, where a large number of oasis farmland is distributed. Population growth, socio-economic development and the large-scale expansion of farmland in the last decade has led to the

expansion of the oasis, and the demand for irrigation water has increased tremendously in the study area. Irrigation water deficit is becoming a serious problem, and groundwater has become an increasingly important resource for irrigation. However, the amount of irrigation water from the Heihe River decreased from $5.06 \times 10^7 \text{ m}^3$ to $4.33 \times 10^7 \text{ m}^3$ in the study area, in the last decade (table 3).

The groundwater irrigation area increased from $0.15 \times 10^4 \text{ ha}$ in 2002 to $1.38 \times 10^4 \text{ ha}$ in 2011 (table 3). Consequently, intensive abstraction of groundwater was conducted for summer irrigation, and a large amount of groundwater was pumped in order to meet the high demand for irrigation water. In the recent decade, the number of irrigation wells increased from 280 to 354, and the ratio of groundwater irrigation area to total irrigation area reached 69% (table 3). Irrigation is becoming the most important driving force of increasing groundwater depth in farmland and desert-oasis ecotones (table 3). We found that the annual fluctuations in groundwater depth were very large, sometimes reaching 1.43 and 1.10 m between the irrigation season and the non-irrigation season, in farmland and desert-oasis ecotones, respectively. The groundwater depths in farmland and desert-oasis ecotones generally were at a deeper level during the main irrigation season (June–October). Starting in November, as the irrigation activity

basically ended, the groundwater depths decreased due to infiltration of excess farmland irrigation water in summer (figure 2). From 2002–2012, the groundwater depths in farmland and desert-oasis ecotones both showed significant increasing trends; the increase rates were 0.13, 0.18 and 0.18 m in farmland wells and 0.10, 0.15 and 0.15 m in farmland shelter-belt wells (figure 3). Since these fluctuations in groundwater depth were caused mainly by irrigation, the fluctuations belong to the category of human-induced fluctuations. In view of the results of both the annual and the inter-annual fluctuations, it is clear that the groundwater system in the study area is unstable in both farmland and desert-oasis ecotones, that the increase trend has been steady in last decade, and that increasing groundwater irrigation in summer was the key reason for this trend. The timing of the lowest depths in farmland and shelter-belts are all in the late fall or early winter month of December (figure 2). This suggests that it takes two months (after October) for the infiltration of excess farmland irrigation water to replenish the groundwater in this study area.

The annual fluctuations in groundwater depth in the desert were very small. The range was only 0.18 m and a decreasing trend is obvious over the last decade. Rainfall is the main water source for recharging the groundwater system in the desert (Zhao *et al.* 2002). When the amount of rainfall is large, the groundwater depth can decrease, due to the strong permeability of the particles in the sandy desert soil. But since rainfall is erratic in the desert, most desert vegetation relies on groundwater (Dawson and Ehleringer 1991; Synder and William 2000). If the amount of rainfall is less than the amount of groundwater abstracted by vegetation, the groundwater depth would increase. Our study results indicated that the groundwater condition in the desert can be improved without manual intervention.

In this study area, the groundwater depth in the southern area is lower than in the northern area, because the river channel is located in southern area and it can replenish the groundwater (figure 4a). From west to east, the groundwater depth first increases, and then decreases, while there is no significant trend in variation in longitudinal direction (figure 4b).

Generally, the farther the land is from the river, the deeper the groundwater depth and the more unstable the groundwater system (Wang *et al.* 2007). In this study, we found that the groundwater depths increased from floodplain, to farmland, to desert-oasis ecotone, to desert. However, some studies in arid land have shown that groundwater depth could be affected only within a certain distance range, and the distance range varied over the different areas. The distance range in

the lower reaches of the Heihe River varies from < 1000 m to 1000–2000 m (Xu *et al.* 2003; Si *et al.* 2005; Zhao *et al.* 2009). In this study area, oasis farmland is a unique landscape that is created by exploitation of water resources from an inland river and from groundwater. Yet this farmland is the most important area of an oasis in arid zones, and the groundwater dynamics are a key component constraining the sustainable development of the oasis. The groundwater depths in farmland and desert-oasis ecotones are both directly affected by irrigation. The variations in seasonal and inter-annual groundwater depths in farmland and desert-oasis ecotones show the same pattern, with similar variabilities (figures 2, 3 and table 2). These results suggest that the distance from the river in which land is affected by farmland irrigation is about 1000–2000 m – the very distance where farmland and desert-oasis ecotone areas are located (table 2).

5. Conclusions

In this study, we analyzed the temporal and spatial changes in the groundwater depth in a typical desert-oasis ecotone in northwestern China. In the last decade, the groundwater depths for different land-use types in the desert-oasis ecotone have changed in different ways. The natural seasonal fluctuation in the floodplain and desert did not cause significant changes of groundwater depths and the groundwater depths were basically stable. But the human-induced fluctuations of intensive exploitation caused a significant increase in groundwater depths in both the farmland and the desert-oasis ecotone, seriously affecting sustainable agriculture development and the environment in the oasis. For the desert-oasis ecotone, the development of agriculture and the area of farmland should be planned based on the available amount of water resource in the local area.

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