SCIENCE CHINA
Earth Sciences

• RESEARCH PAPER •

doi: 10.1007/s11430-014-4927-z

The effect of hydrologic process changes on NDVI in the desert-oasis ecotone of the Hexi Corridor

ZHAO WenZhi[1*] & CHANG XueLi[2]

[1] *Linze Inland River Basin Research Station, Key Laboratory of Ecohydrology of Inland River Basin, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China;*
[2] *School of Geography and Planning, Ludong University, Yantai 264025, China*

Received September 11, 2013; accepted December 11, 2013

In the arid inland river basins of northwestern China, human activities control almost all the surface hydrologic processes. The potential effects of these altered hydrologic processes are gradually becoming clear, especially since the 2000 implementation of the integrated water resources management projects in the Shiyang River, the Heihe River, the Tarim River, and the Shuler River. While the appearance of these eco-hydrology changes and consequent environmental effects in the oasis has attracted broad attention, related research is still lacking. Eco-hydrological process changes in the desert-oasis ecotone were investigated in the Pingchuan irrigation district in the middle reaches of the Heihe River. The results showed that the annual average amount of surface water irrigation during the past 20 years has decreased by 1.498×10^7 m^3, while the annual average amount of well irrigation has increased by 1.457×10^7 m^3, since 2000, when the State Council of China approved the water diversion scheme for the Heihe River Basin. The groundwater depth before the water diversion scheme generally varied between 2.44–3.19 m (average 2.73±0.24 m), while that after the water diversion scheme has varied between 3.08–4.01 m (average 3.79±0.62 m). The distribution area of <3 m groundwater depth decreased from 3612 to 394 hm^2; while the distribution area of >3 m groundwater depth increased from 853 to 3843 hm^2. However, although the hydrologic processes changed dramatically, no significant effects on vegetation productivity in the desert-oasis ecotone were detected during the study period.

Hexi Corridor, desert-oasis ecotone, Pingchuan irrigation district, hydrologic processes, groundwater depth, NDVI

Citation: Zhao W Z, Chang X L. 2014. The effect of hydrologic process changes on NDVI in the desert-oasis ecotone of the Hexi Corridor. Science China: Earth Sciences, doi: 10.1007/s11430-014-4927-z

Although China's oasis system accounts for less than 10% of its arid region area, about 90% of the region's social and economic activity is concentrated there (Jia et al. 1996; Han, 1999). And since the 1980s, environmental issues have become more and more prevalent in the artificial oases region of northwestern China, due to the increasing population and the rapid development of the social economy. This situation has been reflected in two main trends: (1) in the oases themselves, forest land and grassland were replaced by farmland, and then construction began crowding out both forest land and the new farmland; and (2) in the oasis fringe, natural grassland reclamation from farmland and forest land has caused the desert-oasis ecotone to shrink and even disappear entirely in some places (Jia et al., 2000; Jiao et al., 2003; Chen et al. 2008). The desert-oasis ecotone is a major component of the oasis, and plays an important role in checking the movement of sand dunes, reducing the intensity of sand flow activities, and lowering the hazards of sand flow. The desert-oasis ecotone is the most sensitive region, and is not only affected by the sand environment (Zhang et al. 1995; Han, 1999; Wang et al., 1999; Li et al., 2004), but is also sensitive to hydrologic process changes (Fang et al., 2007).

---

*Corresponding author (email: zhaowzh@lzb.ac.cn)

In recent years, the interaction among eco-hydrological processes has become the hot research topic in the fields of ecology and hydrology—especially the unique ecohydrological interactions between human intervention and the natural ecological process of the water cycle. For example, Chen et al. (2007) analyzed the effects of ecological restoration projects on water conveyance in the lower reaches of the Tarim River. Zhao et al. (2005) studied the spatial and temporal dynamics of soil water content in a desert-oasis ecotone. Li et al. (2008) investigated how *Haloxylon annodendron* responded to precipitation pulses, to explore the adaptation strategies of this dominant native desert shrub. Zhao et al. (2003a) investigated the response of protective forest distribution patterns in the Ejina Oasis, to hydrologic processes; the results showed that the area of degraded patches within the protective forest increased with the groundwater depth in the vertical channel direction, but decreased with the groundwater depth in the parallel channel direction. Li (2011) reviewed the mechanism of coupling, response and adaptation, among soil, vegetation and hydrology in arid regions, at the individual, slope, and watershed scales, and put forward an adaptation theory of water-harvesting systems in arid environments. This last work analyzed and discussed the composition, structure, and characteristics of the water-uptake system via trunk sap flow, scrub plaque, and river water. A complete oasis ecosystem includes both the highly productive oasis and the desert-oasis ecotone. The survival and stability of the desert-oasis ecotone, while dependent primarily on precipitation, may also be correlated with groundwater levels, and at the same time be linked to lateral infiltration from irrigation water (Yan et al., 2006). At present, however, an understanding of the mutual feedback mechanism and hydrologic processes among precipitation, surface water, and groundwater in oasis ecosystems, is still lacking.

The Zhangye Oasis, in China's second largest inland river basin, is the largest artificial oasis in the Heihe River basin, and is also the largest concentrated oasis in western China. Since 2000, when water resources management in the Heihe River was implemented, Zhangye Oasis development was rigidly controlled by surface water resources (Fang et al., 2007). When the amount of river irrigation was reduced, the deficit was replaced by underground water, and the overall area of the Zhangye Oasis continued to increase (Chang et al., 2012). In order to understand such interactions, more innovation is needed in research methods and ideas, on how hydrologic process changes in arid regions cause ecological process changes in an oasis, as well as eco-hydrological process changes in a desert-oasis ecotone. The present study, focused on the Pingchuan irrigation district of the Zhangye Oasis fringe, investigated the vegetation productivity distribution pattern and the corresponding change processes of groundwater, surface water, and precipitation, over a period of 23 years, to reveal the eco- hydrological interaction mechanisms. The study analyzed the NDVI dynamics of the irrigation district unit with special consideration to the effects of changes in the irrigation amounts and sources. It aimed to develop a method for estimating the interactions between ecological and hydrological processes, and to provide a useful reference for evaluating the environmental effects of altered hydrologic processes caused by human regulation in the inland river basins of arid regions.

1 Study area and methods

1.1 Description of study area

The study area is located in the Hexi Corridor in Gansu Province—the second largest inland river basin in the middle reaches of the Heihe River—in the Pingchuan irrigation district of Linze Town in the middle of the Zhangye Oasis (Figure 1). As one of the major oases distributed in the Hexi Corridor, Zhangye Oasis includes portions of 3 counties — Linze, Gaotai, and Ganzhou. The ecological and environmental problems in Zhangye Oasis are typical and representative for most oasis regions of northwestern China (Jiao et al., 2003).

The study area is 975.8 km^2, comprising 73.5 km^2 oasis and 902.3 km^2 desert. The average annual precipitation over the study area is 117 mm; about 65% of it falls between July and September. The average annual evaporation is 2390 mm. The average annual temperature is 7.6°C with the

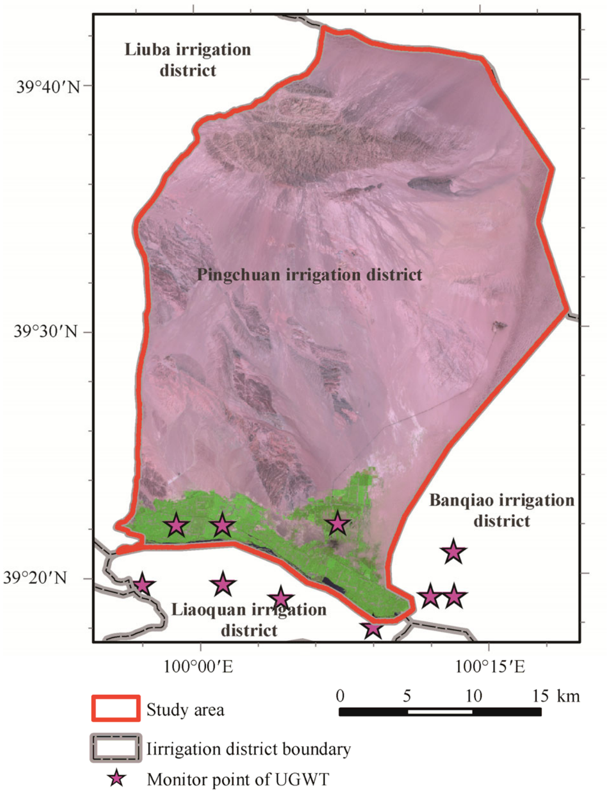


Figure 1 Location of the study area (Pingchuan irrigation district of Zhangye oasis).

highest temperature 39.1°C in summer and the lowest temperature −27.3°C in winter. The main vegetation types are protective poplar forest, protective shrub vegetation, and desert sand-fixing vegetation. The specific plants are: protective forest (*Populus gansuensis*, *Populus alba*, etc.), shrubs (*Haloxylon ammodendron*, *Caragana Korshinskii Kom*, *Hedysarum scoparium*, *Zygophyllaceae*, etc.), and annual plants (*Bassia*, *Eragrostis pilosa*, etc.). The characteristics of these typical plant communities are shown in Table 1.

2 Methods

2.1 Remote sensing data processing

2.1.1 Data

In this study, Landsat TM images spanning five different periods were used as the information sources (Track No. 134-33 and 134-34). The acquisition dates were August 15, 1987, August 26, 1992, August 13, 2001, August 23, 2005, and August 14, 2010. The pixel resolution of the images was 30 m by 30 m. All the images were from Landsat 5 except the one on August 13, 2001, which came from Landsat 7.

2.1.2 Landsat data correction

The radiation error resulting from the optical remote sensing acquisition process has to be corrected with both radiation calibration and atmospheric correction. The effect of atmospheric correction on surface reflectivity, however, was minor (Xu et al., 2008), and since in the following analysis the oasis boundary was determined by surface reflectivity, the information was preprocessed only through radiation calibration.

For radiation calibration, the illumination correction model (ICM) developed by Markham et al. (1986) was used. ICM mainly handles the image grey value in pixel reflectivity in satellite sensors. The algorithm of ICM converts the grey value (DN) of a pixel into a spectral radiation value in the sensors, and then into reflectivity in the sensors.

For Landsat 5 TM images, the spectral radiant transformation model is

$$L_\lambda = \frac{L_{\max_\lambda} - L_{\min_\lambda}}{Q_{\max}} (Q_\lambda) + L_{\min_\lambda}, \tag{1}$$

where λ is the band value; L_λ is the spectral radiant value of the sensor pixels; Q_λ is the quantitative calibrated pixel value expressed in DN; $Q_{\max}$ is the theoretical maximum of an 8-bit DN value (255); $L_{\max}$ is the stretched maximum spectral radiant value based on $Q_{\max}$; and $L_{\min}$ is the stretched minimum spectral radiant value based on the theoretical minimum of an 8-bit DN value. $L_{\max}$ and $L_{\min}$ were obtained from a look-up table.

For Landsat 7 ETM+ images, NASA introduced the $Q_{\min}$ value and revised eq. (1). The spectral radiant transformation model was revised to

$$L_\lambda = \frac{L_{\max_\lambda} - L_{\min_\lambda}}{Q_{\max} - Q_{\min}} (Q_\lambda - Q_{\min}) + L_{\min_\lambda}, \tag{2}$$

where $Q_{\min}$ is the theoretical minimum of an 8-bit DN value.

To determine the oasis boundary, the low gain parameters from the look-up table were used for the Landsat 5 TM images calibration, for solar altitudes above 45°. The high gain parameters in bands 1–3 and 5 were used for Landsat 7 ETM+ images calibration, for solar altitudes below 45°.

2.1.3 Reflectivity calculation

After calculating L_λ, the atmospheric reflectivity in the sensors, or reflectivity at the top without atmospheric effect, was calculated as

$$\rho_\lambda = \frac{\pi \cdot L_\lambda \cdot d^2}{E_{\mathrm{SUN}_\lambda} \cdot \cos\theta_{\mathrm{s}}}, \tag{3}$$

where ρ_λ is the reflectivity in sensors or reflectivity at the top of the atmosphere; E_{SUN_λ} is the average solar irradiance at the top of atmosphere; and θ_{s} is the solar zenith angle (complement of the solar altitude angle). Solar altitude angle can be obtained from the images' head file. d is the earth-sun distance (AU).

2.2 Determination of vegetation boundary (oasis boundary), largest oasis area and radiation boundary in oasis

Oases can be divided into peripheral desert, desert-oasis ecotone, and central oasis according to the landscape features. This research mainly investigated the vegetation

Table 1 Characteristics of typical plant communities in the study area

Plant community	Dominant species			Coverage (%)	Density (individual number/m^2)	Species number
	Coverage (%)	Height (cm)	Density (individual number/m^2)			
Haloxylon ammodendron	55.2±8.2	179.5±60.8	0.22±0.06	59.7±7.6	102.6±46.4	6
Zygophyllaceae+Calligonum mongolicunl	18.2±5.6	63.9±15.8	3.62±1.46	21.4±6.2	40.7±6.9	9
Tamarix aphylla (*Linn.*) *Karst.*	13.6±4.6	204.3±112.6	0.42±0.12	15.3±5.5	33.8±7.36	13
Populus	65±0.53	14.5±0.87	0.15±0.01	72±5.2	29±0.15	6
Tamaricaceae + *Sagina saginoides*	1.56±0.23	13.2±3.5	0.35±0.11	3.86±0.56	0.67±0.21	11

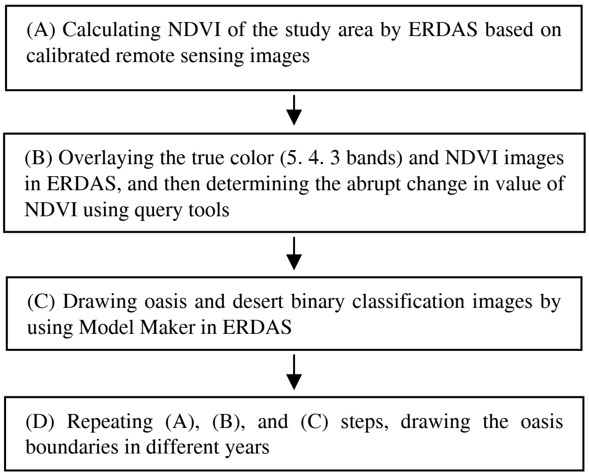
distribution pattern, including farmland, in the oasis fringe; and artificial sand-fixing vegetation and desert vegetation outside the oasis (natural vegetation). The farmland vegetation and desert vegetation were categorized based on more than 30 grids, and on abrupt changes in the NDVI value. The range of vegetation changes is given to the 0.1 unit.

2.2.1 *Oasis boundary*

The oases in arid regions were developed from desert. The boundary between oasis and desert for each image is drawn based on abrupt change of the NDVI value. The specific flowchart is shown in Figure 2, and the result is shown in Figure 3.

2.2.2 *Largest oasis area and radiation zone of oasis*

The largest oasis area is a computational reference space used to analyze the radiant effect of an oasis. It is determined by overlaying the largest oasis areas for each of the years during the study period; this was determined to be 79.6 km^2 from 1987 to 2010. The radiation zone of an oasis is defined as the NDVI change within a certain range of area caused by hydrologic process changes. For example, overlaying five period images showed that the NDVI change within 1000 m was significant in the oasis fringe. Therefore, the radiation zone reaches 1000 m in the oasis fringe within a 49.5 km^2 area (Figure 4).



(A) Calculating NDVI of the study area by ERDAS based on calibrated remote sensing images

(B) Overlaying the true color (5. 4. 3 bands) and NDVI images in ERDAS, and then determining the abrupt change in value of NDVI using query tools

(C) Drawing oasis and desert binary classification images by using Model Maker in ERDAS

(D) Repeating (A), (B), and (C) steps, drawing the oasis boundaries in different years

Figure 2 Flowchart for drawing the oasis boundary.

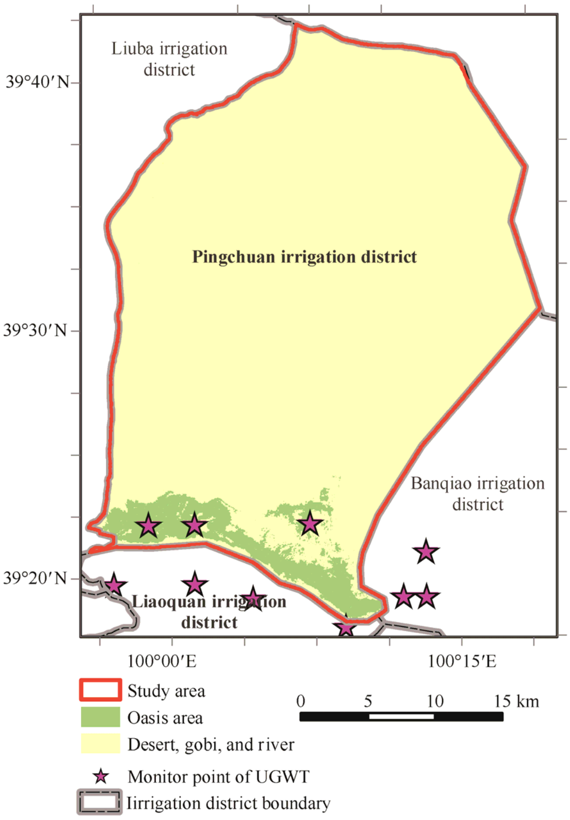


Figure 3 Distribution area of oasis in 1987.

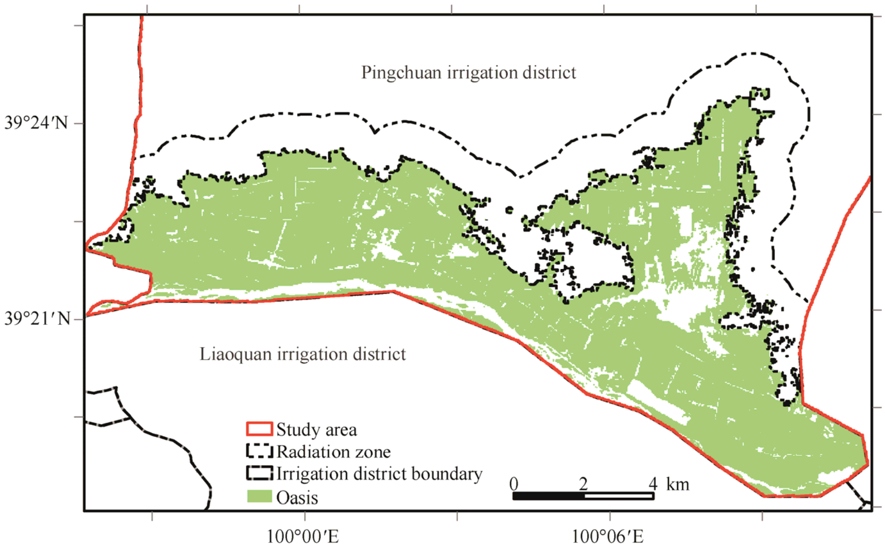


Figure 4 Maximum oasis area and radiation zone.

2.2.3 *Hydrologic processes*

Hydrologic process information, including groundwater dynamics, irrigation application rates, and precipitation during the five different periods, were either collected from field monitoring or provided by the local government. The groundwater data were collected from 14 observation wells during 1985–2005 in Zhangye, and employed to interpolate a regular grid through the inverse distance weighted module in ArcGIS (Figure 5). The irrigation data were collected from the annual report of the Pingchuan irrigation district presented by the local government. The precipitation data were the monthly average data of Zhangye (52652) and Gaotai (52546), collected from the national weather data sharing website (http://cdc.cma.gov.cn).

3 Results

3.1 Hydrologic process

The variation of precipitation during the period from 1985 to 2011 is shown in Figure 6(a). The State Council of China approved the water diversion scheme in the Heihe River Basin in 2000 (vertical black line in Figure 6). Precipitation before 2000 varied between 72.1 and 168.9 mm (average 116.6±27.1 mm), whereas the precipitation after that year was 80.0–201.4 mm (average 130.7±31.5 mm). The variation of groundwater depth for three representative observation wells from 1985 to 2011 in the study area is shown in Figure 6(b). The groundwater depth before the water diversion scheme varied between 2.44–3.19 m (average 2.73±0.24 m), whereas that after the water diversion scheme varied between 3.08–4.01 cm (average 3.79±0.62 m).

The distribution areas for the different groundwater levels are shown in Figures 5 and 7, and in Table 2. The distribution area of <3 m groundwater depth was significantly decreasing over the study period, while the distribution area of >3 m groundwater depth was significantly increasing. During the 20 years from 1985 to 2005, the distribution area of 2–3 m groundwater depth decreased from 3612 hm^2 (51.3%) to 394 hm^2 (5.6%), while the distribution area of 4–5 m groundwater depth increased from 853 hm^2 (12.1%) to 3843 hm^2 (54.6%).

The amount of surface water irrigation is shown in Figure 8(a). The annual average amount of surface water

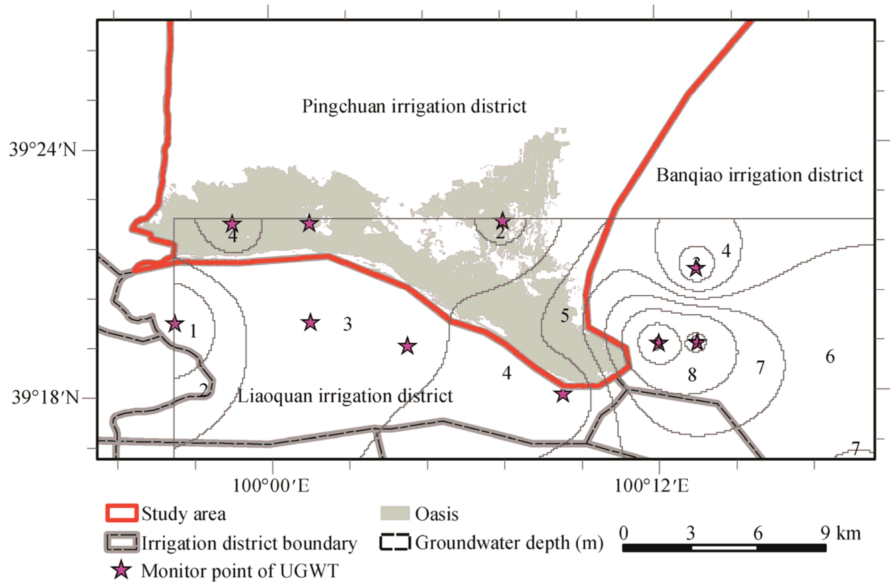


Figure 5 Distribution of groundwater depth (1985). The values of 1–8 are the groundwater depth.

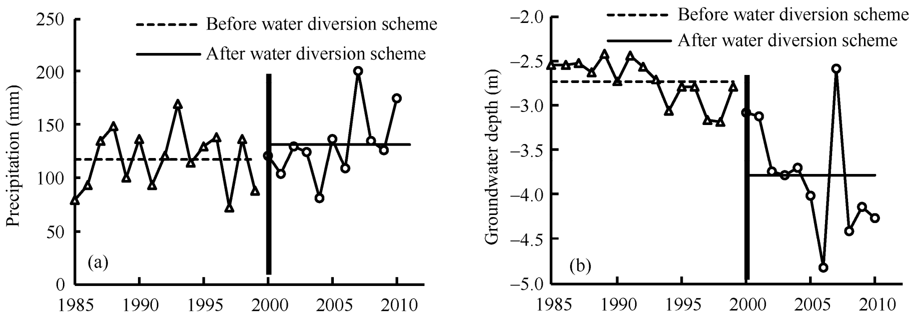


Figure 6 Hydrologic processes in study area. (a) Precipitation; (b) groundwater depth.

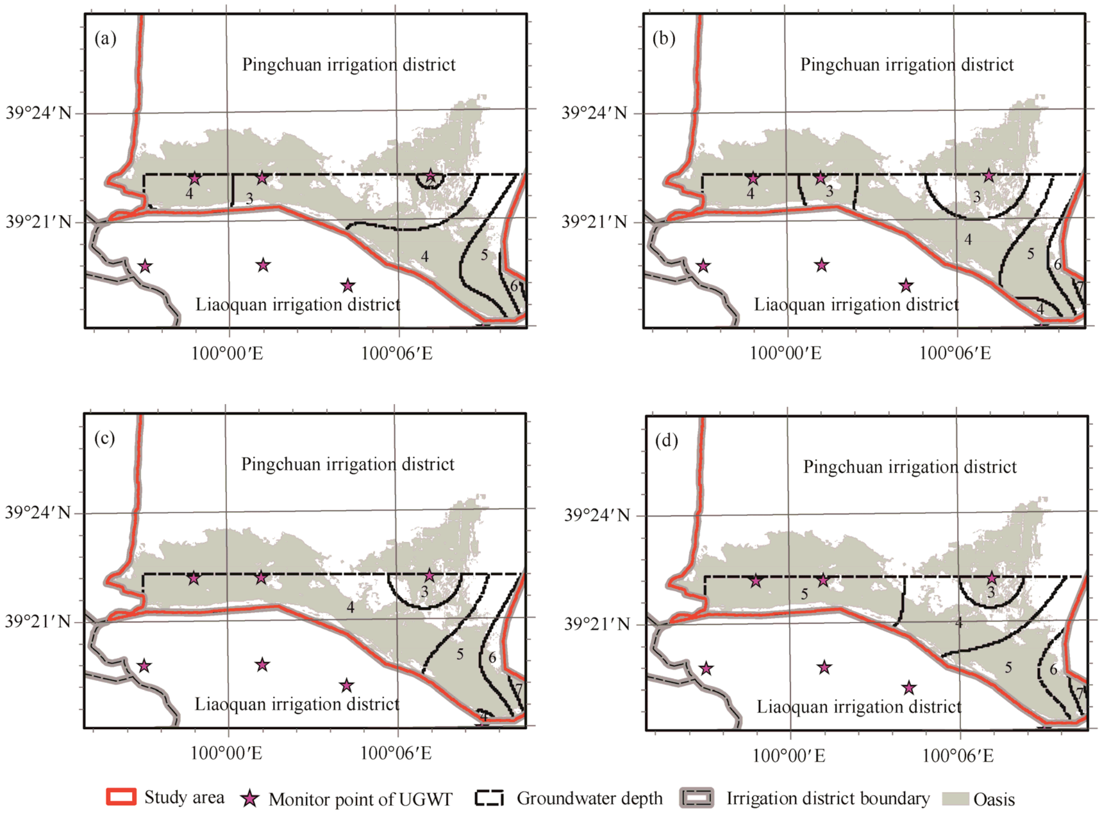


Figure 7 Distribution of groundwater depth in study area. (a) 1990; (b) 1995; (c) 2000; (d) 2005. The values of 1–8 are the groundwater depth (unit: m).

Table 2 Distribution area at various groundwater depths, during study years (hm^2/%)

Groundwater depth (m)	1985	1990	1995	2000	2005
<2	207/2.94	77/1.09			
2–3	3612/51.33	2758/39.19	1429/20.30	498/7.08	394/5.60
3–4	2085/29.63	2922/41.52	3747/53.24	4235/60.18	2084/29.61
4–5	853/12.12	976/13.87	1321/18.78	1546/21.96	3843/54.60
5–6	184/2.61	200/2.84	394/5.60	571/8.11	494/7.02
6–7	88/1.25	90/1.28	109/1.55	128/1.82	137/1.95
7–8	7/0.11	14/0.20	37/0.53	60/0.86	75/1.07
>8					10/0.14
Sum	7038/100	7038/100	7038/100	7038/100	7038/100

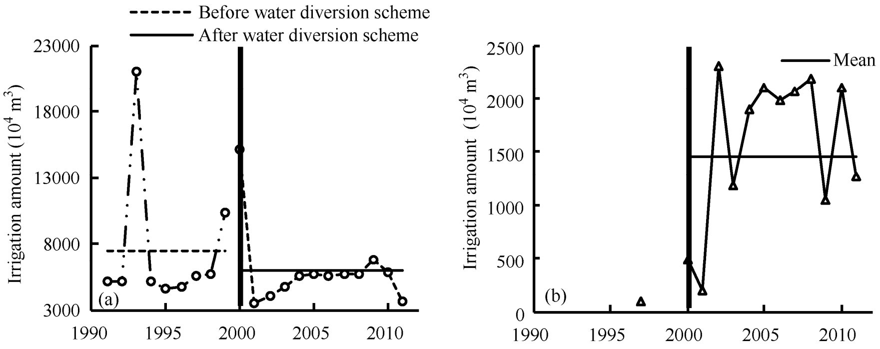


Figure 8 Surface water irrigation amount (a) and well irrigation amount (b).

irrigation before the water diversion scheme varied significantly, between 4.518×10^7 and 20.990×10^7 m^3 (average 7.469×10^7 m^3), whereas that after the water diversion scheme was relatively constant (varied between 3.620×10^7 and 15.554×10^7 m^3, with an average of 5.970×10^7 m^3). Well irrigation was rare before the water diversion scheme. However, well irrigation after the water diversion scheme was becoming widespread, the annual average amount increasing by 1.457×10^7 m^3.

3.2 The variation of oasis vegetation

Significant variation of the oasis vegetation in the study area was mainly observed in the northern part of the desert-oasis ecotone and the southern part of the floodplain-oasis ecotone (Figures 1, 9). According to the analysis of the image data (Table 3), the oasis area was expanding during the period of the study (even after the water diversion scheme was implemented in 2000 in the Heihe River Basin). The oasis area increased from 5459 hm^2 (5.6%) to 7216 hm^2 (7.4%).

3.3 The NDVI variation in radiation zone of oasis fringe

The NDVI variation in the radiation zone of the oasis fringe presents an obviously low value for the time scale (Figure 10

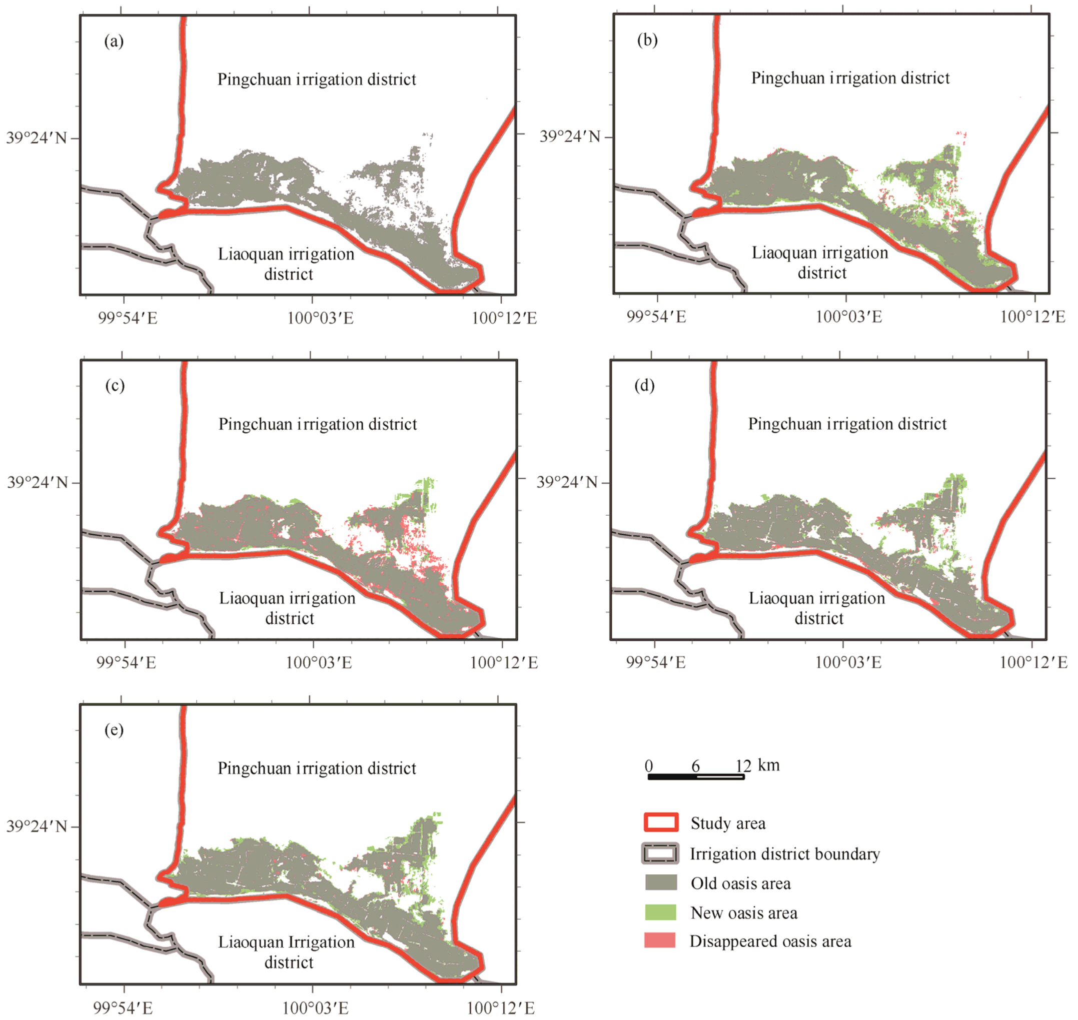


Figure 9 Oasis area in different periods. (a) 1987; (b) 1992; (c) 1995; (d) 2001; (e) 2010.

Table 3 Variation of oasis area

Year	1987	1992	2001	2005	2010
Old oasis area (hm^2)/(%)	5501/5.64	5309/5.44	5735/5.88	5989/6.14	6506/6.67
New oasis area (hm^2)/(%)		1195/1.22	494/0.51	654/0.67	848/0.87
Vanished oasis area (hm^2)/(%)		192/0.20	769/0.79	239/0.25	138/0.14
Total oasis area (hm^2)/(%)	5501/5.64	6312/6.47	5459/5.59	6404/6.56	7216/7.39

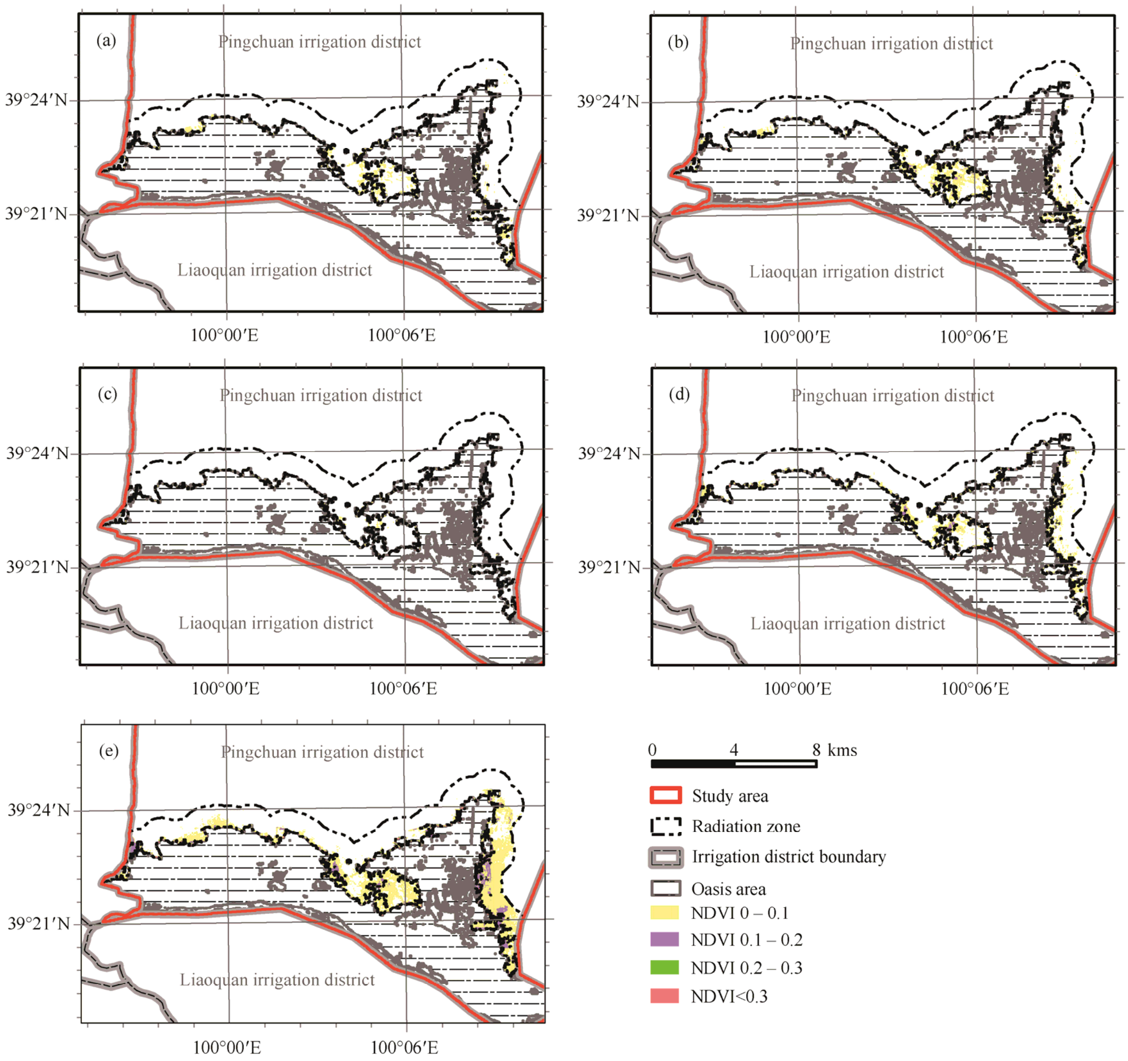


Figure 10 NDVI variation of radiation zone in oasis fringe. (a) 1987; (b) 1992; (c)1995; (d)2001; (e) 2010.

Table 4 Distribution area (hm^2)/(%) of NDVI classification in radiation zone of oasis fringe

Year	0–0.1	0.1–0.2	0.2–0.3	>0.3
1987	243.25/5.99	14.96/0.37	1.28/0.03	0.32/0.01
1992	372.04/9.16	82.54/2.03	6.22/0.15	1.73/0.04
2001	34.38/0.85	6.41/0.16	1.78/0.04	1.07/0.03
2005	379.71/9.34	74.96/1.84	10.59/0.26	7.80/0.19
2010	1138.29/28.01	334.49/8.23	47.97/1.18	17.64/0.43

and Table 3). The distribution areas for NDVI classification are listed in Table 4. All the different NDVI partition areas were low, and the lowest NDVI > 0 area came to only 43.64 hm^2, in 2001. There was only a minor variation in the vegetation area, from 259.81 to 473.07 hm^2, over the years 1987, 1992, and 2005. The widest variation of distribution area of NDVI was in the 0–0.1 range: the minimum area of NDVI in the 0–0.1 range was 34.4 hm^2, in 2001, accounting for 0.9% of the radiation zone, while the maximum area of NDVI in the 0–0.1 range was 1138.3 hm^2, in 2010, accounting for 28% of the radiation zone.

4 Discussion

In the arid inland river basins of northwestern China, inappropriate development of water resources has caused, and keeps causing, contradictions in water utilization among upstream, middle, and downstream areas. Therefore, a number of integrated water resources management projects have been implemented in those inland river basins since 2000, in the Heihe River, the Tarim River, the Shiyang River, and the Shule River. As a result, human interventions in the hydrologic processes have been gradually intensified (Yuan et al., 2006; Shi et al., 2011). The Zhangye Oasis, located in the middle reaches of the Heihe River, is in the part of the inland river basin most affected by human regulation, and has thus experienced the greatest changes in the eco-hydrological process interactions. From the perspective of water resources utilization in the study area, the annual amount of surface water irrigation after implementation of the water diversion scheme decreased by 1.498×10^7 m^3, while the annual average amount of well irrigation increased by 1.457×10^7 m^3, with minor inter-annual variability (Figure 8). The increase in groundwater extraction amount may eventually cause fluctuant increase in groundwater depth in the study area. The average annual groundwater level has declined by about 9.6 cm, and the affected depth keeps expanding (Table 2). From the distribution pattern of groundwater depth (Figures 5 and 7), we can see that the variation trend in the west is faster than that in the east, and that the groundwater depth is gradually increasing. The surface irrigation volume after implementation of the water diversion scheme decreased by 4.1×10^6 m^3, but was balanced by the increase in groundwater irrigation. Meanwhile the oasis area expansion trend continued, increasing by 1757 hm^2 between 2001 and 2010. This shows an improvement in efficiency of the irrigation technology. The amount of irrigation water filtrating into the groundwater, however, is decreasing, another cause of the increase in groundwater depth. The average annual precipitation over the study area was 120 mm before implementation of the water diversion scheme—ten times the amount of condensate. The precipitation increased by 14.1 mm from 1985 to 2011, most of it occurring after the water diversion scheme. Precipitation is not very important to the oasis ecosystem, while it has an important role in the desert-oasis ecosystem.

The eco-hydrological interactions in an oasis ecosystem are affected by groundwater, surface water, and precipitation, all of which depend not only on hydrologic processes but also on the amount of water absorbed by plants, an observation confirmed by related study results from many scholars around the world (Mensforth et al., 1994; Thorburn et al., 1994; Dawson et al., 1995; Jolly et al., 1996). The decrease in surface water, the increase in the extraction of groundwater, and the increase in groundwater depth have caused complicated eco-hydrological interactions in oasis ecosystems. The present study focused mainly on the effect of groundwater depth on vegetation distribution. However, research on the response of groundwater depth variation to vegetation distribution is still lacking. The vegetation in the short term would not respond to groundwater decline, because the plants can only absorb soil moisture during a certain period in their growth. The response of vegetation to groundwater decline would also be hysteretic because of the drought resistance of desert-oasis plants. This relationship, though, would be an important area of research in the future.

In an oasis ecosystem, the soil, the precipitation, the surface water, and the groundwater all play important, and interacting, roles in the formation of vegetation productivity. For example, when the irrigation amount per unit area exceeds a certain level, oasis productivity does not increase proportionately. Rather, the excess irrigation water will recharge the groundwater through percolation, and will also leak laterally into the river. The expansion of water-saving irrigation technology was intensified after implementation of the diversion scheme in the Heihe River in 2000. At the landscape scale, water consumption in the oasis, per ha, is 7500 m^3, and ecological water use accounts for about 22% (including riparian wetland water use) (Zhao et al., 2010). The decrease in irrigation amount, however, reduces the recharge amount available to groundwater. Survey data in the Pingchuan irrigation district in 2005 showed that about 50% of the irrigation water came from groundwater. The original irrigation pattern—by surface water—has changed into a mixed pattern of both surface and groundwater, which further aggravates the groundwater level decline. The mechanism of interactions between vegetation and hydrologic processes is also relatively complicated in the forest and desert-oasis ecotone. For example, the protective forest, especially the poplar shelterbelt, must be irrigated three times per year because of insufficient natural precipitation; poplar in some areas have experienced withering and even death when irrigated less than three times per year since the water diversion scheme was into effect. Artificial sand-fixing vegetation (*Haloxylon ammodendron*, *Caragana Korshinskii Kom*, *Hedysarum scoparium*, etc.) and natural desert plants (*Tamaricaceae, Sagina saginoides*) both rely on precipitation (Xu et al., 2006), and natural shrubs (*Zygophyllaceae*, etc.) rely on both precipitation and groundwater. The growth of other vegetation (*Tamarix aphylla (Linn.) Karst., Phragmitescommunis*) is also affected by variation in the groundwater depth (Zhao et al., 2003a).

According to the field-determined radiation zone, the main plant community in the study area consisted of *Haloxylon ammodendron*, *Caragana Korshinskii Kom*, *Hedysarum scoparium*, *Zygophyllaceae*, etc. The coverage of annual ephemeral plants was small, making only a minor contribution to the vegetative productivity (NDVI). The distribution area of NDVI in the 0–0.1 range in the radiation zone varied greatly and was the most sensitive. The distribution area of all the NDVI classifications tended to increase from 1987 to 2010. The relatively small distribution area of NDVI was affected by the irrigation decline attributable to the water diversion scheme in the Heihe River (Figure 8). The correlation coefficients between the distribution area of NDVI in 0–0.1 range, and total irrigation amount (both surface water and wells), precipitation, and groundwater depth, were 0.760, 0.976, and 0.438, respectively. The relationship

Table 5 Correlation between precipitation and NDVI of both desert and sand dunes vegetation[a)]

Precipitation	NDVI of desert vegetation			NDVI of sand dunes vegetation		
	April–June	July–September	April–September	April–June	July–September	April–September
Cumulative precipitation from October to April	0.793*	0.729*	0.761*	0.761*	0.627	0.736*
Cumulative precipitation from May to September	0.339	0.283	0.108	-0.014	0.302	0.232

a) * Significant correlation at 0.05.

between the NDVI of non-irrigated desert vegetation and precipitation in the non-growing season (October–April) is significantly correlated. But the relationship between the NDVI of non-irrigated sand dunes vegetation from July to September and precipitation in the non-growing season (October–April) is not significantly correlated (Table 5). This result shows that the growth of zonal desert vegetation was affected by precipitation. The growth of zonal sand dune vegetation in the early growing stage is affected primarily by soil moisture, while that in the late growing stage might be affected by precipitation, groundwater depth, and lateral infiltration from irrigation water. Although surface water irrigation decreased and groundwater depth dropped after implementation of the water diversion scheme in the Heihe River, the vegetation productivity of the protective forest in the whole has not yet been significantly affected, while vegetation productivity in the oasis fringe has improved due to the abundant precipitation of recent years.

5 Conclusions

This study, based on one typical irrigation district, has shown that the hydrologic processes have been significantly changed in the desert-oasis ecotone of the Hexi Corridor, especially since the implementation of the water diversion scheme in the Heihe River in 2000. The results show that the available amount of surface water has been decreasing, the amount of groundwater mining has been increasing, and the groundwater level has been dropping. The annual average amount of surface water irrigation after implementation of the water diversion scheme decreased by 1.498×10^7 m^3, and the annual average amount of well irrigation increased by 1.457×10^7 m^3. The groundwater depth before the water diversion scheme varied between 2.44 and 3.19 m (average 2.73±0.24 m), whereas that after the water diversion scheme varied between 3.08 and 4.01 cm (average 3.79±0.62 m). The distribution area of groundwater depth of <3 m has decreased and the area of >3 m has increased. From 1985 to 2005, the distribution area of 2–3 m groundwater depth decreased from 3612 hm^2 (51.3%) to 394 hm^2 (5.6%). The distribution area of 4–5 m groundwater depth, however, increased from 853 hm^2 (12.1%) to 3843 hm^2 (54.6%). NDVI meanwhile presents an increasing trend in the desert-oasis ecotone, indicating that although the hydrologic processes in the oasis were changed, theses changes have not yet significantly affected vegetation productivity in the desert-oasis ecotone.

This work was supported by the National Natural Science Foundation of China (Grant No. 41125002). We thank two anonymous referees for valuable suggestions concerning this manuscript.

Chang X L, Zhang N, Sun X Y, et al. 2012. Landscape change during the oasis expansion process in an arid zone (in Chinese). J Desert Res, 32: 857–862

Chen X, Luo G P. 2008. Research and progress of oasis ecology in arid areas (in Chinese). Arid Land Geogr, 31: 487–495

Chen Y N, Li W H, Chen Y P, et al. 2007. Water conveyance in a dry riverbed and ecological restoration in the lower reaches of the Tarim River, China (in Chinese). Acta Ecol Sin, 27: 538–545

Dawson T E, Pate J S. 1995. Seasonal water uptake and movement in the root systems of phraeatophytic plants of dimorphic root morphology: A stable isotope investigation. Oecologia, 107: 13–20

Fang C L, Bao C, Huang J C. 2007. Management implications to water resources constraint force on socio-economic system in rapid urbanization: A case study of the Hexi Corridor, NW China. Water Resour Manag, 21: 1613–1633

Jia B Q. 1996. Approach to some theoretical problems on oasis landscapes (in Chinese). Arid Land Geogr, 19: 58–65

Jia B Q, Ci L J, Han D L, et al. 2000. Review and problem analysis of oasis research in arid regions (in Chinese). Adv Earth Sci, 15: 381–388

Jiao Y M, Ma M G, Xiao D N. 2003. Research on the landscape patterns of Zhangye Oasis in the middle reaches of the Heihe River (in Chinese). J Glaciol Geocryol, 25: 94–99

Han D L. 1999. The progress of research on oases in China (in Chinese). Sci Geogr Sin, 9: 313–319

Jolly I D, Walker G R. 1996. Is the field water use of *Eucalyptus largiflorens* F. Muell. affected by short-term flooding? Australia J Ecol, 21: 173–183

Li Q S, Zhao W Z, Ma C C. 2004. Theory and application of forage and livestock coupling for mountainous-oasis-desert country in the Heihe River basin—A study of the Linze demonstration area in the middle reaches of the Heihe River basin (in Chinese). Acta Pratacul Sin, 13: 13–20

Li X Y. 2011. Mechanism of coupling, response and adaptation among soil, vegetation and hydrology in arid and semiarid regions (in Chinese). Sci Sin Terrae, 41: 1721–1730

Li Y, Xu H. 2008. Water and carbon balances of Haloxylon ammodendron: Integrated study at the physiological, plant, and community level (in Chinese). Arid Land Geogr, 31: 313–323

Markham B L, Barker J L. 1986. Landsat MSS and TM post calibration dynamic ranges, exoatmospheric reflectances and at-satellite temperature. Earth Observation Satell Landsat Techn Notes, 1: 328–343

Matlack G R. 1993. Microenvironment variation within and among forest edge sites in the eastern United States. Biol Conser, 6: 185–194

Mensforth L J, Thorburn P J, Tyerman S D, et al. 1994, Sources of water used by riparian Eucalyptus camaldulensis overlying highly saline groundwater. Oecologia, 100: 21–28

Shi P L, Li W H, Wang J X. 2002. Three-dimensional canopy structure in the Timberline ecotone dominated by *Abies faxoniana* (in Chinese). Acta Ecol Sin, 22: 1819–1824

Thorburn P J, Walker G R. 1994. Variations in stream water uptake by *Eucalyptus camaldulensis* with differing access to stream water. Oecologia, 100: 293–301

Wales B A. 1972. Vegetation analysis of north and south edges in a mature oak-hickory forest. Ecol Monogr, 42: 451–470

Wang P Y, Li K Q, Gao W Y, et al. 2011. Glacier changes in the Heihe River basin over the past 50 years in the context of climate changes (in Chinese). Resour Sci, 33: 399–407

Wang Y X, Zhang X L, Kuo Y P. 1999. Study on oasis regional systems and the spatial development (in Chinese). Arid Land Geogr, 22: 72–79

Xu H, Li Y. 2006. Water use strategy of three central Asian desert shrubs and their responses to rain pulse events. Plant Soil, 285: 5–17

Xu H Q. 2008. Comparison of the models for the normalization of Landsat imagery (in Chinese). Geo-Inf Sci, 10: 294–301

Yan J F, Chen X, Luo G P, et al. 2006. Temporal and spatial variability response of groundwater level to land use/land cover change in oases in arid areas. Chin Sci Bull, 51(Supp1): 51–59

Yuan W, Guo Z L, Wu J L, et al. 2006. Analysis of water resources carrying capacity of the Heihe River basin (in Chinese). Acta Ecol Sin, 26: 2108–2114

Zhang L Y, Wang L A, Shi Q. 1995. On the oasis genesis types and evolution in time and space (in Chinese). J Arid Land Resour Environ, 9: 32–43

Zhang X S, Shi P J. 2003. Theory and practice of marginal ecosystem management (in Chinese). Acta Bot Sin, 45: 1137–1138

Zhao C Y, Wang Y C. 2005. Study on spatial and temporal dynamic of soil water content in a desert-oasis ecotone (in Chinese). J Soil Water Conserv, 19: 124–127

Zhao W Z, Chang X L, He Z B. 2003a. The response of distribution patterns of protective forest in Ejina to hydrological processes (in Chinese). Sci Sin Terrae, 33(Suppl): 21–30

Zhao W Z, Chang X L, Li Q S, et al. 2003b. Relationship between the structural component biomass of a reed population and ground water depth in a desert oasis (in Chinese). Acta Ecol Sin, 23:1138–1146

Zhao W Z, Niu Z R, Chang X L, et al. 2010. Water consumption in an artificial desert oasis based on net primary productivity. Sci China Earth Sci, 53: 1358–1364