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Policies, Land Use, and Water Resource Management in an Arid Oasis Ecosystem

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Abstract This paper addresses two questions concerning the relationship between state policies and environmental transformation in China in the past four decades. The first one deals with the promotion of agricultural productivity since the 1980s; the second, the water conservation measures as a response to the water crisis that peaked in the early 2000s. We had chosen Minqin County in northwestern China, one of the most fragile arid oasis systems in the world, as the study area. We found that the irrigated farmland in up and midstream areas had greatly expanded between the 1980s and the 2000s under the government policy of promoting commodity grain production. As a result, the runoff flowing into Minqin Oasis had reduced 80 % from the 1950s to early 2000s. Irrigated farmland in Minqin Oasis expanded 15.76 % from 1995 to 2000. In the 2000s, because of the changing policy discourse that has shifted from productivity to conservation, a new set of environmentally framed policies has restructured agricultural production in Minqin by 2005. These new policies included establishing a watershed-level water management system, promoting drought resistant crops, introducing water-saving irrigation measures, and forced reduction of irrigated farming acreage. These policies have produced positive results in terms of greater coverage of vegetation, rising ground water table, and reduction of evaporation. Nevertheless, new policies have also brought new challenges to both farmers and policy makers to keep the balance between poverty reduction and environmental sustainability in Minqin Oasis in the historically poor region in China's Northwest.

Keywords State policies · Watershed management · Agricultural restructuring · Land degradation and restoration · Remote sensing data analysis

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Introduction

The word "oasis" comes from Ancient Greek and means "a fertile area in deserts or drylands with a continuous water supply" (Krevisky and Jordan 1989). The oases of Central Asia, Middle East, North Africa, and Northwest China were sites of ancient civilizations in history (Dikareva 2006; Yamna 2010). Today, oases are still very important for people living in drylands covering approximately 41 % of the world's land surface and being home to more than 38 % of the total global population of 6.5 billion (Reynolds et al. 2007; UNCCD 2008), because they provide habitats for animals and humans of drylands (Mainguet 1991). Take northwest China as an example, oases lying in the arid regions only occupy 4–5 % of the arid lands in China, but support 90 % of the population and produce 95 % of the social wealth of the arid lands (Li et al. 2007). Water supply is vitally important for the sustainability of oases because of sustaining the lives of local people, livestock and agriculture, as well as

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environment health and ecosystem service. However, climate change, irrational land use, mismanagement of water resources, and the competition for water from industry and urbanization had dramatically bring fresh water scarcity in oases of the arid regions (Muhammad and Mohsen 2000; Ragab and Prudhomme 2002; UNDP 2006; Alemayehu et al. 2009; Vörösmarty et al. 2010; Wada et al. 2010; Shahid 2011).

Using RS and GIS technologies, Gebresamuel et al. (2010) found that the rapid increase in cultivated land and decrease in forest and shrub lands over four decades result in land degradation, weakening of water-storage capacity, and reduction of surface runoff in two catchments of Northern Ethiopia. The same patterns have also been reported in Southern Great Plains (Ferguson and Maxwell 2012) and the San Pedro of Arizona (Stromberg et al. 1996) in USA, the Hoanib River catchment of northwestern Namibia (Leggett et al. 2003), Hexi Corridor and Tarim Basin of northwest China (Zheng and Yin 2010), even in the largest irrigated area of the world, the region of the Indus, Ganges, and Brahmaputra (Esteban and Albiac 2011). It can be seen that almost all of the oases in the world are suffering from severe water shortages in recent decades.

The water crisis and the fragile arid environment destabilize the oasis ecosystem; consequently, people who live in oases need to carefully manage land and water use. Otherwise, the mismanagement of land and water resources can very easily lead to oasis degradation. Actually, water and land degradation resulting from water deficits and mismanagement has already occurred in many oases located in arid countries and regions, such as China (Li 2010), Central Asia (Karajeh et al. 2002), the Middle East (Adeel 2003; Abbaspour et al. 2009), and North Africa (Rayan et al. 2001; Yamna 2010). Water tables have fallen in a number of countries due to the use of powerful diesel and electric pumps used to extract groundwater (Rodell et al. 2009). Falling water tables and traditional flood irrigation can result in a series of environmental problems, such as vegetation degradation, eolian desertification, and salinization, thus causing the oasis ecosystem crash (Saiko and Zonn 2000; Aleksandrova et al. 2014). Therefore, among all of these factors affecting oases ecosystem survival, land use and water resources management determined by regional and national policies are thought as the most important factors.

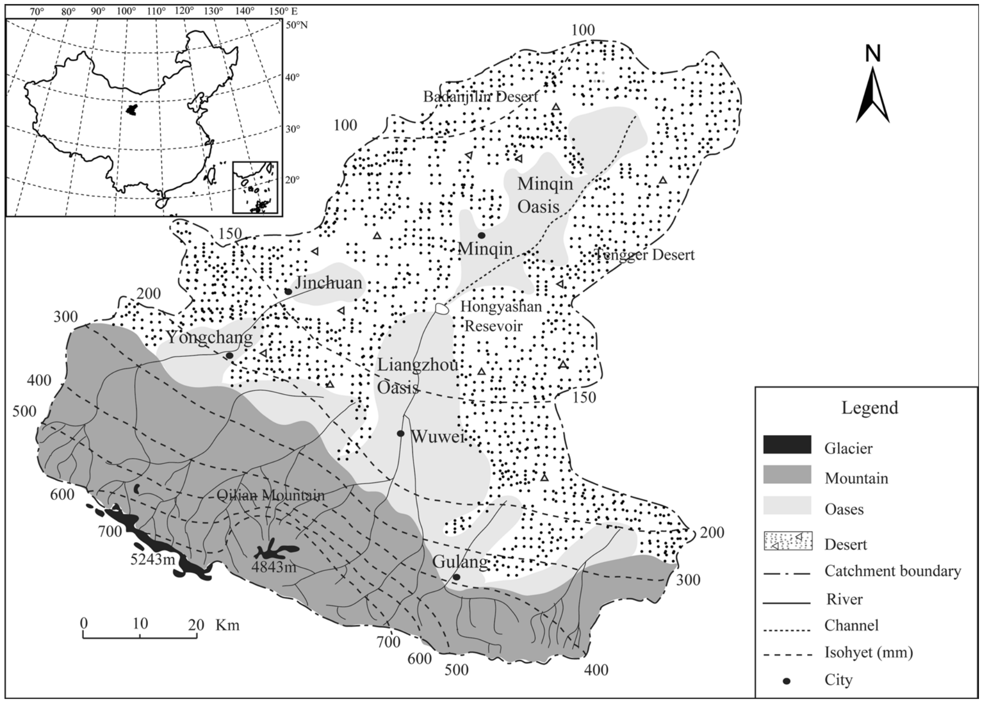
Along with the leaping development of aerospace technologies, RS and GIS have already become one of the most important methods monitoring land use change and land degradation patterns (Nemani and Running 1995; Defries and Townshend 1999; Giri et al. 2003; Latifovic et al. 2004; Kovalskyy and Roy 2013). This, therefore, provides feasibility for studying oases ecosystem changes and managements. Using RS and GIS accompanied with traditional field surveys and data analysis, this paper addresses a typical and common case occurring in Minqin Oasis of the northwest China. We try to (1) reveal land use change patterns in Minqin Oasis over 20 years; (2) assess its impacts on water resources and ecological environment; and (3) analyze the influence of state policies on land use changes and water resources management. Our research aims to help people to understand the importance of policies, and their influence on land use and water resources management, and provide a guideline on how to improve the efficiency of scarce water resources for the other arid oases ecosystem in the world.

Study Areas

The Minqin Oasis' geographical coordinates are 102°45′–103°55′N and 38°20′–39°10′E. It is located in the downstream area of the Shiyang River, adjacent to the Badanjilin Desert in the west and Tengger Desert in the east (Fig. 1).The Shiyang River, which is about 300-km long, is the easternmost inland river in northwest China and originates in the Qilian Mountain Ranges, which run from the southeast to the northwest with an altitude ranging between 2700 and 4500 m ASL. From the Qilian Mountains, the Shiyang River flows into the pre-mountain alluvial–proluvial plain, which is a flat terrain with fertile soil. Inside the plain, oases are found on both sides of the river and at various spring outlets. The Liangzhou and Gulang oases are located in the southern part of the plain with altitudes ranging between 1400 and 2500 m above sea level (ASL). The Minqin Oasis is located in the northern part of the plain with an altitude of less than 1400 m ASL. The climate in the Shiyang River catchment is characterized as a zonal climate, which causes the regional unbalance of water resources distribution; the precipitation decreases from 700 mm in the Qilian Mountains, which has a subhumid climate, to less than 150 mm in the Minqin Oasis area, which has an arid climate (Fig. 1).

The Minqin Oasis, which includes the Hongyashan irrigation area (HIA), the Nanhu irrigation area (NIA), the Changning irrigation area (CIA), and the irrigation area along the Shiyang River, which runs from the south end of the Minqin Oasis to the Hongyashan Reservoir (referred to as the along river irrigation area, ARIA) (Fig. 2), covers an area of about 2000 km^2 and is located inside Minqin County. The total area of Minqin County is 1.59×10^4 km^2, of which the Minqin Oasis occupies 13 % of the total area. Due to its distance from the ocean and the adjacent Badanjilin and Tengger Deserts, the Minqin Oasis has a typical arid continental climate. Such a climate is characterized by low and irregular rainfall with an annual

Fig. 1 Location of the study area



average of 125 mm, and strong evaporation with an annual average of 2640 mm, with an annual average temperature of 6.3–8.9 °C. The accumulated active temperature $\geq$0 °C is 3655 °C and $\geq$10 °C is about 3114 °C. Due to the arid climate, agriculture depends heavily on irrigation.

The Minqin Oasis has existed for over 2000 years. According to the archeological evidence and historical documents, Xie et al. (2009) showed that people first started to exploit the Minqin Oasis in the 2nd century BC; the oasis area increased from 14,800 ha in the second century BC to 123,170 ha in 1998. At present, irrigation farming and sheep herding are the main livelihoods of the local people living in the Minqin Oasis. Farmers and herders account for over 90 % of the total population. The per capita area of cultivated farmland in the Minqin Oasis is about 0.3–0.35 ha, which is higher than in other regions of China.

The Shiyang River and groundwater are the main water resources available to local inhabitants. The river's annual average runoff in the midstream area is about 13.7×10^8 m^3, but the water flowing into the Minqin Oasis was not more than 5×10^8 m^3 after the 1950s and only 0.98×10^8 m^3 in 2003. The groundwater table of the Minqin Oasis was 10–30 m deep and the thickness of the shallow phreatic zone was 60–100 m in 2003. The soil particles of the oasis' phreatic zone gradually became thinner from south to north, which caused the groundwater to flow slowly northward. Along the flow direction, the groundwater chemical pattern changed from a sulfate type to a chloride type (Zhang et al. 2012; Chen and Feng 2013). The total dissolved solids (TDS) in the groundwater increased from 0.83–1.97 g l^{-1} in the south to 1–3 g l^{-1} in the midstream area, increasing again to 3–9 g l^{-1} along the northern part of the oasis (Chen and Feng 2013). The maximum TDS can even reach 17 g l^{-1} in some parts of the northern margin (Chen and Feng 2013). Vertically, the shallow groundwater is salty and the deep groundwater is fresh (Zhu et al. 2007), which results the local people to overexploit the deep water. In 2003, the total consumed water resource in the Minqin Oasis was 7.82×10^8 m^3, including 6.65×10^8 m^3 groundwater. Around 6.87×10^8 m^3 was used to irrigate farmland, 0.76×10^8 m^3 was used to irrigate forests and grassland, 0.09×10^8 and 0.03×10^8 m^3 were used for rural and urban living purposes, respectively, and 0.07×10^8 m^3 was used by industry. The average water consumption of irrigated farmland is 5100–6100 m^3 ha^{-1}, but the GDP per cubic meter of water was only 0.71 USD in 2003 (The Water Resource Bureau of Minqin County). The GDP from the irrigated agriculture accounts for 85 % of the total GDP for the Minqin Oasis area. Agricultural water use and management not only directly control the oasis ecosystem's pattern, but also affect the sustainable development of local society, economy, and environment (Mainguet 1991; Li et al. 2006; Zhang et al. 2008; Zheng and Yin 2010).

Methods

Remote sensing monitoring was used to identify changes in oasis area and land use during different periods. Environmental data, including climate and groundwater level, and

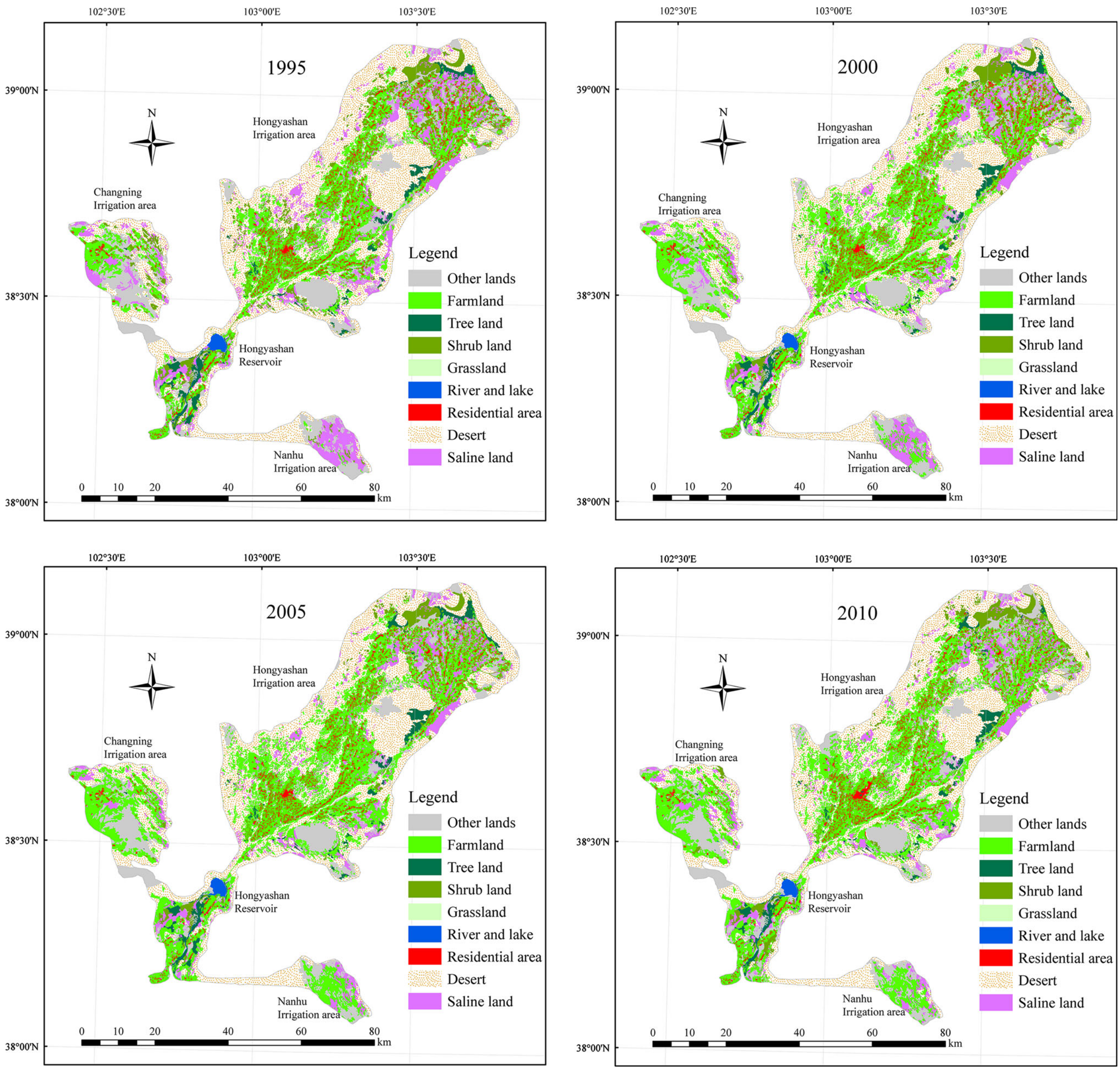


Fig. 2 The land use patterns in 1995, 2000, 2005, and 2010 in Minqin Oasis

social data including population levels and farmland area were collected and analyzed to evaluate the influence of human activities in the oasis ecosystem. In addition, some information from the field investigation and publication were also utilized to support the discussion.

Remote Sensing Monitoring

The remote sensing data used in this study comprised images with a spatial resolution of 30 m taken by the Thematic Mapper (TM) sensors on the Landsat-5 satellite in 1995, 2000, 2005, and 2010, and then by the Enhanced Thematic Mapper plus (ETM+) sensor on the Landsat-7 satellite in 2000, 2005, and 2010. The near infrared (Band 4), green (Band 3), and blue (Band 2) bands were combined to build a standard false-color image to monitor the changes in the oasis area and land use/cover areas; in a 432 NIR composite image, different vegetation types can be easily distinguished from the other lands because they are depicted in varying shades of red (Lillesand et al. 2007). The late summer and early autumn images were selected because they better reflected the vegetation conditions (Wang et al. 2004a). All of the image data were then projected into a uniform Albers Conical Equal Area coordinate system and were geometrically rectified based on the digitized topographic map at a scale of 1:100,000. After geometric rectification, the mean location error of the images was less than 1 pixel (30 × 30 m).

Training areas with typical image features were selected first in the 2010 images; next, a field survey was carried out using GPS positioning to confirm actual land use/cover of the training areas. Comparing actual land use types and the corresponding image features, land use classification criteria were established. Based on the criteria, all images were interpreted manually using ARCGIS 9.3. In order to confirm the reliability of the interpreted results, a field survey was conducted again to resolve questionable areas in the autumn of 2013. Finally, the confusion-matrix method was used to validate the reliability of interpreted results. The verification results show that overall accuracy reaches 95.1 % and that the Kappa coefficient is 0.8977.

Environmental and Social Data Collection

Water resource data used in this research comprise the Shiyang River's annual mean runoff in the sections located in front of the Qilian Mountain and in the section located in the Minqin Oasis inlet from 1962 to 2011, and the groundwater table and quality in the Minqin Oasis from 1998 to 2011. The annual mean runoff was calculated using the measured runoff through the observation cross section per unit area per unit time. The original measured runoff data were collected from the Shiyang River Basin Management Bureau (SRBMB). The Water Resource Bureau of Minqin County has regularly observed the groundwater table and quality in the Minqin Oasis since 1998. The 59 observation wells for the groundwater table and the 74 observation wells for groundwater quality were scattered about in a fairly equal manner inside the oasis (Chen and Feng 2013). Among 59 observation wells for groundwater table in Minqin Oasis, there are 41 wells in the HIA, 7 wells in the CIA, 4 wells in the NIA, and 7 wells in the ARIA. Among 74 observation wells for groundwater quality in Minqin Oasis, there are 61 wells in the HIA, 5 wells in the CIA, 3 wells in the NIA, and 5 wells in the ARIA. Water table measurement and water sample tests have been conducted each spring and fall. By calculating the measured and tested data, we obtained the annual mean water table and water quality for the oasis and different irrigation areas. The annual mean air temperature, annual precipitation, and annual evaporation in the Minqin Oasis from 1953 to 2011 were collected from the local meteorological station. Social data used in the research include the population and irrigated farmland areas in Wuwei, Gulang, and Minqin Oases from 1950 and 2011, and were collected from the Wuwei and Minqin Statistical Agencies.

Field Survey and Publication Analysis

Biyearly field surveys for determining land use patterns, water use, and land degradation in the Minqin Oasis were conducted from 2005 to 2013 to understand the environment change process and causes. Two basin-wide surveys, involving water conservancy facilities and vegetation distribution and land use patterns, were conducted in Summer of 2010 and Autumn of 2013. The other field surveys were conducted in four irrigation areas of the Minqin Oasis and the margin region between desert and oasis. Based on remote sensor monitoring results and data collected, 125 villages out of the total of 249 in Minqin County with the evident land use changes were selected in this research. Interview surveys at farm household, observation, and measurement for land use and water use were made in 125 villages in past 9 years.

Additionally, publication research and results about soil and vegetation changes in the Minqin Oasis were collected and analyzed in order to help to grasp the relationship between water use and management and changes in the local ecosystem.

Statistical Analysis

Using the SPSS 13.0 statistical software for Windows and Microsoft Excel, the annual change rates and standard deviations for runoff, groundwater tables, and groundwater quality were all calculated. The significance of the annual change in each factor was evaluated using a Bivariate Pearson regression analysis at a significance level of 0.01. In addition, the non-parametric Mann–Kendall test at the significance levels of 0.01, 0.05, and 0.10. (Table 5) was also used in this research to further evaluate the temperature, precipitation, runoff, groundwater table, and quality trends with time.

Results

Land Use Change

The remote sensing monitoring results revealed that the oasis areas, including forest and shrub lands, grassland, farmland, water, and residential areas, were 1985.94, 2122.59, 2298.85, and 2285.96 km^2 in 1995, 2000, 2005, and 2010, respectively (Table 1; Fig. 2). The area of the oasis increased by 312.91 km^2 from 1995 to 2005. After 2005, there was a slight decrease; the decrease area is about 12.89 km^2. Tables 2, 3, and 4 show the transfer areas of the different land use types in the monitoring area from 1995 to 2010.

Table 1 Areas of different land use types in Minqin Oasis (km^2)

Year	Area of different land use types (km^2)											
	Tree land	Shrub land	River	Reservoir	Residential land	Sand land	Gobi	Saline land	Farmland	Grassland	Others	Total
1995	106.45	216.88	3.66	18.18	131.38	1306.20	446.11	507.14	1153.29	356.10	284.28	4529.67
2000	116.36	113.23	3.74	14.66	135.49	1303.76	405.55	421.48	1421.91	316.59	276.28	4529.67
2005	121.79	116.71	3.74	17.22	119.38	1254.69	378.73	332.76	1626.89	292.11	264.64	4529.67
2010	95.35	160.10	3.74	16.41	115.13	1207.72	376.93	332.73	1606.26	288.97	326.33	4529.67

From Table 2, it can be seen that the farmland increased by 268.62 km^2 from 1995 to 2000, and occupied 23.28 % of the total farmland in 1995. Of the increased farmland, 32 % came from saline land, 28 % from shrub land, and 20 % from sand land and the Gobi Desert, and 18 % from grassland. The shrub land area declined by 103.03 km^2 and occupied 47.64 % of the total shrub land area in 1995. Overall, from 1995 to 2000, opening up wasteland was the main land use type, the Minqin Oasis enlarged by 136.65 km^2 and presented a pattern of increasing farmland and decreasing shrub land.

From 2000 to 2005, the farmland increased by 205.98 km^2 and occupied 14.49 % of the total farmland of 2000. Among the newly increased farmlands, 40 % came from saline land, 30 % from sand land and the Gobi, and 22.5 % from grassland. During this period, saline land, sand land, the Gobi, grassland, and rural residential lands all decreased, while farmland, forest, and shrub lands increased. On the whole, the Minqin Oasis enlarged 176.26 km^2 with a pattern of increasing farmland and decreasing grassland from 2000 to 2005 (Table 3). However, measures for prevention and control of desertification such as afforestation campaign also led forest and shrub land to increase in this period.

After 2005, the transfer from the other land use types to farmland stopped and the farmland had reduced by 21.63 km^2 from 2005 to 2010 (Table 4). Among the reduced farmland, most had been transferred into forest and shrub lands as well as grassland. From 2005 to 2010, the Minqin Oasis shrank by 12.89 km^2 demonstrating a pattern where most of the farmland decreased.

Figure 3 shows the regional pattern of farmland transfer. From 1995 to 2000, newly increased farmland was mainly distributed in the CIA, the NIA, and in the surrounding areas of the HIA. The newly increased farmlands occupied 85.05, 36.00, and 15.98 % of the total farmland in CIA, NIA, and HIA in 2000, respectively. From 2000 to 2005, the growth of farmland in the HIA and CIA was slow, while steadily increasing in NIA. The newly increased farmland occupied 59.16, 12.55, and 9.71 % of the total farmland in NIA, CIA, and HIA in 2005, respectively. From 2005 to 2010, the farmland growth basically stopped entirely; the decreasing farmland area was larger than the increasing farmland area. The newly increased farmland only occupied 6.9, 3.23, and 1.5 % of the total farmland in NIA, CIA, and HIA in 2010, respectively. The results show that opening up wasteland including saline land, grassland, wasted, and sand lands mainly occurred in the CIA and the NIA, although there is no fresh river water in the two regions.

Water Resources Change

Figure 4 shows the Shiyang River's annual mean runoff change from 1962 to 2011. The annual mean runoff flowing out the Qilian Mountains was 13.74×10^8 m^3 and has shown no significant ($P = 0.874$) change since 1962. However, the runoff flowing into the Minqin Oasis significantly ($P = 0.000$) decreased at a rate of 5.6×10^6 m^3 per year. The Mann–Kendall test results on the runoff trends with the time series can be seen in Table 5. The annual mean runoff flowing into the Minqin Oasis was 2.17×10^8 m^3 from 1962 to 2011; the maximum value was 5.11×10^8 m^3 in 1967, and the minimum value was 0.71×10^8 m^3 in 2001.

Figure 5 shows the groundwater table change in the Minqin Oasis. The average groundwater tables significantly (Table 5) decreased by 6.84, 7.47, 10.01, 4.3, and 2.73 m, respectively, in the Minqin Oasis, the HIA, the CIA, the NIA, and the ARIA from 1998 to 2011. It can be seen that the groundwater tables in the CIA and HIA having more farmland had rapidly decreased.

Figure 6 shows the change in groundwater quality in the Minqin Oasis and four irrigation areas from 1998 to 2011. The average value of TDS in the groundwater significantly (Table 5) increased by 0.77 g l^{-1}, 0.76 g l^{-1}, 0.45 g l^{-1}, 1.01 g l^{-1}, and 0.10 g l^{-1}, respectively, in the Minqin Oasis, the HIA, the CIA, the NIA, and the ARIA. The NIA, the most important reclamation region and totally depending on groundwater irrigation, had the maximum increasing rate of TDS.

Change of Climate

In the Minqin Oasis, the annual mean air temperature significantly (Table 5) increased by a rate of 0.03 °C per

Table 2 Transfer areas among different land use types in Minqin Oasis from 1995 to 2000 (km^2)

Year	2000												
	Land use types	Tree land	Shrub land	River	Reservoir	Residential land	Sand land	Gobi	Saline land	Farmland	Grassland	Others	Total
1995	Tree land	101.79	0.00	0.00	0.00	0.00	0.47	0.18	0.34	2.25	1.04	0.37	106.45
	Shrub land	0.00	101.02	0.00	0.08	0.11	17.97	3.32	2.45	75.65	14.48	1.19	216.88
	River	0.00	0.00	3.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.66
	Reservoir	0.00	0.25	0.09	14.58	0.12	0.00	0.00	0.21	0.91	0.04	1.99	18.18
	Residential land	0.00	0.00	0.00	0.00	131.38	0.00	0.00	0.00	0.00	0.00	0.00	131.39
	Sand land	9.97	1.41	0.00	0.00	0.04	1200.30	56.01	2.69	33.12	2.65	0.00	1306.20
	Gobi	3.32	2.11	0.00	0.00	0.00	66.71	344.44	0.16	28.82	0.52	0.00	446.11
	Saline land	0.31	0.16	0.00	0.00	0.22	8.72	0.00	407.68	85.02	2.44	2.59	507.14
	Farmland	0.97	1.57	0.00	0.00	3.32	4.56	0.57	4.02	1131.65	5.08	1.55	1153.29
	Grassland	0.00	6.71	0.00	0.00	0.10	4.19	1.02	3.02	51.41	289.66	0.00	356.10
	Others	0.00	0.00	0.00	0.00	0.19	0.84	0.00	0.91	13.08	0.67	268.59	284.28
	Total	116.36	113.84	3.74	14.66	135.49	1303.76	405.55	421.48	1421.91	316.59	276.28	4529.67

Table 3 Transfer areas among different land use types in Minqin Oasis from 2000 to 2005 (km^2)

Year	2005												
	Land use types	Tree land	Shrub land	River	Reservoir	Residential land	Sand land	Gobi	Saline land	Farmland	Grassland	Others	Total
2000	Tree land	109.93	1.29	0.00	0.00	0.00	0.00	0.00	1.00	4.14	0.00	0.00	116.36
	Shrub land	0.20	97.47	0.00	0.55	0.16	0.00	0.00	0.65	2.18	12.62	0.00	113.84
	River	0.00	0.00	3.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.74
	Reservoir	0.00	0.00	0.00	14.60	0.00	0.00	0.00	0.00	0.06	0.00	0.00	14.66
	Residential land	0.48	0.35	0.00	0.19	117.29	0.01	0.00	2.52	13.77	0.87	0.01	135.49
	Sand land	0.64	0.80	0.00	0.00	0.10	1252.08	0.10	1.54	47.86	0.23	0.42	1303.76
	Gobi	6.22	5.14	0.00	0.00	0.01	1.34	378.10	1.07	13.57	0.10	0.00	405.55
	Saline land	0.60	2.50	0.00	0.21	0.25	0.12	0.03	315.39	82.28	9.47	10.64	421.48
	Farmland	2.38	7.41	0.00	1.58	0.93	0.91	0.50	2.32	1400.47	4.49	0.93	1421.91
	Grassland	0.92	1.38	0.00	0.11	0.27	0.18	0.00	6.72	43.89	262.91	0.19	316.59
	Others	0.41	0.36	0.00	0.00	0.37	0.05	0.00	1.55	19.66	1.43	252.45	276.28
	Total	121.79	116.71	3.74	17.22	119.38	1254.69	378.73	332.76	1627.89	292.11	264.64	4529.67

Table 4 Transfer areas among different land use types in Minqin Oasis from 2005 to 2010 (km^2)

Year	2010												
	Land use types	Tree land	Shrub land	River	Reservoir	Residential land	Sand land	Gobi	Saline land	Farmland	Grassland	Others	Total
2005	Tree land	90.61	21.51	0.00	0.00	0.02	0.00	0.00	1.21	0.75	7.09	0.60	121.79
	Shrub land	0.45	104.86	0.00	0.00	0.12	0.00	0.00	1.34	3.27	4.75	1.91	116.71
	River	0.00	0.00	3.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.74
	Reservoir	0.00	0.00	0.00	16.41	0.00	0.00	0.00	0.00	0.00	0.00	0.82	17.22
	Residential land	0.15	0.25	0.00	0.00	106.90	0.37	0.00	1.03	6.98	0.76	2.92	119.38
	Sand land	0.00	5.29	0.00	0.00	0.00	1201.80	0.00	6.28	1.79	13.11	26.41	1254.69
	Gobi	0.00	0.96	0.00	0.00	0.00	1.41	375.65	0.20	0.49	0.00	0.02	378.73
	Saline land	1.43	1.66	0.00	0.00	0.82	0.69	0.97	306.30	9.92	3.78	7.18	332.76
	Farmland	2.64	18.58	0.00	0.00	4.83	1.37	0.16	6.54	1575.02	4.58	14.16	1627.89
	Grassland	0.08	4.93	0.00	0.00	2.44	2.08	0.00	7.40	5.33	253.82	16.04	292.11
	Others	0.00	2.06	0.00	0.00	0.00	0.00	0.14	2.41	2.70	1.07	256.27	264.64
	Total	95.35	160.10	3.74	16.41	115.13	1207.72	376.93	332.73	1606.26	288.97	326.33	4529.67

year from 1953 to 2011. The annual average relative humidity non-significantly decreased by a rate of 0.02 percent per year from 1953 to 2011. The annual precipitation presents a slight and non-significant increasing trend (Fig. 7a). Conversely, the annual evaporation slightly and non-significantly decreased from 1953 to 2011 (Fig. 7b), which can be speculated as a result of descending in wind velocity over the past decades.

Change of Policies, Population, and Irrigated Farmland Area

There were two opposite state policies affecting land use and water resources management in Minqin Oasis in past 50 years. From early 1950s to early 1970s, Chinese government formulated "take grain as the key to the national agriculture (TGK)" policy and encouraged opening up the wasteland and grassland, even devastating forests for arable land. In 1977, Chinese Communist Party Central Committee approved the Hexi Corridor as one of the ten Commodity Grain Bases of China. In 1978, Chinese Communist Party Gansu Provincial Committee published *Eight-year Construction Planning of Commodity Grain Base of Hexi Corridor*, and pointed out that the aims of "rapidly develop agriculture" and "opening up wasteland." Liangzhou and Gulang Oases, located in the middle reach of Shiyang River (Fig. 1), were listed in the Commodity Grain Bases of Hexi Corridor. Therefore, a majority of wasted land, grassland, and forest in Middle reach of Shiyang River were reclaimed into farmland to provide grain for China's eastern regions. People were encouraged to move to these regions for reclaiming. The population in the above two oases significantly increased from 59.1×10^4 people in 1950 to 140.3×10^4 people in 2011 (Fig. 7c). The actual sown area significantly increased from 118.04×10^3 ha in 1950 to 175.77×10^3 ha in 2011 (Fig. 7d). Due to their location in the semi-arid regions, almost all local farmlands need irrigation. In the Liangzhou Oasis, irrigation consumed almost 80 % of the total water resources in the river basin.

The irrational water consumption in the middle reaches caused the volume of water from the Shiyang River flowing into Minqin Oasis to dramatically decrease, while the population in Minqin Oasis also significantly increased from 1950 to 2011 (Fig. 7c). For supplying the increasing population and using the limited water resources, the water from the Shiyang River flowing into the Minqin Oasis is stored in the Hongyashan reservoir which was built in 1965 for most of the year and is only released downstream during the irrigation season (Figs. 1, 8a). At the same time, artificial cement channels have gradually replaced the natural river course in order to

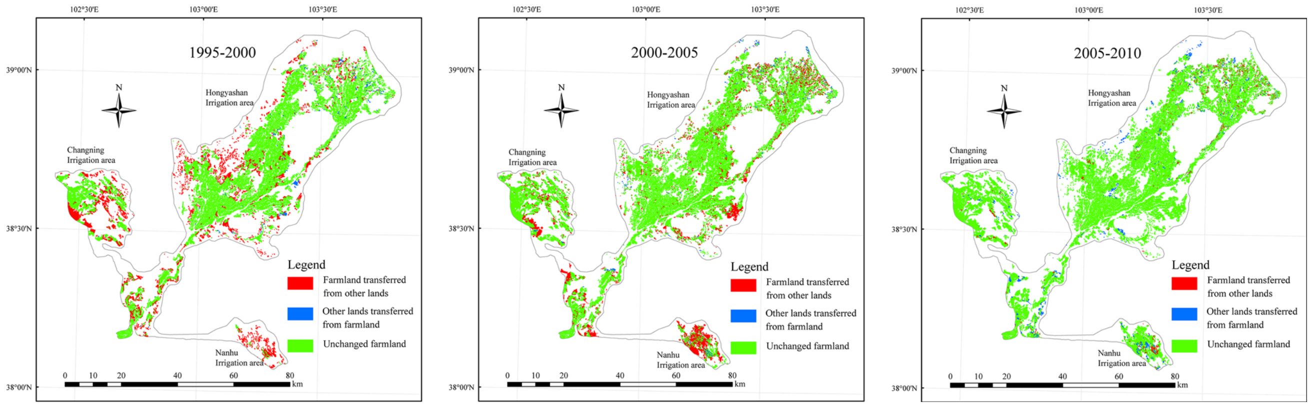


Fig. 3 The land use change patterns from 1995 to 2000, from 2000 to 2005, and from 2005 to 2010 in the Minqin Oasis

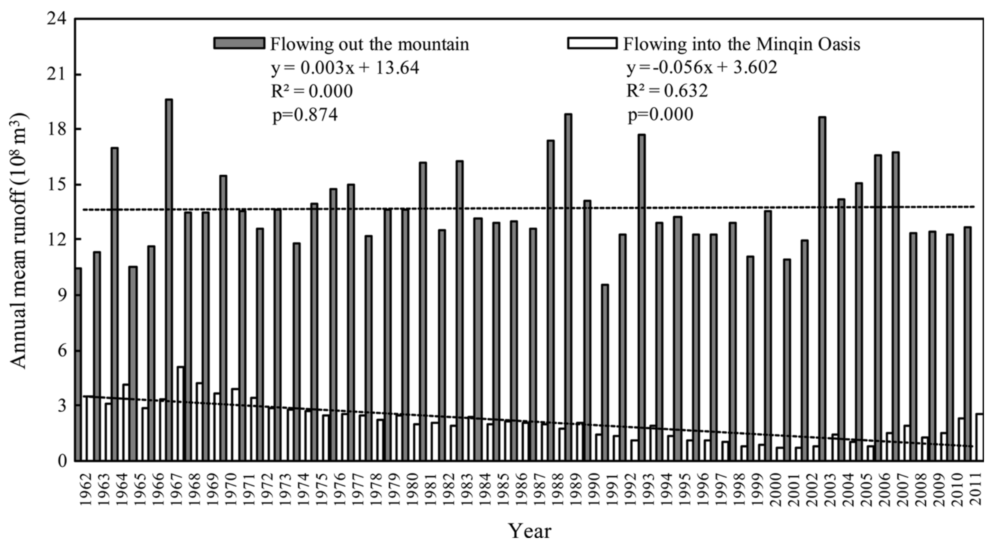


Fig. 4 The runoff change in the Shiyang River flowing out the mountains and flowing into Minqin Oasis from 1962 to 2011

Table 5 The Mann–Kendall (MK) statistical test results for runoff, groundwater table and total dissolved solids, and precipitation in Minqin Oasis

Item	The MK test statistics (Z)
Annual runoff of flowing out the mountain from 1962 to 2011	0
Annual runoff of flowing into the Minqin Oasis from 1962 to 2011	−6.6668
Annual average groundwater table in Minqin Oasis from 1998 to 2011	−4.8176
Annual average groundwater table in Changning irrigation area from 1998 to 2011	−3.7227
Annual average groundwater table in Nanhu irrigation area from 1998 to 2011	−4.5986
Annual average groundwater table in Hongyashan irrigation area from 1998 to 2011	−4.927
Annual average TDS of groundwater in Minqin Oasis from 1998 to 2011	4.5528
Annual average TDS of Groundwater in Changning irrigation area from 1998 to 2011	4.3549
Annual average TDS of groundwater in Nanhu irrigation area from 1998 to 2011	2.8703
Annual average TDS of groundwater in Hongyashan irrigation area	3.959
Annual average precipitation from 1953 to 2011	0

reduce infiltration (Fig. 8b). Under the policy of strengthening the construction of water conservancy facilities, 11,000 wells have been drilled, among which, 250 wells are deep wells with a depth of 300 m and the remaining are shallow wells with a depth of 60–150 m to resolve the shortage of fresh river water since the mid-

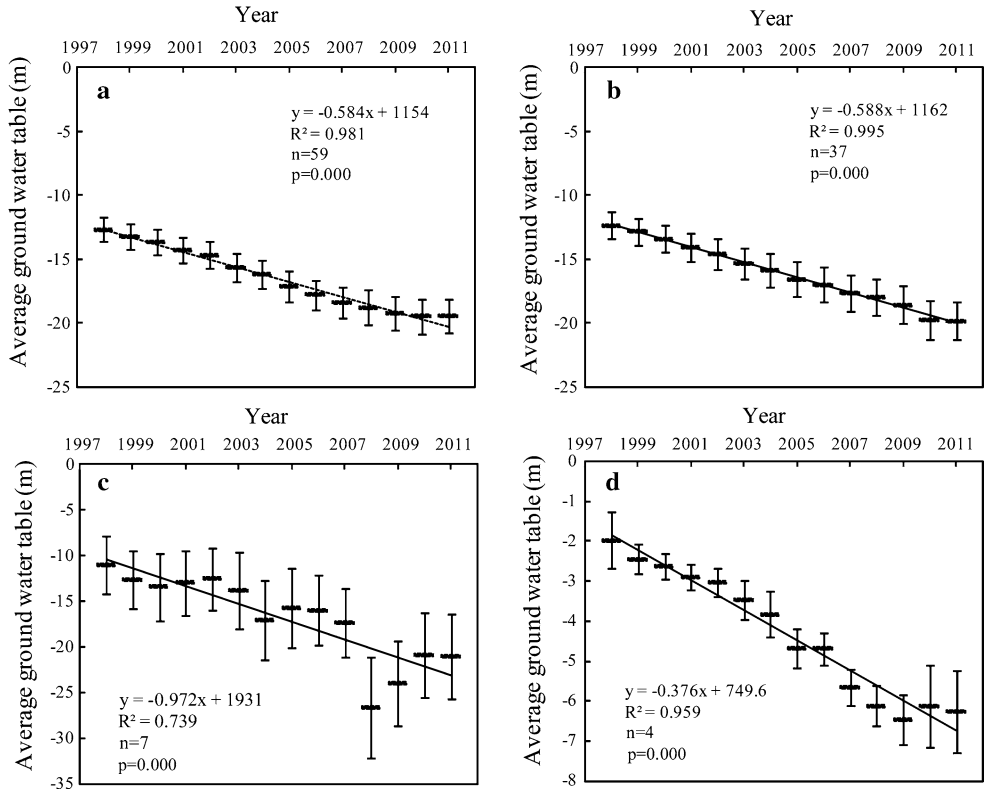


Fig. 5 The average ground water tables from 1998 to 2011 in **a** the Minqin Oasis **b** the Hongyashan irrigation area, **c** the Changning irrigation area, and **d** the Nanhu irrigation area. *Error bars* indicate standard error and *n* means the number of the observed wells

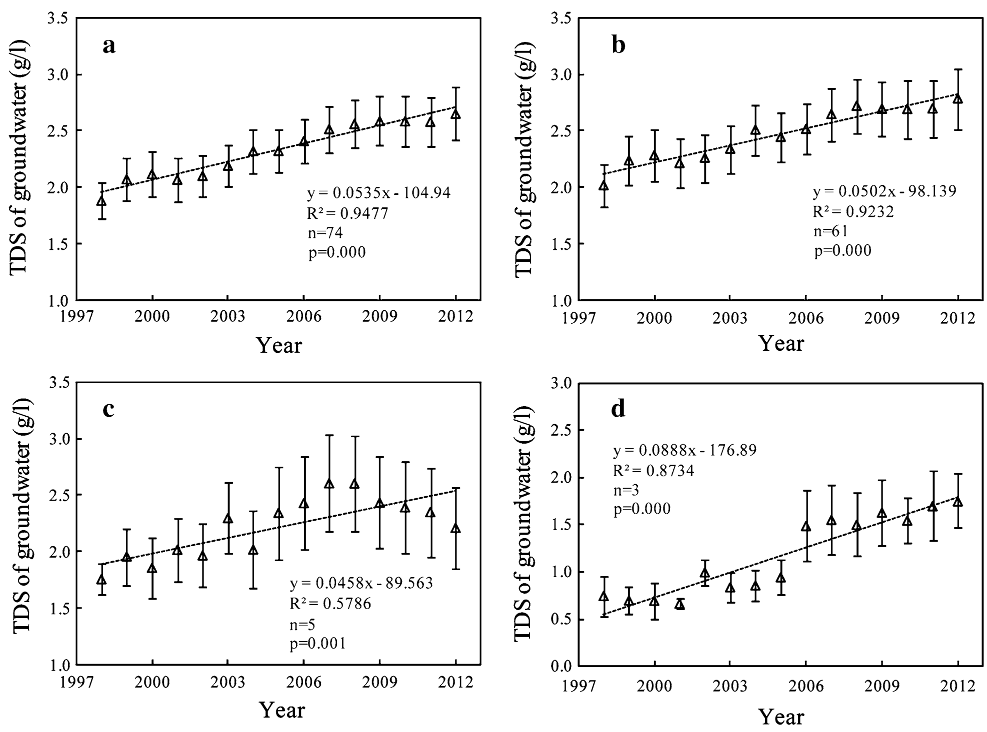


Fig. 6 The averagely total dissolved salt in the ground water from 1998 to 2012 in **a** the Minqin Oasis, **b** the Hongyashan irrigation area, **c** the Changning irrigation area and **d** the Nanhu irrigation area. *Error bars* indicate standard error and *n* means the number of the observed wells

1970s. In addition, a great area of saline land, shrub land, and grassland in NIA and CIA having a shallow groundwater table were reclaimed into farmland.

"Ecological construction (EC)," as the second policy affecting land use and water management in Minqin Oasis, was initiated in the early of this century, and further

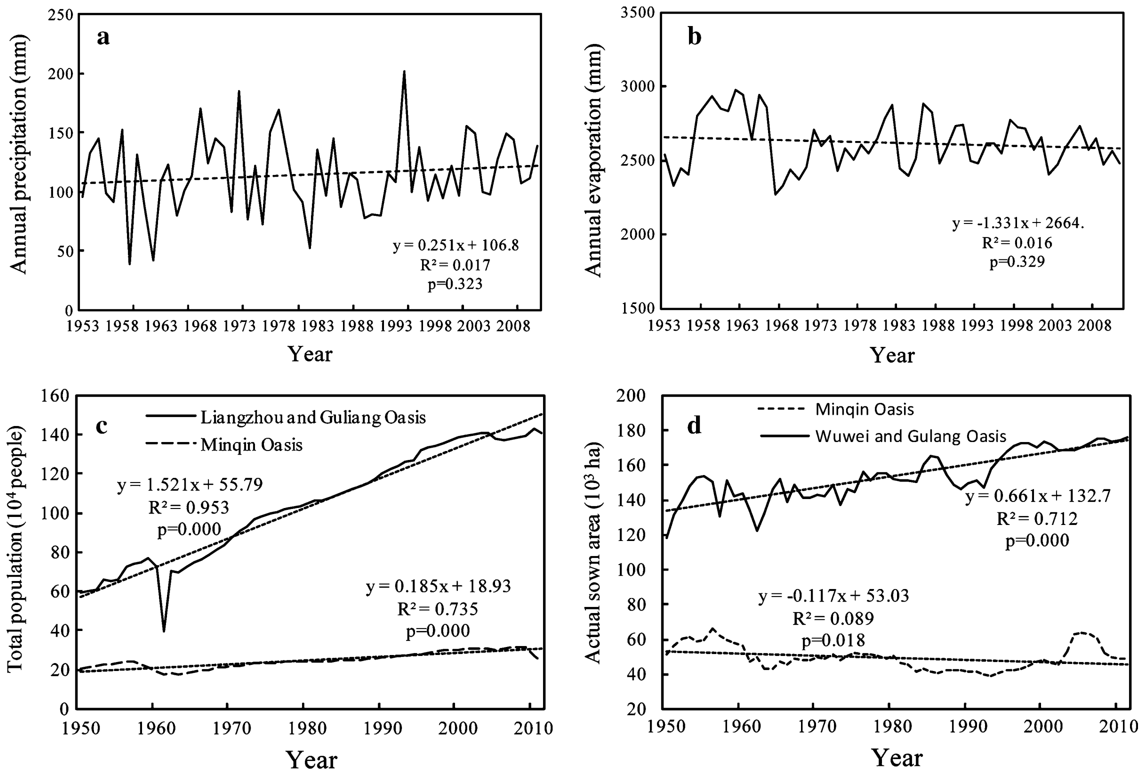


Fig. 7 The recorded **a** annual precipitation and **b** evaporation from 1953 to 2011 in the Minqin Oasis, **c** the annual change in population and **d** actual sown area in the Minqin Oasis and in the midstream oases from 1950 to 2010

promoted in 2005 when Premier Wen Jiabao visited Minqin Oasis and declared that he would never allow the Minqin Oasis to disappear into the desert. With the strong support of the central government, a series of measures were implemented and funds were invested to address water resource degradation in the Minqin Oasis area. Based on the average annual water allocation plan, the amount of water flowing into the Minqin Oasis must make up 22 % of the total water volume of the river flowing out of the mountains and can change in high and low years depending on mountain water volume. The average cultivated farmland area for each person and water consumption amount for a given unit of farmland was regulated. From 2004 to 2009, 3,161 wells were closed, including all of the wells with a depth over 100 m. Traditional flood irrigation has gradually been substituted by tube irrigation and drip irrigation. By the end of 2010, drip and tube irrigation systems had been set up in half the total irrigated farmland area of the Minqin Oasis, including 15,000 ha of drip irrigation and 3700 ha of tube irrigation in open fields and 1827 ha of drip irrigation in greenhouses. Adjusting the agriculture structure is another important measure used to save water and improve water use efficiency. Fruits trees with a high water use efficiency, vegetables in greenhouses, and stable feeding animal husbandry have become popular and are replacing the traditional grain crops.

Discussion

The Relationship Between Land Use and Water Resource Change

In arid regions, land use is the most important factor affecting the quality and quantity of the water resource. Our research results prove this very well. Figure 9a shows a significant ($P = 0.000$) negative relation between the sown area in the middle reach and the water volume flowing from the middle reach into the Minqin Oasis. From 1971 to 2000, over farming in middle reach led the accumulated reduction of the water flowing into the Minqin Oasis reach 30×10^8 m^3, with an average reduction rate of 0.83×10^8 m^3 year^{-1}. In 2000, the per capita water consumption was 1552 m^3 in the middle reach oases, but only 537 m^3 in the Minqin Oasis. The shortage of fresh river water and the increase of farmland irrigation forced local farmers to dig wells and extract groundwater to irrigate their crops in Minqin Oasis. Especially in the new irrigation area such as the CIA and NIA (Figs. 2, 3), extracting groundwater is the only available irrigation method, given its desert location, where river water is unavailable. Considering the reduction in groundwater table always lags behind the reduction in surface runoff, the relation between runoff flowing into the Minqin Oasis from 1989 to 2002 and the average

Fig. 8 The landscape of **a** the Hongyashan reservoir, **b** artificial cement water channel, **c** flood irrigation, **d** sand encroaching the farmlands, **e** sand encroaching the settlements, and **f** land subjected to salinization

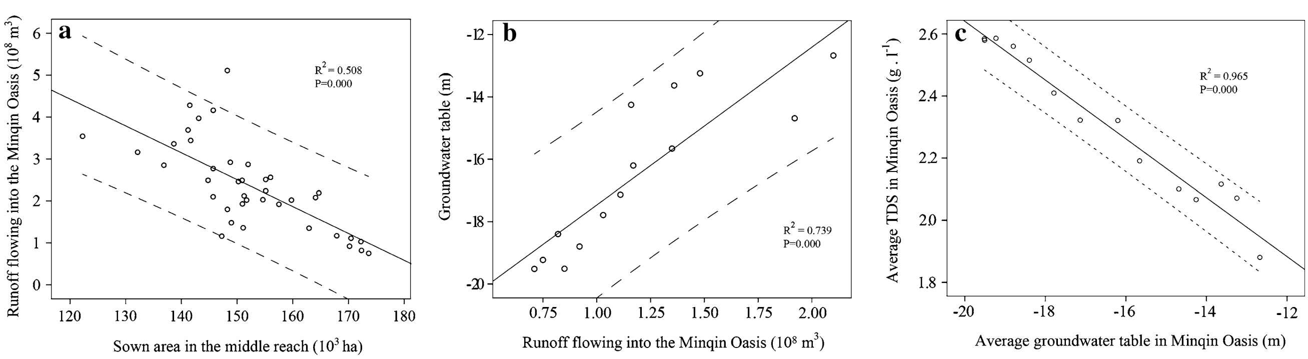


Fig. 9 The relationships among runoff, sown area, groundwater table, and total dissolved solids in Minqin Oasis

groundwater table from 1998 to 2011 was set up to understand the impact of land use on groundwater quantity. A significant ($P = 0.000$) negative relation between the two can be seen in Fig. 9b. Actually, the average groundwater extraction volume is 6×10^8 m^3 per year; the overexploited volume reaches 3×10^8 m^3 per year from 1998 to

2011 in Minqin Oasis (The Water Resource Bureau of Minqin County).

Consequently, the groundwater being used to flood irrigate the cropland over many years has led to an increase in the salinity of the groundwater as a result of strong evaporation and high salt concentrations. Based on the observed data collected from 1998 to 2011, Figs. 6 and 9c show the obvious decreasing trend in TDS and a significant ($P = 0.000$) negative relation between groundwater table and TDS. Field surveys and publication analysis also prove that the average value of TDS in the Minqin Oasis' groundwater increased from 0.7 g l^{-1} in 1950s to 2.5 g l^{-1} in 2005. In the northern region of the Minqin Oasis, TDS reached 6–10 g l^{-1}, even 16 g l^{-1} in the north end area of the oasis (Li et al. 2006; Zhu et al. 2007). The similar patterns of water quantity and quality degradation from overuse of water resources also extensively exist in the other arid regions (Wada et al. 2010).

Degraded Water Resource Caused Land Degradation

In addition to the reclamation of natural shrub lands and grasslands destroying the vegetation, the descended groundwater table directly caused a large area of natural and artificial vegetation to dry up and shelter forest to degrade because the tree roots could not absorb water from the shallow soil layer. Compared with measurements taken from 1995, the total area of both shrub lands and grasslands in 2005 reduced by about 100 and 60 km^2, respectively (Tables 1, 2, and 3). Similar with our research results, published research (Xie and Chen 2002) also shows that the vegetation cover decreased from 44.8 % in the 1950s to 15 % at the end of the 1990s in the Minqin Oasis. In addition, the deterioration in groundwater quantity and quality can change the composition, structure, and function of the ecosystem. Some research results have shown that vegetation type numbers have fallen from 19 varieties in the 1950s to 9 varieties in 2010; additionally, the herbaceous communities and wet meadow communities have gradually been substituted with halophytic and xerophytic shrub communities (Wang et al. 2002; Peng et al. 2004; Li et al. 2011). Without the protection of the shelter forest, sand dunes have moved toward the oasis and buried farmlands and settlements (Fig. 8d, e).

The decreasing vegetation cover inside the oasis, a result of saline land and abandoned farmland, has also increased the danger of wind erosion and eolian desertification. Irrigation with saline or high-sodium water can result in the formation of alkaline soil, damaging the soil structure. Our field experiment on saline water irrigation in the Minqin Oasis showed that topsoil salinity increased by 22.67–35.30 % when irrigated using saline water with a TDS of 2–5 g l^{-1}. Saline water irrigation also increases pH values, soil exchangeable sodium percentages (ESP), and soil's water-holding capacity (WHC), while decreasing the total porosity and the index of aggregate stability in water (Huang et al. 2011). Based on a regular irrigation requirement of 7500–9000 m^3 ha^{-1} during the crop growing season, it is possible to calculate that irrigation with saline water with a TDS of 3 and 6 g l^{-1} can accumulate salt in the topsoil at a rate of 22.5–27.0 and 45.0–54.0 t ha^{-1} $year^{-1}$, respectively. When salt in the soil surpasses the tolerance range of the crops, the farmland must be wasted. Our research results show that over 10 km^2 farmland degraded into sand land, the Gobi, saline land, and wasted land from 1995 to 2000 (Table 2).

In the Minqin Oasis, vegetation degradation has caused eolian desertification, characterized by wind erosion in farmland and rangeland, and sand dune moves at the margin of the oasis. Since the 1950s, desert areas located in the north have encroached southward into the oasis by 50–70 m and destroyed 400 ha of farmland. Desert areas located in the west have moved eastward by 30–60 m and have destroyed 467 ha farmland (Zhang et al. 2004; Sun et al. 2005; Dong et al. 2010). In addition, 70 % of farmland have been affected by eolian desertification and 85 % have been affected by different of degrees of salinization (Sun et al. 2007). Based on satellite remote sensing, eolian desertification has rapidly developed from the 1970s to the 1990s and eolian desertified land has increased by 1.13×10^4 ha at the margins of the oasis (Zhang et al. 2004). Severe eolian desertification has made the Minqin Oasis one of the major sources of sandstorms in China (Wang et al. 2004b).

The Impacts of Policies on the Use of Water and Soil Resources

From the above results, we can find that land use types and water resources management depends largely on state policies in Minqin Oasis. State policies induced—over farming was the main cause of the unreasonable allocation of regional water resources and water competition between the middle and downstream areas, also the reason of land degradation in Minqin Oasis. Actually, policy induced—land degradation is ubiquitous in the history of the arid region over the world. For example, land degradation in the arid region of the west United States in the late 19th and early 20th centuries and the famous "dust bowl" in 1930s firmly comes from over farming and overgrazing supported by the Homestead Act of 1862, the Enlarged Homestead Act of 1909 and the Stock-Raising Homestead Act of 1916 enacted by Congress (Hess and Holechek 1995). In the Sahel region, drought, famine and the sharp increase in dust emission occurred in the late 1960s and in the early

1970s are attributed to policy-oriented cattle grazing and commercial agriculture (Wade 1974; Mulitza et al. 2010). The same tragedy also can be found in the other arid regions. However, the most notable example should be the ecological disaster of the Aral Sea region (O'Hara 1997; Saiko 1998; Saiko and Zonn 2000; Aleksandrova et al. 2014).

Until the 1960s, the Aral Sea was the fourth largest inland water body in the world covering an area of 60,000 km. Two major rivers, the Amu darya and the Syr darya, discharge their waters into the Aral Sea. During the Soviet period, the government vigorously developed the cotton industry and expanded irrigated lands in Central Asia in order to achieve self-sufficiency policy in cotton. The annual output of cotton production in Central Asia in 1980 exceeded the 1913 level by 13.7 times. Most farming in this region required irrigation. Between 1960 and 1995, ever-increasing water withdrawal from the Amu darya and Syr darya resulted in the total volume of discharge into the Aral Sea decrease by 78 %, the area of the sea halve, water volume decrease by almost two-thirds, the sea level drop by 17.4 m, and water salinity double. At the same time, groundwater table declined, mineralization and chemical pollution of watercourses increased, xerophytic and halophytic vegetation spread, soil salinization, eolian desertification and salt storms were widespread throughout the region. Policy-generated distortions in land use have lead to unanticipated land degradation in the Aral Sea regions and make it become one of the ecological distress regions (O'Hara 1997; Saiko 1998; Saiko and Zonn 2000; Aleksandrova et al. 2014).

Today, the effects of policies on land and water use in fragile arid ecosystems have been extensively recognized. More effective, sustainable and environment-friendly policies are needed for large tracts of unproductive degraded land, aggravating water crisis and food security. EC policy implemented since the early 21th century has brought an evident positive outcomes in the Minqin Oasis area. The actual volume of water flowing into the Minqin Oasis increased from 0.97×10^8 m^3 in 2005 to 2.36×10^8 m^3 in 2010 and 2.59×10^8 m^3 in 2011 (Fig. 4). Groundwater extraction decreased by 2.4×10^8 m^3 and the irrigation area decreased to 41,700 ha in 2010. The groundwater table has risen 45 cm between 2005 and 2011 in the northern part of the Minqin Oasis. Irrigation water efficiency has improved from 0.56 in 2006 to 0.61 in 2010. Average water consumption decreased by 1500 m^3 ha^{-1} for grain crops and by 1800 m^3 ha^{-1} for cash crops, and the output per cubic meter of water has improved by 80 % for grain crops and 87 % for cash crops. The evident increase in shrub land area (Table 1) is a direct result of extensive afforestation in degraded farmland and sand land.

Even though the central government has developed corresponding policies to restore the degraded land, there still a need to scientifically evaluate the sustainability of these policies. Actually, in the field surveys, the authors found that farmers don't welcome many of these new policies, such as drip irrigation, resettlement and closing wells, and have even been met with passive resistance. Truly realizing a sustainable development that works on a social, economical and environmental level is a subject still requiring a great deal of exploration over time. There is a need to develop new technologies to mitigate these environmental problems and at the same time there is a critical need to develop adaptation strategies to cope with the farmers' demands.

The history in past one and half centuries has proved that irrational policy is the root of land degradation in fragile arid ecosystems. However, the same ecological tragedies goes on and on in arid regions, even in non-arid regions over the world. The Minqin case occurred in 1980s, half a century after eco catastrophes in west USA, the Sahel region and the Aral Sea region, reminds policies makers again to think how to draw a lesson from the history, and how to avoid similar tragedies in the future.

Conclusions

Based on the results of this study, three main conclusions can be drawn.

1. The degradation of the Minqin Oasis could certainly be attributed to the reckless exploitation and mismanagement of water resources. Over-exploitation and mismanagement were developed as a result of water competition, including competition between upstream and downstream areas, competition between developing the economy and protecting the ecology, and competition between agriculture and industry. However, national policy plays a leading role in balancing these relationships between economic development and ecological protection, between upstream and downstream areas, between industry and agriculture.

2. Regional water competition is a widespread problem but is also very difficult to resolve, especially between states. People living in the upstream areas always strive to maximize their utilization of water, neglecting the demands of people living in the downstream areas. This kind of competition has existed for thousands of years, growing more intense in recent years as a result of population growth. The Minqin experience demonstrates the need to implement integrated water management throughout the watershed. Water carrying capacity, population, water demand, society development, and future disaster risks all need to be analyzed and evaluated at the watershed level. Based on these analyses, an administrative body should be

set up to oversee the whole watershed, developing and implementing water resource allocation plans within the watershed through legal, administrative, and economic channels. When water shortages in the watershed are severe and difficult to resolve using internal water allocation, or when there is a degraded ecosystem in urgent need of rehabilitation over a short period of time, then diverting water from outside the watershed into the watershed may also be necessary.

3. It is widely accepted that water scarcity is a new challenge worldwide, especially in arid regions. The challenge is likely to be exacerbated by 2050 when an expected two billion more people are added to the current population of seven billion. To meet the increasing population and water demands, traditional water use has to change so that water use efficiency can be enhanced, allowing for improvements in water resource productivity. The water-saving practices used in the Minqin Oasis area show us that applying water-saving technology, developing water-saving agriculture, and establishing a highly efficient and sustainable artificial oasis ecosystem are important methods that can be used to better manage water scarcity and land degradation in arid regions.

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