

Evaluation of landscape changes and ecological degradation by GIS in arid regions: a case study of the terminal oasis of the Shiyang River, northwest China

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Abstract The development and utilization of water and land resources in the Shiyang River basin are the highest among the inland rivers in northwestern China. Using GIS and the landscape structure analysis program FRAGSTATS, landscape metrics of a study area in the lake-district in Minqin Oasis in the lower reaches of Shiyang River basin were calculated and analyzed based on TM images from 1987 to 2001 at class level and landscape level, respectively. Transformation matrix of the landscape mosaics was also examined. The driving forces of landscape changes were analyzed, including the dynamics of runoff and groundwater resources and their exploitation, and influences of policies and market economy. The results showed that: (1) Patch number of farmland and desert decreased, but their mean patch area increased, indicating that reclamation and desertification was very serious in the study

area. Contagion index for oasis increased and edge density and landscape diversity were reduced. (2) Farmland and desert areas have enlarged by 1,520.46 and 4,941.27 hm², respectively. This increase was at the cost of woodland and grassland, which shrank by 1,520.46 and 4,941.27 hm², respectively. (3) The net utilization of surface water decreased by 50% in the last 10 years, and dropped to 22.3×10^6 m³ in the later 1990s. Exploitation of groundwater increased remarkably, up to 80×10^6 m³ per year in the last 5 years. (4) The capability of the economic structure to withstand pressures of the market economy has depressed distinctly because of the simplified planting pattern, which is dominated by salinity-enduring cash crops, such as cotton. Based on the above analysis, strategies of ecological reconstruction in the lake-district were suggested.

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Introduction

Oases are unique humanistic-natural landscapes in arid zones. Landscape patterns and water-ecological processes are the focal points in the research of landscape ecology in arid zones (Li et al. 2001, 2003, 2005; Jia et al. 2004; Li and Xiao 2005). The Shiyang River is famous in China for the utilization of its water resources and environmental problems. The development of water and land resources in the Shiyang River Basin is high. The basin's ecological crisis is largest among the three interior river basins in the Hexi Corridor Region (Wang et al. 2002, 2003; Ma et al. 2005).

In the development of oases in the interior river basins, generally oases extend from the lower reaches to the upper reaches. Some terminal lakes, which existed in historical periods, today have almost entirely dried up and form a downstream delta. Water resources are mainly consumed for land development in the upper and middle reaches, while salts built up in soils in the dry delta. Too little water and too much salt became a salient problem for the region (Feng et al. 2001; Zhang et al. 2003).

Minqin Oasis, especially the lake-district oasis, is a typical example of dry downstream delta. Surrounded on three sides by the Badain Jaran Desert and the Tengger Desert, the eco-environment of the oasis is extremely fragile. In recent decades, surface water flowing into the downstream basin has decreased with population growth and continuous economic expansion in the middle reaches. From the 1980s onward, continual lowering of the groundwater table led to the degradation and loss of a large area of artificially established forests. By the 1990s, soil salinization in the lake-district aggravated and desertification posed a threat to the livelihood of local people. Some farmers abandoned their lands and became ecological refugees (Shi et al. 2002; Li et al. 2005). The lake-district is an islet-like oasis in the interior of two large deserts. It is a green ecological barrier to help maintain the healthy development of the Minqin Oasis and the Liangzhou Oasis. The lake-district also serves as a “bridgehead” to prevent the encroachment of drifting sand from the northern desert, even though it is in close proximity to the Hexi Corridor region. The ecological security of the lake-district in Minqin is a touchstone for sustainable development of the whole Shiyang River Basin. Although a number of research works on the lake-district in Minqin have been reported, they mostly focused on the description of its current states (Li et al. 2002). Little information on the landscape changes and ecological processes are available (Wang et al. 2002). This study attempts to give an analysis of the landscape changes and their driving factors in the lake-district and suggests some strategies for the region’s ecological restoration.

Description of the study region

The Minqin lake-district is a terminal oasis of the lower Shiyang River, with a total land area of 95,300 hm^2 (Fig. 1). Tectonically it is located at the southeastern edge of the Alxa platform, bordered by a Miocene sag (i.e., Minqin depression) to the south and the Qingtu Lake sag to the north. The lake-district mostly lies

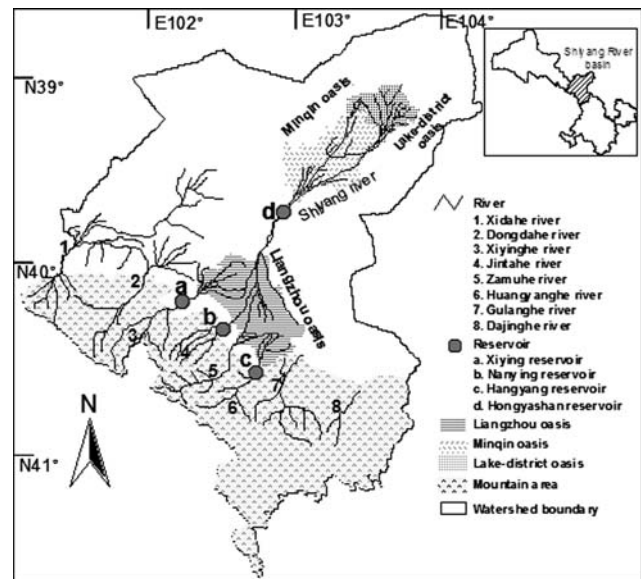


Fig. 1 Shiyang River basin and its typical oases

between 1,310 and 1,320 m above sea level, with a gradient of less than 0.002. Owing to low-lying terrain and drainage patterns, the Shiyang River terminates here. As a depositional zone of alluvial deposits and soluble salts, this region has a large area of lacustrine strata developed as fan-shaped alluvial belts along the Shiyang River. These deposits form the alluvial-lacustrine plain (Zou and Wang 1999; Du 2002; Shi et al. 2002). As an arid desert zone, the region’s mean annual precipitation is less than 100 mm, annual evaporation exceeds 2,600 mm, and mean annual temperature is 7.8°C. The region has five townships, Xiqu, Zhongqu, Donghu, Shoucheng, and Hongshanliang; 87 villages; and 16,860 peasant households, with a total population of 73,274 people. The arable land area is $3.35 \times 10^4 \text{ hm}^2$, but only 1.07×10^4 to $1.27 \times 10^4 \text{ hm}^2$ were under cultivation in recent years (Du 2002). With continuous expansion of land reclamation and irrigation in the upper and middle reaches, inflow of the river into the terminal lake greatly decreased. Usage, combined with vigorous evaporation of lake water, has caused the lake to dry up. About $1.6 \times 10^8 \text{ kg}$ of salts carried by the river water annually were deposited in the region, exacerbating land salinization (Zou and Wang 1999; Tang and Zhang 2001; Wang et al. 2002).

Methods

In the study of land use and its changes, manual interpretation results of 1987 and 2001 TM image data were used as the basic data. Land use characteristics in

the oasis of the study region were divided into six types: farmland, forestland, grassland, residential area, sandy land, and salinized land (Xiao and Zhong 1998). The landscape structure analytical software FRAG-STATS was used to calculate the landscape pattern indexes. The landscape transfer matrix in the Minqin lake-district was calculated using GIS. Field investigations of cultivated areas and planting structure were performed. Planting cost and net income of representative peasant households in the lake-district were taken from 1980 to 2003 statistical data of national economy and social development. Surface and groundwater consumption data were provided by the Minqin Water Resource Bureau. The ecological construction plan of the lake-district of Minqin county, landuse changes in the lake district, their driving forces, and their relation to water resource use and planting structure were analyzed.

Results

Oasis landscape patterns and their dynamical changes

Through the comparison of landscape pattern changes in Minqin lake-district in 1987 and 2001 (Fig. 2), the landscape pattern indexes in different periods at class level and landscape level (Tables 1, 2) and the landscape transfer matrix (Table 3) were calculated as follows.

Analysis of landscape patterns and their dynamical changes at class level

In the lake-district oasis, farmland occupied the largest percentage of land area (Table 1). It increased from

36.4% in 1987 to 42.97% in 2001. Grassland decreased by 6.3% in 15 years. Salinized land decreased from 14.01 to 11.83%, and sandy land increased by 3.39% in the same timespan. The number of patches was greatest in residential areas, followed by grassland; these did not change much, but the mean patch area of grassland decreased by 15.82 hm². Although the number of patches of farmland decreased, its mean patch area increased by 45 hm², suggesting that the lake-district was in an unchecked land reclamation state. Similarly, the number of patches of sandy land also significantly decreased, but the mean patch area increased by 2.55 times the 1987 value. Sandy lands in the lake-district increased. Spatially, they tended to be connected and desertification was increasing. The residential land had the largest patch density, followed by grassland and farmland, and sandy land had the smallest patch density. Sandy land had the smallest fragmentation degree, and the distribution of residential land was the most scattered.

The edge density of farmland was largest, followed by grassland and residential area, and sandy land had the smallest edge density. Farmland had most complex edge shapes and largest fragmentation degree, while sandy land had simple shapes. The aggregate degree of sandy land was largest, while that of the residential area was smallest. Sandy land in the lake-district oasis was concentrated and its aggregation degree increased. The residential lands were the most scattered. The smaller interspersion and juxtaposition index for residential lands implies fewer adjacent patch types. The index of salinized land in the lake-district was smallest, while that of sandy land was somewhat larger. The adjacent patch types of salinized land were singular, while those of sandy land were diversified. Salinized land is mainly bordered by sandy land, while sandy land is bounded by various landscape types, including farmland.

Fig. 2 Maps showing the landscapes in Minqin lake district in 1987 and 2001. 1 Farmland, 2 Forestland, 3 Grassland, 4 Residential area, 5 Sandy land, 6 Salinized land

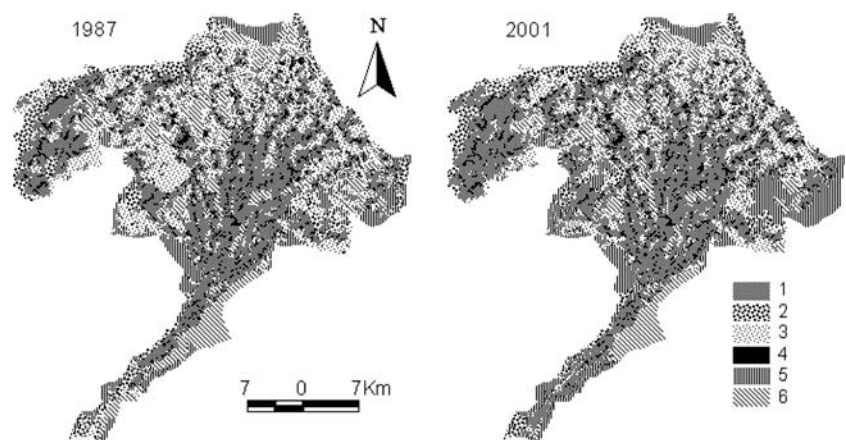


Table 1 The landscape metrics at the class level in the Lake-district oasis in 1987 and 2001

	Landscape type percentage (%)		Number of patches		Patch density (P/100 hm ²)		Edge density (m/hm ²)		Mean patch area (hm ²)		Aggregation index (%)		Interspersion and juxtaposition index (%)	
	1987	2001	1987	2001	1987	2001	1987	2001	1987	2001	1987	2001	1987	2001
Farmland	36.34	42.97	259	217	0.3322	0.2784	33.36	36.69	109.37	154.37	93.28	93.74	78.81	83.87
Forestland	9.13	7.18	143	65	0.1834	0.0834	7.68	5.16	49.77	86.10	93.30	94.11	85.39	77.04
Grassland	25.31	18.97	303	300	0.3887	0.3848	26.20	21.09	65.12	49.30	92.25	91.71	79.22	67.62
Residential area	6.30	6.75	679	691	0.8710	0.8864	15.35	16.32	7.23	7.61	82.06	82.20	36.55	28.79
Sandy land	8.91	12.30	96	52	0.1231	0.0667	5.28	5.49	72.38	184.46	94.76	96.02	84.42	81.82
Salinized land	14.01	11.83	174	130	0.2232	0.1668	11.89	9.81	62.79	70.95	93.74	93.87	68.04	64.10

Table 2 Comparison of landscape pattern indexes and their changes at landscape level in Minqin lake-district oasis

	Number of patches	Patch density (P/100 hm ²)	Mean patch area (hm ²)	Landscape shape index	Perimeter-area fractal dimension	Percentage of like adjacencies (%)	Aggregation index	Contagion index (%)	Shannon's diversity index
1987	1654	2.12	47.13	37.02	1.39	92.28	92.51	45.66	1.60
2001	1455	1.87	53.58	35.21	1.40	92.67	92.90	47.34	1.56

Table 3 Landscape transfer matrix in Minqin lake-district during the 1986–2001 period (%)

	Farmland	Forestland	Grassland	Residential area	Sandy land	Salinized land	Total	Transformed area (hm ²)
Farmland	76.75	4.32	14.76	0.49	0.42	3.26	100.00	+5,171.85
Forestland	7.18	75.67	14.24	0.18	1.53	1.20	100.00	-1,520.46
Grassland	9.95	3.91	74.89	0.44	1.43	9.40	100.00	-4,941.27
Residential area	5.60	0.54	4.82	88.61	0.02	0.41	100.00	+351.90
Sandy land	2.49	7.92	18.16	0.00	65.49	5.95	100.00	+2,640.33
Salinized land	2.29	0.76	9.98	0.08	2.49	84.41	100.00	-1,702.35

The row presents the data of 2001. The transformed column presents the difference in the data of 1987–2001

D_{ij} represents the percentage of landscape i (in row) transformed into landscape type j

In summary, both the farmland and sandy land landscape types were increasing in area; they tended to extend in space, and their aggregation degree also increased.

Analysis of pattern indexes and their dynamics changes at landscape level

The changes in pattern indexes at landscape level in the lake-district in the past 15 years (Table 2) show that the patch number of the oasis decreased by 199, patch density reduced by 0.26 P/100 hm², and mean patch area increased by 6.45 hm². The landscapes in the lake-district oasis as a whole exhibited a merging trend, mainly manifested as an increase in sandy land and its spatial expansion. The decrease in landscape shape index means a lowering of the complexity of landscape patch shapes and an increase in the proximity ratio and aggregation degree.

Contagion index is also an indicator commonly used to describe the distribution state of patches at landscape level. It is inversely proportional to the edge density of patches. When the contagion index is zero, landscapes have the largest separation degree (each patch represents a different type) and dispersion degree (all patches connect at approximate proportion); when the contagion index is 100, the whole landscape consists of only one patch. The increase in the contagion index in the lake-district oasis shows its spatial extension, but its edge density tends to decrease. Shannon's diversity index is an indicator used to measure diversity in a community ecology and is also used in landscape ecology. The diversity index in the lake-district tends to decrease and the land use to develop in a single direction. The lowering of landscape heterogeneity and biological habitat diversity leads to the deterioration of the eco-environment in the lake-district.

Analysis of landscape transfer matrix

From the landscape transfer matrix (Table 3) and area changes of various landscape types (Figs. 2, 3), the increase in sandy land and farmland are shown to be the two largest. Their area variation percentages are 34.51 and 23.5%, respectively, increasing by 5,171.85 and 2,640.33 hm². This increase was achieved at the expense of grassland and forestland. About 14.76% of the increase in farmland (4,943.60 hm²) in 2001 came from grassland and another 4.32% (1,447.02 hm²) came from forestland. About 18.6% of the increase in sandy land came from grassland and another 7.92% came from forestland. In the same period, forestland and grassland area converted from farmland occupied less than 30% of the 1987 farmland. Forestland and grassland converted from sandy land was about 11.9% of the 1987 sandy land. The forestland and grassland areas decreased by 1,520.46 and 4,941.27 hm², respectively, in 15 years.

The aggregation degree at landscape level in the lake-district oasis increased, spatial extension was exacerbated, patch shapes became simple, landscape diversity decreased, and land use patterns increasingly became singular. Concurrently, land reclamation at the expense of forest land and grassland increasingly exacerbated oasis desertification, furthering the lake-district's development toward farmland and sandy land.

Analysis of driving forces for landscape changes

Great increase in farmland led to a serious shortage of freshwater resources in the lake-district. Groundwater drawdown caused by excessive withdrawal worsened water quality. As a result, large areas of farmland were

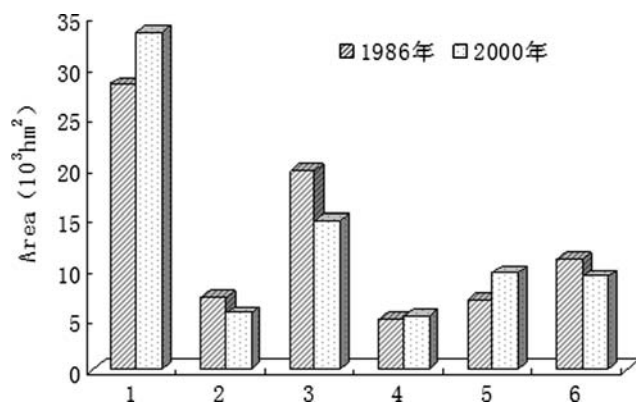


Fig. 3 Area changes of various landscape types in Minqin lake-district oasis. 1 Farmland, 2 Forestland, 3 Grassland, 4 Residential area, 5 Sandy land, 6 Salinized land

abandoned. In recent years, the cultivated area is about one-third of existing farmland. Large areas of abandoned lands are suffering from desertification, resulting in more rapid degradation of the eco-environment. Abandonment and rehabilitation of farmlands are also related to the prices of agricultural products. In the years with high-agricultural product prices, abandoned land area decreases and rehabilitation increases. Water resources, market economy and policy are all factors responsible for landscape changes in the Minqin lake-district.

Analysis of water resource regime

According to the investigative data of the Minqin Water Resource Bureau, mean net water consumption of fields in the lake district is 7,200 m³/hm². The water use coefficient for the canal systems is 0.42. For groundwater, the water use coefficient is 0.74. In terms of cultivated arable land in the past 15 years, the net water requirement in the lake district was calculated and the annual net water consumption of surface water and the water input into the lake-district from the Hongyashan reservoir and water use coefficient of canal systems were estimated (Fig. 4). Mean net water requirement of farmland in the lake-district in the past 15 years was 0.83×10^8 m³. The net water consumption of surface water decreased year-by-year, from 0.45×10^8 m³ in the late 1980s to 0.22×10^8 m³ in the late 1990s, a decrease of 50%. Since the cultivated area did not decrease and the water requirement continuously increased from 0.37×10^8 m³ in the 1980s to 0.67×10^8 m³ in the 2000, such a difference can only be compensated by extracting more ground water, thus furthering the cycle of eco-environment degradation.

Year-to-year groundwater extraction amounts in the lake-district were computed using electrical power

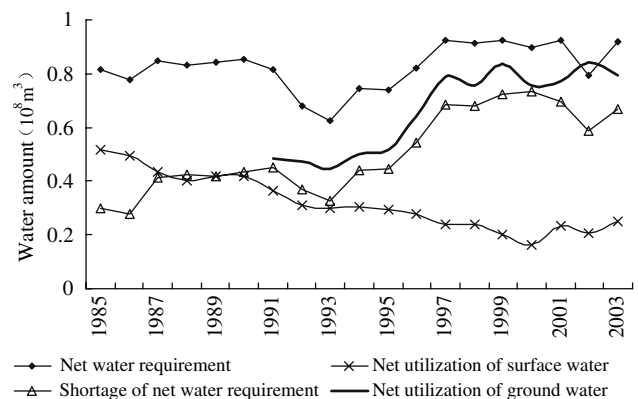


Fig. 4 Agricultural water requirements in Minqin lake-district oasis

consumption records for agricultural irrigation since 1991. Using a factor of per kwh of electrical energy required to pump 3.5 m^3 of groundwater, multiplied by the water use coefficient of the canal system (0.74), the net groundwater consumption per year in the lake-district was calculated. During the most recent 5 years, the average groundwater extraction reached $0.80 \times 10^8 \text{ m}^3/\text{a}$ (Fig. 4). Calculated net groundwater consumption and the net water requirement difference exhibited a consistent variation, but groundwater consumption was larger than net water requirement. This result is mainly because farmland abandonment and rehabilitation in the lake-district were frequent. In the years with high-agricultural product prices, large areas of abandoned farmland were recultivated, but not always included in the local governmental statistics. Through comparison of the groundwater consumption with the net water requirement difference, the farmlands not included in the statistics for the lake-district in different years were estimated. Its annual mean value was $1,350 \text{ hm}^2$ since 1991, maximum value was $3,500 \text{ hm}^2$ (2002), and minimum value was 330 hm^2 (2000). Irrigated land reclamation in the lake-district was serious and excessive extraction of groundwater and the high salinity itself led to the deterioration of water quality. As water quality deteriorated, large areas of farmland in the lake-district were abandoned. In the 1987–1994 period, $263 \text{ hm}^2/\text{a}$ were abandoned. Between 1998 and 2001, up to $1,419 \text{ hm}^2/\text{a}$ were abandoned (Song et al. 2003). Deteriorating water quality also caused a serious drinking water crisis for about 38,000 people and 80,000 livestock in 49 villages. Some residents now have to travel more than 10 km to fetch drinking water from wells deeper than 300 m, which were installed by the local government to supply drinking water. The deterioration of water quality in the lake-district has had disastrous results for the local people.

Market economy and policy factors

The deterioration of groundwater quality in large parts of the lake-district exacerbated soil salinization, and thus reduced crop yield. Some grain crops such as wheat and corn cannot be planted. The planting ratio of grain crops decreased from 75% in 1985 to 25% in 2003. As a result, some salt-tolerant cash crops such as cotton and melons held absolute predominance and formed a single economic structure, reducing resistance to market risk. With increases in production costs, farmer income sharply decreased due to lack of market planning, a skewed planting structure, and fluctuating agricultural product prices (Fig. 5). Since 2001, agricultural product prices have dramatically

decreased. Production was very difficult. Many farmers were forced to migrate to other regions. As a result, farmland abandonment was aggravated and eco-environment degradation furthered yet again in a vicious circle.

Although surface water resources are scarce in Minqin, they do exist. Unfortunately, large amount of water in reservoirs is lost through evaporation. In the seven-year period from 1995 to 2001, the accumulated difference between inflow and outflow of reservoirs reached $2.0 \times 10^8 \text{ m}^3$. On an average, annual reservoir conservation storage was $0.3 \times 10^8 \text{ m}^3$. Due to the cost difference in using surface or ground water, farmers prefer not to use surface water. Excessive withdrawal of groundwater increases eco-environment problems.

Ecological restoration ways and measures

Readjusting agricultural structure and decreasing sown area

With serious deterioration of groundwater quality, land area devoted to grain crops significantly decreased, while that of cash crops continuously increased (Fig. 6). The proportion of grain crops, cash crops, and grasses decreased from 73:17:1 in the late 1980s to 33:49:18 in 2000. The planting structure is dominated by cash crops with larger market risk. This type of farming is not well suited to the lake-district with its very fragile eco-environment. To check further deterioration of the eco-environment of the lake-district and enhance resistance to market risk for agricultural products, greater effort should be made to educate farmers to readjust the planting structure. From a long-term point of view, the cultivated land area of grain crops and of cash crops should both be

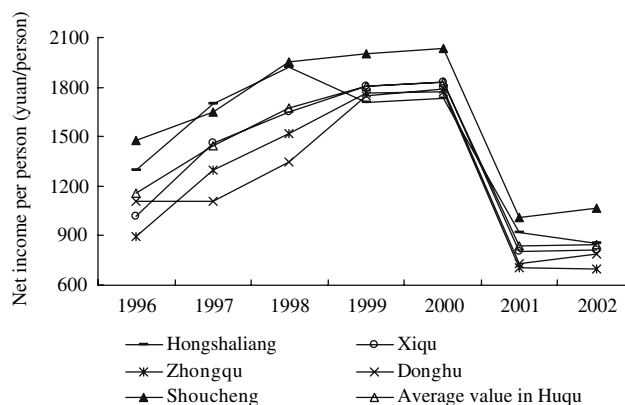


Fig. 5 Annual per capita net income of farmers in the Minqin lake-district oasis

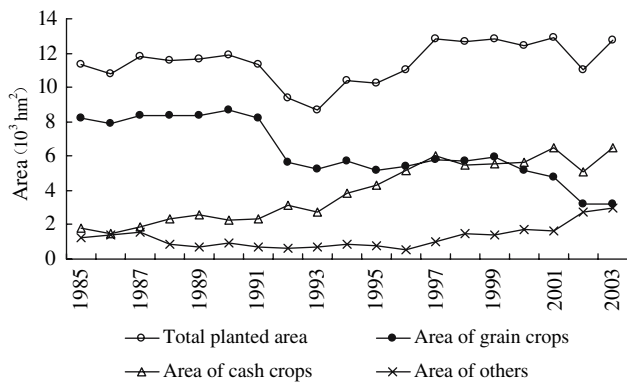


Fig. 6 Changes in planting structure in the lake-district

decreased, and the planting proportion of green fodder and green manure crops increased and the proportion of animal husbandry in the agricultural economy increased. The cultivated area of grain crops should be able to ensure the local people’s food demand. The planting proportion of commercial grain crops, cash crops, and grasses should be 15:30:65, and an animal husbandry-dominated agricultural production pattern established. The existing arable land area in the lake-district is $3.35 \times 10^4 \text{ hm}^2$ and the actually sown area in recent years was 1.07×10^4 – $1.27 \times 10^4 \text{ hm}^2$ (Du 2002). To maintain the stability of the oasis, the cultivated area should be decreased as much as possible. Calculated per capita farmland in the lake area is 0.10–0.13 hm^2 per person. Farmland area in the lake-district should ideally be 0.7×10^4 – $1.0 \times 10^4 \text{ hm}^2$. This goal can be realized by closing wells and returning farmlands to forests and grasses (replant with xerophytes such as *Tamarix chinensis* and *haloxylon ammodendron*, etc.) in light of local conditions, or restoring natural appearance (Shi 2003).

Enhance use efficiency of water resources and reduce extraction amount of ground water

Of the 36.50 km of main canals in the lake-district, about 16.79 km (46%) have not been lined. Annual water conveyance loss is estimated to be $0.1 \times 10^8 \text{ m}^3$ or more. Of the 70.765 km making up the four major canals in the lake-district, only 24.23 km (34.2%) is lined. Only about 10% of main, branch, sublateral, and farm canals are lined. Hence, the overall use efficiency of river water is about 42%. Of the total length of irrigation canals fed by the wells, only 48% is lined. Use efficiency of well water was 74%. Poor infrastructure results in the seepage and loss of freshwater in canal systems and mixing with shallow brackish groundwater in the lake-district. Much of the limited

freshwater resources for irrigation are wasted. Calculated from the mean available surface water resource of $0.6 \times 10^8 \text{ m}^3/\text{a}$ in recent years, if the water use efficiency of canal systems increases by 74%, it should be expected to save about $0.17 \times 10^8 \text{ m}^3/\text{a}$ of water. Canal lining measures and the improvement of water use efficiency of the canal systems have great potential to save water in the Minqin lake-district. In addition, the adoption of newer irrigation systems such as pipe irrigation, small check irrigation, and above-membrane irrigation could also contribute to water conservation. The research on the water-saving irrigation efficiency of purple alfalfa in Minqin shows that the water consumption coefficient of small check irrigation is only about 71.6% of flood irrigation (Wang et al. 2004). At present, irrigation norm in Minqin is commonly high and mean gross irrigation norm for existing crops is $10,050 \text{ m}^3/\text{hm}^2$. If the mean gross irrigation norm per hm^2 could be decreased by $1,500 \text{ m}^3$, it should save about $0.2 \times 10^8 \text{ m}^3/\text{a}$ of water in the lake-district.

Due to lack of surface water, groundwater in the lake-district is excessively extracted. At present, there are 2,448 wells in the lake-district. Mean annual pumpage per well is $3.3 \times 10^4 \text{ m}^3$. In the past 5 years, mean annual extraction volume reached $0.8 \times 10^8 \text{ m}^3$. The groundwater table has dropped rapidly. Before the 1980s, it was less than 5 m; at present it is 15 m, with a mean annual descent rate of 0.5 m or more. Groundwater salinity also has risen rapidly. On an average, it is 6.0 g/L, but the maximum value in some places reaches 16.0 g/L or more (Song et al. 2004; Li et al. 2005), with an annual increase rate of 0.29 g/L. Each year, about $3.3 \times 10^5 \text{ t}$ of salts on average are carried to the lake-district by irrigation water and deposited to the soil cultivated horizon. Salinization of farmland is further exacerbated. To halt further deterioration of water quality in the lake-district, groundwater pumpage must be strictly controlled, and some wells should be closed or the pump output decreased.

Ordered resettlement to reduce population pressure

Owing to poor eco-environment conditions, especially increased deterioration of groundwater quality, no freshwater can be found even below 300 m depth in some villages in the lake-district. The man and animal drinking water problem is very difficult to solve. A large number of villagers have become ecological refugees due to loss of basic living conditions. They were forced to migrate to other regions. In the past 20 years, about 31,929 people in 7,959 households were forced to leave their native places (Table 4), 20,622 of whom

moved to other provinces, accounting for 65% of the relocation total. About 28% of the relocated people, 8,901, moved to other regions of this province; and 2,406 people (7%) moved to other places of the Minqin county. The number of outmigrating people in Zhongqu and Donghu towns were the two largest among various towns in the lake-district, their loss accounting for 38 and 45% of the total, respectively. Due to lack of drinking water and shifting sand encroachment, per capita net income was only 600–800 yuan (Xiao et al. 2005). An additional 32,385 people or about 41% of the total population of the lake-district still needs to be resettled due to lack of basic living conditions. To implement an orderly resettlement plan on a voluntary basis through consultation between the government and the people, three resettlement levels were suggested: resettlement within the border of Minqin county; resettlement outside the county's boundary; and internal readjustment. Internal readjustment means to establish convergent dwelling districts for residents without a drinking water source or those living at desert edge and facing the threat of shifting sand encroachment issue would be resettled in convergent dwelling districts with better drinking water sources. Population resettlement is an arduous task and continuous effort will be needed to solve this problem.

To prevent sand encroachment on the oasis's frontier lands, reduce abandoned land, and protect farmland from being buried by sand, the cultivated lands left by resettled villagers should be rationally arranged, and used in accordance with the unified plan, returning farmlands to forest and grasses to protect the environment.

Rational exploitation and use of brackish water

Freshwater resources in the lake-district are decreasing and groundwater salinity is rising, while on the other hand, about $0.3 \times 10^8 \text{ m}^3$ of the brackish water re-

sources are not effectively used. Some 13,340 hm^2 of farmland were abandoned, and villagers lead a hard life. Scientific development and proper use of brackish water resources have the ability to help alleviate the water crisis and increase farmer income in the lake-district. It has been proved that cotton cannot only can tolerate the dry climatic conditions in the lake-district, but also adapt to brackish water irrigation. Planting cotton in the lake-district is an effective pathway to develop agricultural production using brackish groundwater. According to research by Shi Peize et al., before seeding, the cotton field was irrigated with river water ($1,500 \text{ m}^3/\text{hm}^2$). During the seedling stage, it was irrigated once with freshwater and two or three times with brackish water or two times with brackish water (5 g/L). Normal cotton yield and quality could be ensured and soil salts also kept at a balanced state for many years (Shi 2004). Such a successful experiment provides one example for the brackish water use in the region. Further research is needed on extensive use of brackish water resources and other possible crops.

Water diversion within the basin and interbasin water transfer

The eight tributaries in the upper reaches of the Shiyang River had an annual discharge at the mountain outlet of $12.59 \times 10^8 \text{ m}^3/\text{a}$ in the 1960s. By the 1990s, they still had an annual run off of $12.12 \times 10^8 \text{ m}^3/\text{a}$, and no significant variations were found. The annual inflow into the downstream Hongyashan reservoir decreased from $4.086 \times 10^8 \text{ m}^3/\text{a}$ in the 1960s to $2.29 \times 10^8 \text{ m}^3/\text{a}$ in the 1980s, and further decreased to $1.51 \times 10^8 \text{ m}^3/\text{a}$ in the 1990s, a decrease of 63.1% in 40 years (Li and Xiao 2005). Water distribution in the mid- to downstream oases in the basin was seriously unbalanced. In July of 2000, the Hongyashan reservoir for the first time received no water inflow and dried up. This drew people's attention to the future of the Minqin Oasis. To ensure adequate water supply for the production of

Table 4 Population resettlement in Minqin lake-district oasis since 1985 (unit: household, person)

	1985–1990		1991–2000		2001–2002		Total		Resettled population due to harsh living condition		Total population in 2003	
	House	Person	House	Person	House	Person	House	Person	House	Person	House	Person
Hongshaliang	186	713	86	320	70	223	342	1,256	1,852	6,439	2,785	11,941
Xiqu	456	1,867	212	795	104	312	772	2,974	1,006	3,542	4,338	18,768
Zhongqu	1,540	6,460	898	4,081	503	1,671	2,941	12,212	1,022	4,495	2,495	11,607
Donghu	1,827	7,489	1,510	6,176	183	630	3,520	14,295	1,779	8,004	4,013	18,424
Shoucheng	205	676	78	203	101	313	384	1,192	2,133	9,905	3,966	17,802
Total	4,214	17,205	2,784	11,575	961	3,149	7,959	31,929	7,792	32,385	17,597	78,542

downstream oases and ecological water requirements, the water resources in the basin must be scientifically and rationally allocated and managed. A unified approach is suggested. A water observation and control section should be established at Caiqi or Xiangjiawan in Minqin to distribute water at a fixed proportion and gradually restore the downstream inflow to 18% of the runoff volume in the early 1980s (about 2.5×10^8 m³/a).

In addition, there are still some problems in the construction of the second-stage Jingtai water-power project. Since 2000, the second-stage Jingtai project has started to transfer water from Yellow River at an annual rate of 0.61×10^8 m³ (designed water-diverting volume) to Minqin, but thus far the completed engineering terminal is still in the Changcheng village in Liangzhou district, or 61 km away from the Minqin Hongyashan reservoir. The evaporation and seepage rate in the natural river reach is as high as 25.6%. If a annual water-diverting amount of 0.61×10^8 m³ is calculated, the annual water loss is 0.15×10^8 m³ and the water loss of the 99.04 km of already completed canal accounts for about 2%.

Readjust water price policy

Prior to water diversion from other rivers, Minqin water Resource Bureau calculated the water price in the Hongyashan irrigation district. The cost of per m³ of water at check gate was 0.20 yuan/m³, while the actually levied price was 0.09 yuan/m³. After diverting water from other river in 2001, the water price at the canal head was 0.21 yuan/m³, the use efficiency measured from the canal head to the check gate of Hongyashan reservoir irrigation district was 47%, and the water price at the check gate was 0.447 yuan/m³. As the diverted water mixed with the Shiyang River water (0.09 yuan/m³), the mixed water price was estimated to be 0.25 yuan/m³. Further contributing to a farmer's decreased ability to endure in Minqin, the levied water price was 0.21 yuan/m³ in 2001. As 0.61×10^8 m³ of water was diverted, the deficit caused by the price difference was 2.7 million yuan. In 2003, the levied water price was 0.15 yuan/m³ and the deficit caused by price difference reached 6.8 million yuan. If priority is given to the lake-district irrigation, the deficit value may reach 9.3 million yuan. High-water price not only affects the farmer's initiative to use surface water, but also greatly increases the local government's subsidized price burden.

On the other hand, groundwater was available for irrigation free of charge due to lack of flow-measuring devices. According to groundwater cost (power fee

plus mean annual input in single well), the water price is only 0.11 yuan/m³. The large difference in water cost between surface and groundwater causes excessive withdrawal of groundwater.

Water diversion in the Minqin Oasis should be incorporated into the water distribution plan of the Shiyang River. The diverted water in Minqin should be mainly used in the lake-district. Owing to continuous deterioration of the eco-environment, over 80% of people in the region live below the poverty line and they cannot afford to pay such a high-water price. To fairly use water resources and maintain the stability and sustainable development of the oases in the middle to lower reaches of the Shiyang River, the diverted water charge should be distributed in accordance with surface water consumptions of various counties and cities in the basin. If the policy of using industrial profits to subsidize agriculture is continued, the cost of irrigation water in the downstream basin can be reduced for farmers. In addition, groundwater exploitation in Minqin should be put under the unified management of local government by purchasing motor-pumped wells. Establishing flow-measuring system, working out pricing standards for surface and ground water, and using price levers to control excessive extraction of groundwater are potentially effective measures to ensure ecological water quality in the lake-district.

Conclusion

In this study, the landscape patterns and their dynamical changes in the terminal oasis of the Shiyang River—Minqin lake-district were investigated at the class level and landscape level, and the spatial transformation trend of land use patterns was compared using the transfer matrix. At the class level, two different landscape types, farmland and sandy land, exhibited a continuous expansion in area, and in space they tended to link up and their aggregation degree also increased. At the landscape level, the shape of the oasis patch became simple, landscape diversity reduced. Land reclamation at the expense of grassland and the increasingly exacerbated oasis desertification were coexistent. Greatly increased cultivated land aggravated the contradiction between water supply and demand in the lake-district, the groundwater table dropped, water quality deteriorated due to excessive groundwater pumping, and large areas of croplands were abandoned. Single-crop agricultural structure greatly reduced resistance to market risk and the prices of agricultural products exerted large influences on land abandonment and rehabilitation. Based on the

analyses of landscape changes and their driving factors, some strategies and suggestions to restore the ecosystem in the Minqin lake-district were proposed.

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