Quantifying the impacts of land use/land cover change on groundwater depletion in Northwestern China – A case study of the…

Article *in* Agricultural Water Management · December 2014

DOI: 10.1016/j.agwat.2014.08.017

Lanhui Zhang
Lanzhou University

Chansheng He
Western Michigan University

Agricultural Water Management 146 (2014) 270–279

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Quantifying the impacts of land use/land cover change on groundwater depletion in Northwestern China – A case study of the Dunhuang oasis

Xifeng Zhang[a], Lanhui Zhang[a,b], Chansheng He[a,c,*], Jinlin Li[a], Yiwen Jiang[a], Libang Ma[d]

[a] Center for Dryland Water Resources Research and Watershed Science, Key Laboratory of West China's Environmental System (Ministry of Education), Lanzhou University, Lanzhou 730000, China
[b] College of Earth and Environment Science, Lanzhou University, Lanzhou 730000, China
[c] Department of Geography, Western Michigan University, Kalamazoo, MI 49008, USA
[d] College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, China

ARTICLE INFO

Article history:
Received 29 May 2014
Accepted 19 August 2014

Keywords:
Groundwater depletion
Evapotranspiration
Agricultural irrigation
Dunhuang oasis

ABSTRACT

In recent decades, the Dunhuang oasis in the arid Northwest China has been undergoing significant changes due to social-economic development and expanded irrigation for agricultural production. Groundwater table was found to have significantly declined during the period of 1987–2007 owing to greater pumping. We analyzed the impacts of land use/land cover (LU/LC) changes on the groundwater fluctuations in the study area. The LU/LC types were derived from the satellite images for the years of 1987, 1990, 1996, 2001 and 2007. The water consumptions associated with the LU/LC types were estimated using the FAO-Penman–Monteith method. Results show that during the period of 1987–2007, the area of agricultural land sharply increased by 98.7 km^2, and the cash crops were the main contributor. Under the current market system, farmers had much more autonomy and greater incentives to shift the cropping pattern from the traditional food crops to the high value cash crops with greater water consumption. The total water consumption of the cash crops accounted for 14.1% of the total water consumption in 1987, but increased to 71.6% in 2007, becoming the largest water consumer. The agricultural land use was the main cause of the declining groundwater table during the period from 1987 to 2007.

1. Introduction

Increasing population, expanding agriculture and economic development are drivers for an ever-increasing demand for water worldwide (Wada et al., 2010). Globally, nearly 2 billion people rely on groundwater as their primary source of water supply for both domestic and agriculture uses (Swenson and Famiglietti, 2011), thus groundwater is essential for irrigated agriculture and for global food security. Yet depletion of groundwater is widespread in both semi-arid and humid regions of the world (Aeschbach-Hertig and Gleeson, 2012). In arid areas, groundwater is the most critical factor in maintaining the ecological balance. If groundwater abstraction exceeds the natural groundwater recharge for extensive areas over long terms, overexploitation or persistent groundwater depletion occurs (Gleeson et al., 2010), leading to the deterioration of the ecosystems and expansion of desertification (Chen et al., 2004).

Impacts of the land use/land cover (LU/LC) change on groundwater are being increasingly recognized, particularly at the watershed scale. For example, expanding agricultural irrigation has increased the productivity in the Texas High Plains of the United States but at the cost of declining water tables, putting at risk the sustainability of the Ogallala Aquifer as a principal source of water for irrigation supply (Agam et al., 2012). Harrington et al. (2007) and Allen et al. (1998) examined the relationship between groundwater depletion and agriculture land use change within a single county in the High Plains, Kansas of the U.S. and attribute the groundwater depletion to land use change.

In arid northwestern China, groundwater is the main source of irrigation supply for agricultural oasis. In recent years, expanding agricultural irrigation and increasing urban demands for water have led to the declining water table in much of the region. The

* Corresponding author at: Department of Geography, Western Michigan University, Kalamazoo, MI 49008, USA. Tel.: +1 2693873425.
E-mail addresses: chansheng.he@wmich.edu, he@wmich.edu (C. He).

http://dx.doi.org/10.1016/j.agwat.2014.08.017
0378-3774/

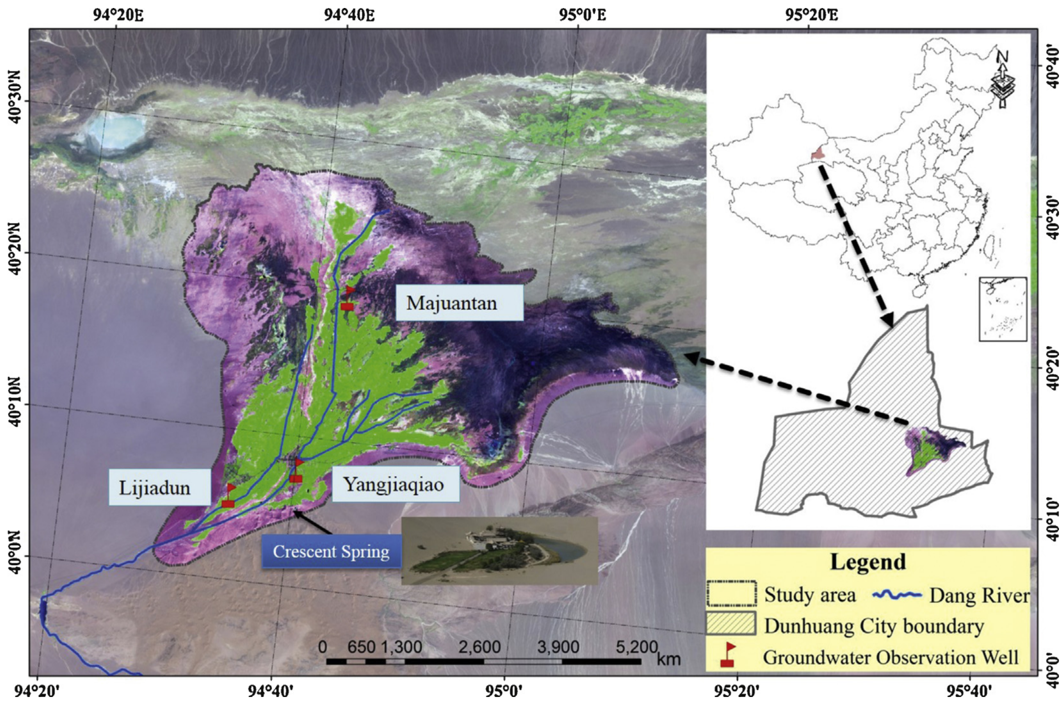

Fig. 1. Map of the study area derived by Landsat TM image (Bands 5-4-2).

Dunhuang oasis, located in the Dang River Watershed, is a microcosm of the inland river (terminal lake) watersheds facing similar groundwater issues in Northwestern China and is selected as the study area in the present paper. The oasis has attracted national and international attention in recent years because the expanding desertification has threatened the safety of Mogao Grottoes, a famous UNESCO World Heritage Site and associated Mingsha Mountain (sounding sand dunes) and Crescent Spring, all are located in the Dunhuang oasis (Fig. 1). Scholars have analyzed the changing trend of groundwater table at annual or inter-annual scale in Northwestern China (Yang and Li, 2011; Deng et al., 2011). Ye et al. (2013) analyzed the correlation of groundwater table and the dynamic changes of land cover in the Shule River (the Dang River is a main tributary of the Shule River), and reported that the natural vegetation is significantly correlated to groundwater level. Ma et al. (2012) used chemical indicators and stable isotopes and radiocarbon data to investigate the groundwater recharge and evolution in the quaternary aquifer beneath the Dunhuang basin, and stated that the groundwater was recharged during a humid climatic phases of the late Pleistocene or early Holocene. Despite these studies, some important questions are yet to be answered: How does the LU/LC change affect the water demands of domestic supply, industrial development, agricultural irrigation and natural vegetation? What were the main drivers of such changes in the study area over the period of 1987–2007?

The present study first analyzed the LU/LC changes during the period of 1987–2007 using both satellite images and social economic data. Then we computed the evapotranspiration of different crops using the Food and Agricultural Organization (FAO)-Penman–Monteith method and corresponding crop coefficients, as well as the evapotranspiration rates of grassland and shrub land in the study area. Subsequently, we compared the water consumptions of different sectors for the period of 1987–2007. It is hoped that findings from the present study can provide partial basis of policy decision making for sustainable use of the water resources in the arid Northwestern China and other similar watersheds.

2. Site description

2.1. Study area

The Dang River is a main tributary of the Shule River originated from the Qilian Mountain. It is the only inland river in the study area and considered as the mother river of the Dunhuang basin. The City of Dunhuang is located in the watershed, surrounded by desert and gobi (Fig. 1). From southwest to northeast, the terrain of the watershed is flat, with an average altitude of 1139 m. The annual average temperature and precipitation are 9.6 °C and 39.2 mm, respectively. At the end of 2007, the total population in the city was 139,400, of which the agriculture population was 100,457. During the 1987–2007 period, high value cash crops such as cotton and grapes had gradually replaced the traditional food crops (corn and spring wheat) as the main crops. In 2007, the agricultural and tourism revenues accounted for 44.5% and 27.1%, respectively, of the total revenue of the study area, placing the local famers' average per capita net income to the top quadrant in Gansu Province (Bureau of Statistics of The City of Dunhuang, 2007; Bureau of Statistics of Gansu Province, 2007).

2.2. Groundwater level

Groundwater data at five day intervals for the period of 1987–2008 were acquired form the Bureau of Hydrology and Water Resources Survey of Gansu Province. Due to the scarcity of data in the study area, three wells were selected to represent the groundwater level fluctuations during the study period: Yangjiaqiao well, Majuantan well and Lijiadun well, respectively (Fig. 2). Specifically, Yangjiaqiao well is located in the southeast of the City of Dunhuang, surrounded by urban area to its west and by cropland for the remaining part. It represents the transition zone between the densely populated urban and farming areas. Majuantan well is located along the edge of the oasis, covered with natural vegetation in the north, such as *Tamarix ramosissima* Ledeb, *Alhagi pseudoalhagi* and *Kalidum cuspicum*, and adjoined by cropland in the south.

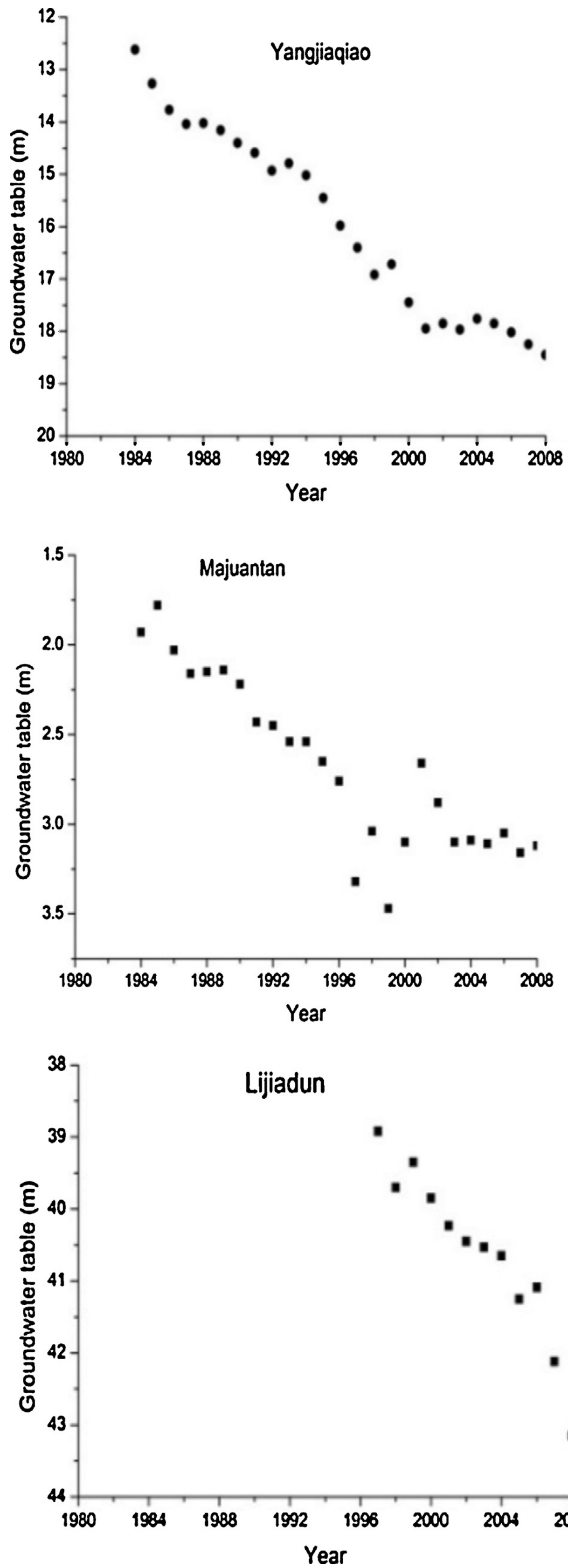

Fig. 2. Groundwater table changes during the period of 1987–2007. *Source*: Groundwater data at five day-intervals were acquired form the Bureau of Hydrology and Water Resources Survey of Gansu Province.

Table 1
Landsat TM images used in land use assessment.

Date	Data type	Path/Raw	Resolution/m	Cloud coverage (%)
1987.07.10	Landsat—5TM	137/32	30	12
1990.09.04	Landsat—5TM	137/32	30	0
1996.08.10	Landsat—5TM	137/32	30	0
2001.10.27	Landsat—5TM	137/32	30	1
2007.08.02	Landsat—5TM	137/32	30	0

Source: All image data were acquired from http://glovis.usgs.gov/ and http://www.radi.ac.cn/.
Note: Although the Cloud coverage is 12% in 1987, but the study area is not in the cloud cover area.

It represents the transition between the grassland and gebi areas. Lijiadun well lies in the expanded cropland and represents the cultivated area. The groundwater table of the Yangjiaqiao well had declined at a rate of 0.23 m yr^{-1}, ranging from12.6 to 18. 5 m during the period of 1984–2008. Water table in the Majuantan well had declined at a rate of 0.05 m yr^{-1}, ranging from 1.9 to 3.1 m during the same period while water table in the Lijiadun well declined at a rate of 0.35 m yr^{-1}, ranging from 38.9 to 43.2 m during the period of 1997–2008. Over the past 40 years, the water table of the Crescent Spring, which is a world famous natural landscape, has been down 9–11 m, and part of the lake bottom was exposed out of the water during the low-water season (Zhou et al., 2007). The declining groundwater table was directly due to the groundwater abstraction in excess of natural recharge rate (Wada et al., 2010).

3. Data and methods

3.1. Land use change

3.1.1. Data sources

The Landsat-5 TM images (with 30 m spatial resolution) of 1987, 1990, 1996, 2001 and 2007 were selected to derive land cover types for the study area. These images were acquired in summer or autumn with dense vegetation cover and low cloud cover (All image data were acquired from http://glovis.usgs.gov/and http://www.radi.ac.cn/). The image information is listed in Table 1.

3.1.2. Image processing

The images were projected in Universal Transverse Mercator (UTM) Projection and the datum was World Geodetic System (WGS) 84 ellipsoid. Image-to-map rectification was performed on the 1987 TM using a quadratic polynomial transformation and a nearest-neighbor resampling technique. The 1987 TM image was geo-referenced using 45–50 uniformly distributed ground control points (such as road and river) from a 1:250,000 topographic map of the Dunhuang area. The root mean square error (RMSE) for the geometrical rectification was less than one pixel. Image-to image registration was performed for all remaining images using the 1987 image as the master image. All image data were processed using the ERDAS 9.1 and ArcGIS 9.2.

3.1.3. Image classification

Following LU/LC classification standard of the National Environmental Protection Agency (State Environmental Protection Administration, 2006), according to the characteristics of vegetation and land use in the City of Dunhuang, the LU/LC type is divided into 8 classes: cropland, water, high density grassland, medium density grassland, low density grassland, shrub land, urban construction land and barren land (Table 2). The images were first classified using the supervised classification module in ERDAS 9.1. Subsequently, visual interpretation was used to derive the

Table 2
Classification schemes of the LUCC types.

Categories type	Definition
Cropland	Irrigated fields
High-density grassland	Grassland with coverage ≥50%, (*Phragm ites australis* (Cav.) Trin. ex Steudel)
Moderate-density grassland	Grassland with coverage ≥20–50% (*Glycyrrhiza inflata* Bat.), (*Alhagi pseudoalhagi*), (*Calligonum mongolicum* Turcz.)
Low-density grassland	Grassland with coverage ≥5–20% (*Alhagi pseudoalhagi*), (*Apocynum venetum* L.), (Acroptilon)
Shrub land	Shrub with a crown density ≥30% and height less than 2 m (*Tamarix ramosissima* Ledeb.)
Urban construction land	Urban and town area
Barren land	Bare soil, with vegetation coverage <5%
Water	Natural river, wetland, natural pools

Source: Ecological environment evaluation of technical specifications (2006), State Environmental Protection Administration, China.

LU/LC change information. Although such visual interpretation was labor intensive and time consuming, the mapping accuracy of this method was higher than that of the image classification by image-processing software for the selected TM and ETM+ images (Zhuang et al., 1999; Song et al., 2009). Following the field investigation, the classification results were verified and revised. The accuracy of f classified cover types for the 1987, 1990,1996, 2001 and 2007 images were 80.9%, 85.0%, 79.9%, 79.7% and 85.0%, respectively, meeting the minimum accuracy requirement of 70.0% (Janssen and Van der Wel, 1994).

3.1.4. Land use/cover type transfer matrix

To understand the LU/LC transfer pattern between different periods, a transfer matrix was established to determine the trend, rate, and magnitude of LU/LC (Shi et al., 2000):

$$C_{ij} = A_{ij}^{k} \times 10 + A_{ij}^{k+1} \tag{1}$$

$$A_{ij} = \begin{vmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{vmatrix} \tag{2}$$

In Eq. (1), C_{ij} is the result of LU/LC from k period to $k+1$ period, which describes the type of LU/LC change and its spatial distribution. In Eq. (2), A_{ij} refers to the changed area from the i type LU/LC of k period to the j type LU/LC of $k+1$ period, and n is the number of LU/LC types.

Based on the transfer matrix, we can derive the transfer-out ratio (X) and transfer-in ratio (Y). X indicates the ratio of the LU/LC type i of k period converted into the LU/LC type j of $k+1$ period; Y indicates the ratio of the LU/LC type j of $k+1$ period converted from the LU/LC type I of k period. The Eq. (3) is:

$$X_{ij(\mathrm{Row})} = A_{ij} / \sum_{1}^{n} A_{ij} * 100 \quad Y_{ij(\mathrm{Column})} = A_{ij} / \sum_{1}^{n} A_{ij} * 100 \tag{3}$$

3.1.5. Dynamic degree of LU/LC

The dynamic degree describes the rate of change of certain land types in specific period. The formula is (Liu and Buheaosier, 2000):

$$K_i = \frac{S_b - S_a}{S_a} * \frac{1}{T} * 100\% \tag{4}$$

In Eq. (4), K_i refers to the dynamic degree of certain LU/LC type in study period i, and S_a and S_b are the areas during the study period ($i-1$) and the study period i, respectively. T is the length of research period (in years).

3.2. Estimation of evapotranspiration of agriculture land

3.2.1. Reference crop evapotranspiration (ET_0)

In this study, the FAO-Penman–Monteith method is used to estimate the ET of each LU/LC type because of both its easiness to use and its applicability to a wide range of climatic conditions worldwide, particularly in arid areas (Allen et al., 1998; Sado and ISLAM, 1996; Young et al., 2006).

The reference evapotranspiration (ET_0) represents the potential evaporation of a well-watered grass crop and is computed by the FAO Penman–Monteith method (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - g) + \gamma \frac{900}{T+273} U_{2(e_s - e_a)}}{\Delta + \gamma(1 + 0.34U_2)} \tag{5}$$

where R_n is the net radiation at the canopy surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m above the ground (°C), U_2 is the wind speed at 2 m above the ground (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), Δ is the slope of the vapor pressure temperature relationship (kPa °C^{-1}), and γ is the psychometric constant (kPa °C^{-1}).

3.2.2. Crop coefficients (K_c)

Since spring wheat and cotton are the main crops in the study area. In 2005, the harvesting area of spring wheat and cotton accounted for 89% and 99% of the food crops and cash crops, respectively, both were selected to compute the crop evapotranspiration rates in the study area.

Crop development stages for both the spring wheat and cotton include the initial stage, development stage, middle season stage and late season stage (Doorenbos and Pruitt, 1975). The lengths of each of the growth stages of wheat and cotton were determined by local natural phonological conditions and farmer's practices. In the Dunhuang oasis the total growth period of the spring wheat is about 120 days. It is planted in the end of March, harvested in mid-July; the growth period of cotton is around 180 days, and is seeded in the early April, harvested in mid-October (Sun et al., 2002). Values of monthly crop coefficients (K_c) were adopted from FAO-56 (Allen et al., 1998) for both spring wheat and cotton (Fig. 3). Adjustments to $K_{c\,\mathrm{mid}}$ in climates where $RH_{\min}$ differs from 45% or where U_2 is larger or smaller than 2.0 m s^{-1}, were made by following the guidelines of Allen et al. (1998):

$$K_{c\,\mathrm{mid}} = K_{c\,\mathrm{mid(Tab)}} + [0.04(U_2 - 2)] - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{6}$$

$$K_{c\,\mathrm{end}} = K_{c\,\mathrm{end(Tab)}} + [0.04(U_2 - 2) - 0.004(RH_{\min} - 45)]\left(\frac{h}{3}\right)^{0.3} \tag{7}$$

where $K_{c\,\mathrm{mid}}$(Tab) and $K_{c\,\mathrm{end}}$ are the tabulated values for $K_{c\,\mathrm{mid}}$ and $K_{c\,\mathrm{end}}$ respectively in Table 12 of FAO-56 (Allen et al., 1998). U_2 is the mean value for daily wind speed at 2 m height over grass during the mid-season and late-season growth stage respectively, for 1 m s^{-1} ≤ U_2 ≤ 6 m s^{-1}. $RH_{\min}$ is the mean value for daily minimum relative humidity during the mid-season and late-season growth stage respectively, for 20%≤ $RH_{\min}$ ≤80%, and h is mean plant height during the mid-season and late-season growth stage respectively, for 0.1 m≤h ≤10 m. In the offseason dormant period, the cropland evapotranspiration (ET) is treated as the same rate as the desert. The

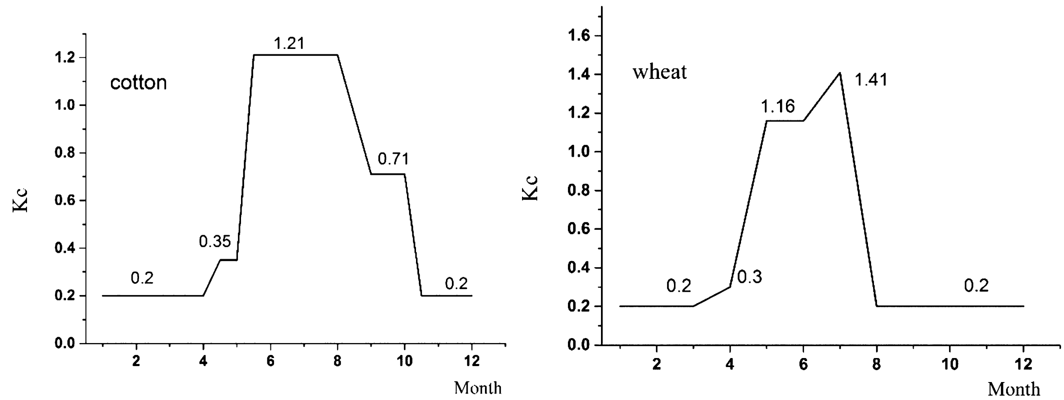

Fig. 3. Crop evapotranspiration coefficients.

method has been widely used because it gives satisfactory results under different conditions across the world (Kashyap and Panda, 2001; Suleiman et al., 2007; Bodner et al., 2007).

Actual ET rates of food crops and cash crops are estimated by (Allen et al., 1998)

$$ET = ET_0 \cdot K_C \tag{8}$$

3.3. *Estimation of evapotranspiration of natural vegetation*

The evapotranspiration of different grassland and shrub land in the Dang River Watershed was estimated based on the results of the "The Ninth Five-Year Plan" national key research projects (Wang et al., 2003), and can find the related results in Chen et al. (2004). The result can be convinced because the research project collected and analyzed the observation experimental data in the northwest China arid areas, especially analyzed the research findings and empirical equation in central Asia region, and eventually put forward a set of regional average evapotranspiration reference value by repeating calculation analysis. The values of ET of the shrub land, high, moderate, and low-density grasslands were 340 mm, 475 mm, 180 mm and 65 mm, respectively, which was verified by Yang et al. (2005).

The total water consumption of each LU/LC type in the study area was calculated by multiplying the estimated ET rate to the interpreted area of the LU/LC type. Due to the small areas of the water and built-up land (both less than 1%), the evaporation of both types was ignored in this study.

3.4. *Domestic and industry water uses*

3.4.1. *Domestic water use*

The total household water use consists of water uses by urban and rural population, tourists, and the livestock. It is positively correlated with living standards of the study region (Zhang and Brown, 2005). Domestic water use is defined as follows:

$$H = (P_1 \times C_1 + P_2 \times C_2 + P_3 \times C_3 + P_4 \times C_4) \times 365 \times 10^{-8} \tag{9}$$

where H is the total household water use (10^8 m^3), P_1, P_2, P_3 are the urban, rural and tourists population, respectively and P_4 is the livestock number (in sheep unit, different livestock types were converted to sheep unit for consistency in computation and comparison). C_1, C_2, C_3 are the average water use coefficients per capita (which changes with living standards) of urban, rural and tourists (L/day) respectively, and C_4 is the average water use coefficient of each livestock (L/day). The data for C_1, C_2, C_3 and C_4 are obtained from the literature for the three periods with different living standards: 1987–1990, 1991–2000, and 2001–2007. The coefficient values are all listed in Table 3 (Water Resources Department of Gansu Province, 2005).

3.4.2. *Industry water use*

The industry water use is affected by the industrial output, technology and processes, and the amount of water used to create 10,000 RMB (Chinese Currency) worth of industrial output. It is defined as follows:

$$P = \text{Indo} \times C_5 \times 10^{-8} \tag{10}$$

where P is the industry water use (10^8 m^3), Indo is the industrial output (RMB), C_5 is the amount of water used to create 10,000 RMB worth of industrial output (m^3/10^4 RMB). The industrial water use coefficient (C_5) was also determined separately for the three periods of 1987–1990, 1991–2000, and 2001–2007, respectively. The coefficient values are listed in Table 3 (Water Resources Department of Gansu Province, 2005).

4. Results and discussion

4.1. *LU/LC change between 1987 and 2007*

4.1.1. *Temporal characteristics of LU/LC change*

From 1987 to 2007, the area of LU/LC types had changed significantly, and the largest changes were rapid urban and cropland increases, and declining grassland. Specifically, the cropland had an increase of 98.71 km^2, and the increment rate during the 1996–2007 more than doubled that of the 1987–1996 period. The urban land had a small increase of 9.76 km^2 but had the highest growth rate (12.07%) (Fig. 4 and Tables 4 and 5), suggesting that the rapid urbanization is significant in the study area. The total grassland area had a decrease of 166.36 km^2, and the main decrease occurred during the period of 1996–2007. The high and medium coverage grasslands had little change, but the low coverage grassland first increased during the 1987–1996 and then rapidly decreased during the 1997–2007. The change pattern of the barren land was just opposite of the low coverage grassland, decreasing during the 1987–1996 and then increasing during the 1997–2007.

4.1.2. *Spatial patterns of LU/LC change*

The change of LU/LC is often bidirectional, including transfer-in/transfer-out among different LU/LC types. Based on the overlay of 1987 and 2007 LU/LC change maps, the transfer matrix of different types of area change is given (Table 6). The value of row indicates the area of the various LU/LC type in 1987, and the value of column represents the area of the various LU/LC type in 2007. For example, the crop land row means 264.22 km^2 of crop land remained unchanged, but there were 0.4 km^2, 1.36 km^2, 0.70 km^2, 0.33 km^2, 4.21 km^2, and 0.99 km^2 crop land transferred out to high density grassland, medium density grassland, low density

Table 3
ET of natural vegetation and other water use coefficient.

Item	Coefficient			Unit
C_a				
Shrub land	340			mm
High-density grassland	475			mm
Moderate-density grassland	180			mm
Low-density grassland	65			mm
	1987–1990	1991–2000	2001–2007	
C_b				
Urban Residents living water use coefficient (C_1)	80	95	110	L/day
Rural Residents living water use coefficient (C_2)	25	45	60	L/day
Tourists water use coefficient (C_3)	100	250	400	L/day
Livestock water use coefficient (C_4)	15	15	20	L/day
Industrial water use coefficient (C_5)	215	205	185	$m^3/10^4$ RMB

C_a from: Wang Hao, Chen Minjian, Qing Dayong. Rational allocation and research of water resources carrying capacity in northwest region. The Yellow River water conservancy press, 2003, 129–136.
C_b from: Water Resources Department of Gansu Province. Industry water use quota of Gansu Province, 2005.

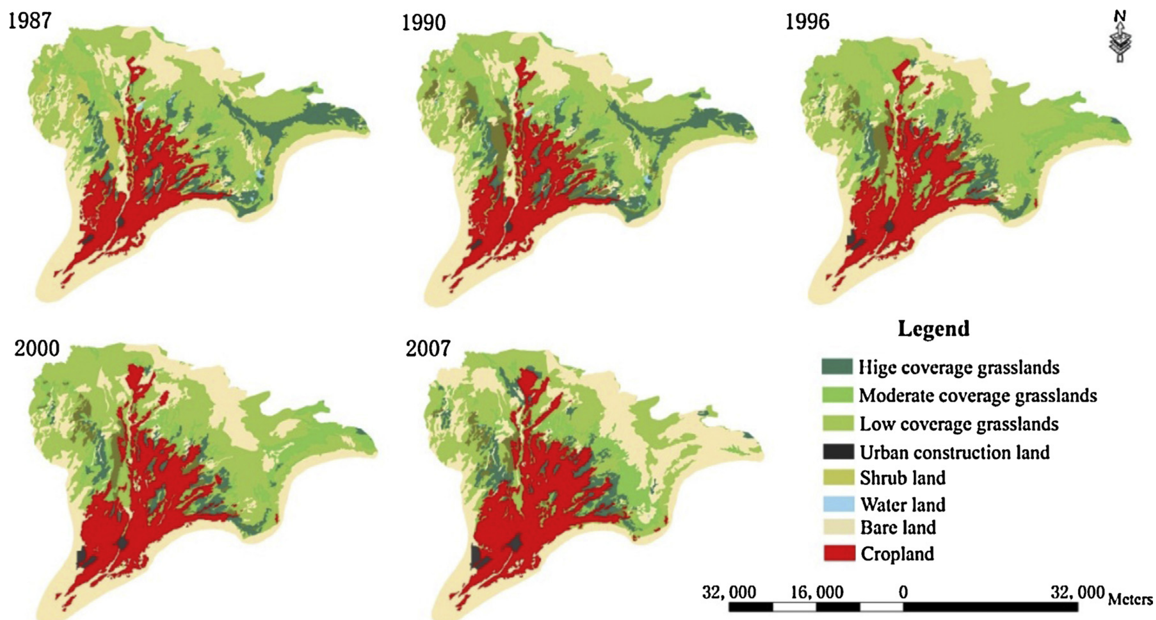

Fig. 4. LU/LC spatial pattern from 1987 to 2007 in Dunhuang oasis.

Table 4
Area statistics of LUCC types at five periods/km^2.

LUCC types		Cropland	Water land	High-grassland	Medium-grassland	Low-grassland	Bare land	Urban construction land	Shrub land
1987	Area/km^2	272.69	4.31	167.1	143.99	506.1	437.89	3.85	85.07
	% of total	16.82	0.27	10.31	8.88	31.22	27.01	0.24	5.25
1990	Area/km^2	276.41	4.00	162.42	157.5	501.39	435.66	4.06	79.56
	% of total	17.05	0.25	10.02	9.72	30.93	26.88	0.25	4.91
1996	Area/km^2	295.33	0.21	88.74	195.17	601.46	371.27	8.78	59.96
	% of total	18.22	0.01	5.47	12.04	37.11	22.90	0.54	3.70
2001	Area/km^2	327.08	0.17	77.61	166.89	553.96	435.22	10.03	49.98
	% of total	20.18	0.01	4.79	10.30	34.18	26.85	0.62	3.08
2007	Area/km^2	371.4	0.36	101.98	141.18	407.67	540.78	13.61	43.94
	% of total	22.91	0.02	6.29	8.71	25.15	33.36	0.84	2.71

Table 5
Amplitude and annual change rate of land use/cover types between 1987 and 2007 (%).

LUCC types	1987–1996		1996–2007		1987–2007	
	Variation (km^2)	Dynamic degree	Variation (km^2)	Dynamic degree	Variation (km^2)	Dynamic degree
Cropland	22.64	0.83	76.07	2.15	98.71	1.72
Water	−4.1	−9.51	0.15	5.95	−3.95	−4.36
High-grassland	−78.36	−4.69	13.24	1.24	−65.12	−1.86
Medium-grassland	51.18	3.55	−53.99	−2.31	−2.81	−0.09
Low-grassland	95.36	1.88	−193.79	−2.68	−98.43	−0.93
Barren land	−66.62	−1.52	169.51	3.80	102.89	1.12
Urban construction land	4.93	12.81	4.83	4.58	9.76	12.07
Shrub land	−25.11	−2.95	−16.02	−2.23	−41.13	−2.30

Table 6
The transfer matrix of LUCC types from 1987 to 2007/km^2.

	Cropland	Water	High-grassland	Medium-grassland	Low-grassland	Barren land	Urban land	Shrub land
Cropland	264.22	0	1.4	1.36	0.7	0.33	4.21	0.99
X	96.71	–	0.51	0.50	0.26	0.12	1.54	0.36
Y	71.12	–	1.36	0.97	0.17	0.06	30.62	2.26
Water	0.04	0.04	0.7	1.36	0.41	1.65	0	0.17
X	0.92	0.92	16.02	31.12	9.38	37.76	–	3.89
Y	0.01	10.81	0.68	0.97	0.10	0.31	–	0.39
High-grassland	15.08	0.29	35.73	21.02	22.76	65.47	0	6.32
X	9.05	0.17	21.44	12.61	13.66	39.28	–	3.79
Y	4.06	78.38	34.83	14.92	5.58	12.12	–	14.42
Medium-grassland	17.22	0	17.68	44.03	39.45	18.92	0	7.27
X	11.91	–	12.23	30.46	27.29	13.09	–	5.03
Y	4.64	–	17.23	31.26	9.67	3.50	–	16.59
Low-grassland	31.14	0.04	20.03	55.06	260.63	135.15	0	2.93
X	6.17	0.01	3.97	10.90	51.61	26.76	–	0.58
Y	8.38	10.81	19.52	39.09	63.85	25.03	–	6.68
Bare land	34.41	0	7.97	8.01	69.02	312.05	5.78	0.83
X	7.85	–	1.82	1.83	15.76	71.23	1.32	0.19
Y	9.26	–	7.77	5.69	16.91	57.78	42.04	1.89
Urban land	0	0	0	0	0	0	3.76	0
X	–	–	–	––	–	–	10	–
Y	–	–	–	–	–	–	27.35	–
Shrub land	9.38	0	19.08	10	15.2	6.48	0	25.32
X	10.98	–	22.33	11.70	17.79	7.58	–	29.63
Y	2.52	–	18.60	7.10	3.72	1.20	–	57.77

"–" represents 0%.

grassland, barren land, urban land and shrub land, respectively. *X* means the proportion of each type's area to the sum total row. In the crop land column, 264.22 km^2 crop land remained the same, approximately 0.04 km^2, 15.08 km^2, 17.22 km^2, 31.14 km^2, 34.41 km^2 and 9.28 km^2 of cropland were transfer from water, high density grassland, medium density grassland, low density grassland, barren land and shrub land, respectively. *Y* means the proportion of each type's area to the sum of the column. The other rows/columns are all the same meaning.

Table 6 shows, changes among LU/LC types. The main patterns are: (1) the increase in the cropland was mainly attributable to the conversion from grassland (17.08%) and barren land (9.26%), respectively; (2) the decrease in the high density grassland was mainly due to its conversion into barren land (39.27%) and medium-low density grassland (26.27%), respectively; (3) the decrease in the low density grassland was attributable to its transfer into barren land (26.76%) and medium-high density grassland (14.87%), respectively, indicating fast grassland degrading; (4) the increase in the barren land was the result of conversion from the grassland to the barren land, and the low density and high density grassland accounting for 25.03%, and 15.63%, respectively; (5) the increase in the urban land was mainly caused by the conversion of the cropland from the cropland and barren land.

4.2. Food crop and cash crop water use

Food crop and cash crop evapotranspiration rates have the similar rising trend during the 1987–2007 (Fig. 5). Specifically, the mean annual actual evapotranspiration rates of cash crop and food crop are 852 mm and 1011 mm, respectively, which are very similar to the conclusion of Li and Gao (2004).

Over the period of 1986–2007, due to the transformation of crop pattern (Fig. 6) and the development of social economy, the annual total food crop water consumption in the study area had decreased from 1.73×10^8 m^3 in 1987 to 1.49×10^8 m^3 in 1996 and 0.02×10^8 m^3 in 2007. The annual total cash crop water consumption had increased from 0.57×10^8 m^3 in 1986 to 1.13×10^8 m^3 in 1996 and 3.40×10^8 m^3 in 2007. The rapidly increasing high value cash crops in the study area were mainly attributed to China's economic reform. Since the early 1980s, farmers have more autonomy in land use activities, and their farming pattern have been more closely associated with market demands. The high value, high water consumption cash crops have been gradually replacing the traditional food crops and become the main income source of the local farmers. For example, the cotton price was 3.8 RMB/kg in 1987 and increased to 17.0 RMB/kg in 1996. During this period, food crop planting area had reduced sharply, but cash crop area had increased substantially, especially cotton planting area had increased from less than 6667 hm^2 in 1996 to 14,667 hm^2 in 2004. The rural per capita net income increased from 644 RMB in 1987 to 6.045 RMB in 2007. The food crops consumed the largest volume of water, accounting for 43.18% of the total water consumption in 1987, but only consumed 0.38% of the total water uses in 2007. The cash crops, however, consumed 14.12% of the total water uses in 1987, and 71.53% of the total water uses in 2007, becoming the largest water consumer in the study area (Zhang et al., 2003).

4.3. Grassland and shrub land water use

The water consumption of total grassland and shrub land decreased from 1.67×10^8 m^3 in the 1987 to 1.37×10^8 m^3 in 1996 and 1.15×10^8 m^3 in 2007. Specifically, in 1987, low coverage grassland, medium coverage grassland, high coverage grassland and shrub land accounted for 8.22%, 6.47%, 19.83% and 7.23% of the total water consumption, respectively. In 1996, the ratios became 9.63%, 8.66%, 10.39% and 5.02%, respectively. In 2007, the ratios changed to 5.58%, 5.35%, 10.20% and 3.15%, respectively. The water consumption of all the grassland-shrub land had decreased from 41.75% in 1987 to 33.70% in 1996 and 24.27% in 2007.

4.4. Domestic and industrial water use

During the 1987–2007 period, the total population of the Dunhuang oasis increased from 108.4×10^3 in 1987 to 139.4×10^3 in 2007, of which the net increase of rural and urban population were 12,588 and 20,816, respectively. The rural livestock decreased from 349,820 sheep unit in 1987 to 305,482 sheep unit in 2007. The tourist number increased from less than 100×10^3 to 1403×10^3 in 2007. The industrial output increased from 21.60×10^6 to 635.58×10^6 RMB (National Bureau of Satistics of China, 2009).

Table 7
Household and production water use/10^3.

	Total population[a]	Tourist population[a]	Livestock number[a]	Industrial output/RMB)[a]	Household water use	Production water use
1987	108.4	92.0	349.8	21,600	3365	430
1990	113.8	338.8	388.5	32,800	3608	722
1996	126.7	500.0	413.0	124,780	5014	2570
2000	131.5	603.5	292.9	217,950	4517	4468
2007	139.4	1403.5	305.5	635,580	6449	11,720

[a] From: Dunhuang National economic statistics yearbook, 1987–2008.

Due to the ongoing increase in population and the booming tourism industry, the annual total domestic water consumption in the study area rapidly increased from 3365×10^3 m^3 in 1987 to 5014×10^3 m^3 in 1996 and 6449×10^3 m^3 in 2007. The annual total industrial water consumption increased from 430×10^3 m^3 in 1986 to 2570×10^3 m^3 in 1996 and $11{,}720 \times 10^3$ m^3 in 2007 (Fig. 7 and Table 7).

Of the total water consumptions, the percentage of domestic water use increased from 0.84% in 1987 to 1.24% in 1996, and 1.36% in 2007, and the percentage of industrial water use increased from 0.11% in 1987 to 0.63% in 1996, and 2.47% in 2007.

4.5. Water consumption in the study area

The estimated total water consumption of the study area increased from 4.00×10^8 m^3 in 1987 to 4.75×10^8 m^3 in 2007, representing an average annual increase of 3.6% (Fig. 8). For

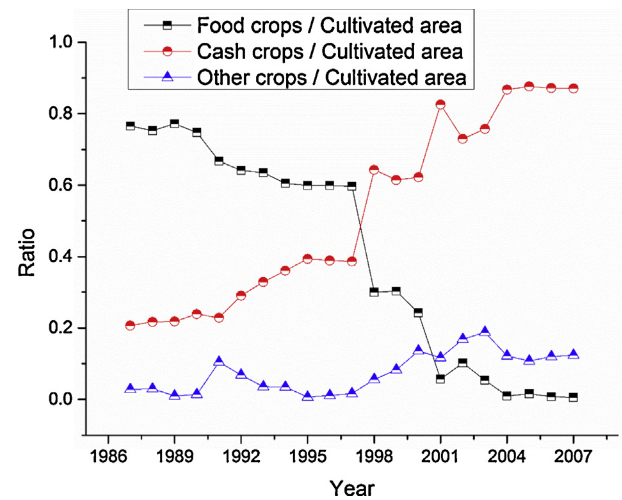

Fig. 6. The change of planting structure in Dang River oasis.

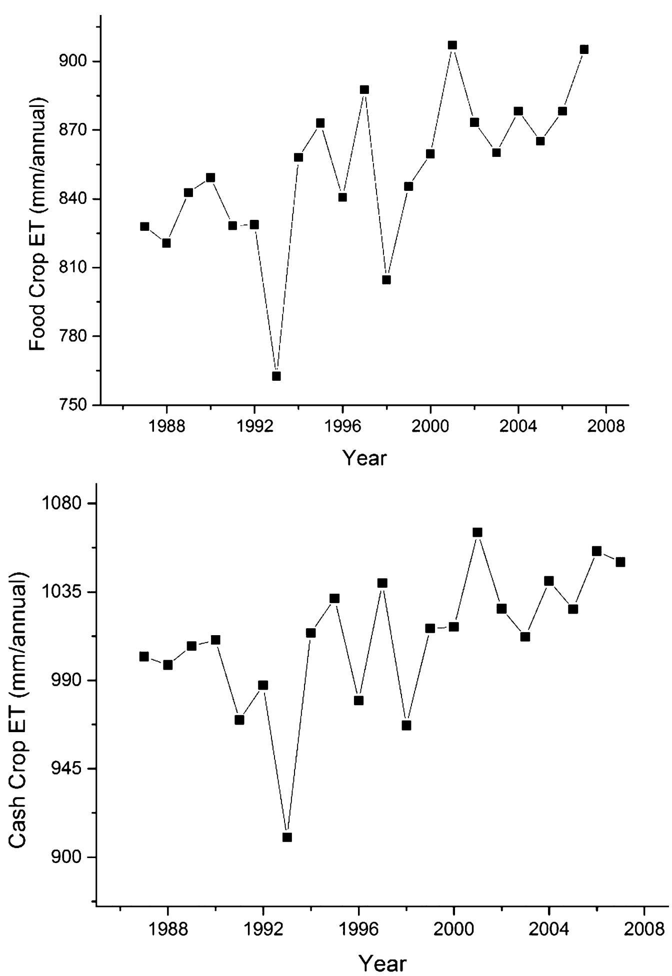

Fig. 5. Average evapotranspiration rates of food crops and cash crops computed by the FAO Penman–Monteith method.

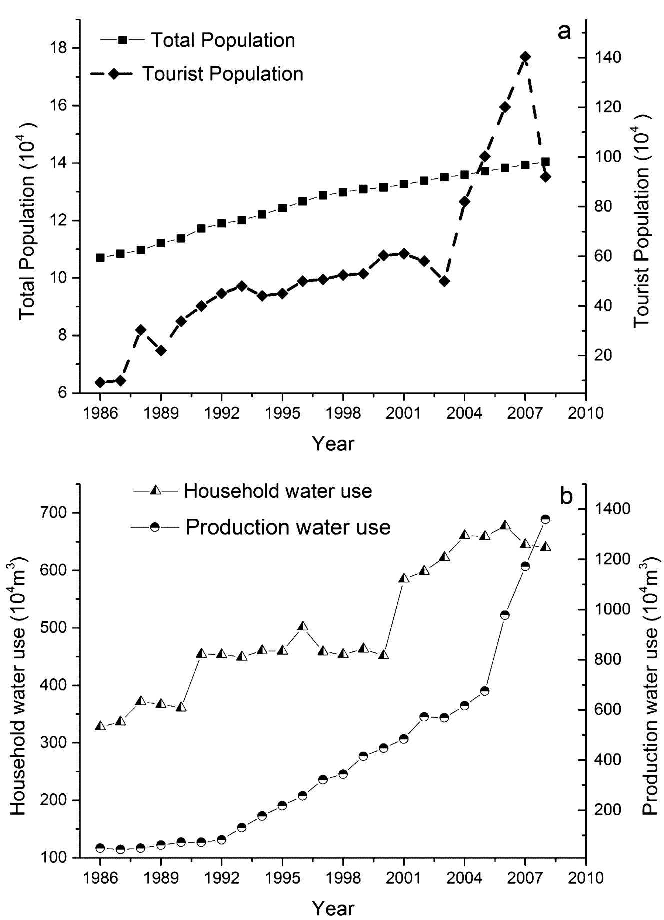

Fig. 7. (a) The change trend of total population and tourist number. (b) The change trend of household and production water use.

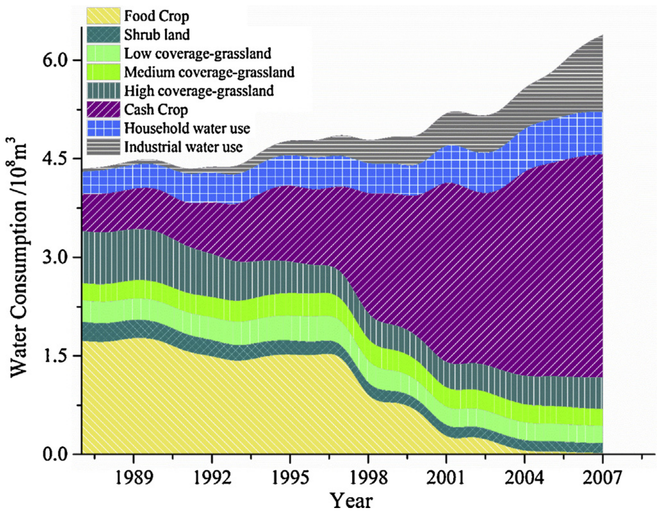

Fig. 8. Water consumption during 1987–2007. (*Note*: the unit of household and industrial water use is 10^4 m^3, others are 10^8 m^3.)

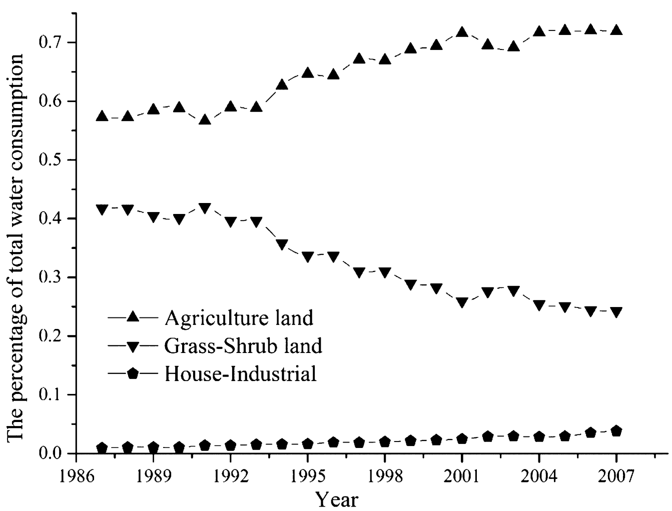

Fig. 9. The proportion of three types.

comparison purpose, the water consumptions of food crops and cash crops were combined as total agricultural water consumption; the water consumptions of low–medium–high density grassland and shrub land were combined as natural vegetation water consumption; and the water consumptions of domestic and industrial uses were merged to the same group (Fig. 9).

We can see that the proportion of the agricultural water consumption has been the largest of all classes during the period from 1987 to 2007 (Fig. 9). The proportion of the natural vegetation had been declining. Although the water consumption of the domestic-industrial uses was growing rapidly, their proportion in the total water consumption is very small.

The irrigation frequency of food crop such as wheat and corn is 4 times per cropping season, and the amount of water used is about 8100 mm/ha per irrigation. In the Dunhuang oasis, the irrigation frequency of cash crop such as cotton and grape is at least 6 times per season, with about and need about 10,200 mm/ha of water used per irrigation (Wang et al., 2011). Surface water was used to irrigate crops 2–3 times per season while the groundwater was pumped to provide sources of the water for the remaining irrigations during the season. Cash crops, particularly grapes and melons used mainly groundwater for irrigation.

In the extreme arid Dunhuang oasis, the mean annual precipitation is approximately 39 mm, while the annual evaporation averages to roughly 2500 mm. The scarce precipitation makes it impossible to recharge ground water while the extremely high evaporation draws down the groundwater table consistently (Ma et al., 2013).

Based on the above analysis, it is clear that agricultural land use was the main cause of the decline of the groundwater table during the period from 1987-2007. The rapid expansion of high water consumption cash crops depleted most of water from the headwater to irrigation canal system, and the canal lining further reduces the infiltration and leakage to groundwater, which accounting for up to 60% of the total groundwater recharge (Zhu and Chen, 1998). Eventually leaving little recharge to groundwater.

5. Conclusions

The present study analyzed the impacts of LU/LC changes on the groundwater depletion in the Dang River Watershed during the period of 1987–2007. Our main findings are:

1. Over the period of 1986–2007, urban land and farmland increased rapidly while the grassland decreased significantly, especially during the 1996–2007.
2. The transformation from grassland and barren land to cropland led to the increasing cropland area. A large area of grassland has been converted to the barren land and cropland, worsening the functions of the ecosystem.
3. Food crop planting area had been reduced sharply while cash crops had increased substantially, especially cotton planting area. Agricultural irrigation consumes the largest amount of water supply and was the main contributor to the groundwater depletion during the period of 1987–2007. Compared to the agricultural irrigation, water use by natural vegetation and domestic-industrial uses were relatively very small.

Acknowledgments

This research was supported by grants from the National Science Foundation of China (NSFC) (D010102-91125010), 2013 Key Research Support Program of Central Government Higher Education Basic Research Founding (lzujbky-2013-m02) and 2014 Key Research Support Program of Central Government Higher Education Basic Research Founding (lzujbky-2014-269). We greatly appreciate the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn) for providing valuable meteorological data, and also thank anonymous reviewers for their constructive comments and suggestions.

References

Aeschbach-Hertig, W., Gleeson, T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. Nat. Geosci. 5, 853–861.

Agam, N., Evett, S.R., Tolk, J.A., Kustas, W.P., Colaizzi, P.D., Alfieri, J.G., McKee, L.G., Copeland, K.S., Howell, T.A., Chávez, J.L., 2012. Evaporative loss from irrigated interrows in a highly advective semi-arid agricultural area. Adv. Water Resour. 50, 20–30.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M.,1998. Crop evapotranspiration – guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy.

Bodner, G., Loiskandl, W., Kaul, H.P., 2007. Cover crop evapotranspiration under semi-arid conditions using FAO dual crop coefficient method with water stress compensation. Agricult. Water Manag. 93, 85–98.

Bureau of Statistics of The City of Dunhuang, Gansu Province, China, 2007. Dunhuang National Economic Statistics Yearbook.

Bureau of Statistics of Gansu Province, Lanzhou City, China, 2007. Gansu Province National Economic Statistics Yearbook.

Chen, M., Wang, H., Wang, F., Tang, K., Wang, Y., 2004. Ecological water demand analysis in Arid Region. Acta Ecol. Sin. 24 (10), 2136–2142.

Deng, Y., Hu, L., Tong, G., 2011. Long-term response of groundwater system to sudden decrease of recharge in arid Dunhuang Basin, China. Water Resource and Environmental Protection (ISWREP), 2011 International Symposium on. IEEE 1, 177–180.

Doorenbos, J., Pruitt, W.O., 1975. Guidelines for Predicting Crop Water Requirements. Irrigation and Drainage Paper.

Gleeson, T., VanderSteen, J., Sophocleous, M.A., Taniguchi, M., Alley, W.M., Allen, D.M., Zhou, Y., 2010. Groundwater sustainability strategies. Nat. Geosci. 3, 378–379.

Harrington, L., Harrington Jr., J., Kettle, N., 2007. Groundwater depletion and agricultural land use change in the high plains: a case study from Wichita County, Kansas. Prof. Geogr. 59, 221–235.

Janssen, L.L., Van der Wel, F.J., 1994. Accuracy assessment of satellite derived land-cover data: a review. Photogr. Eng. Remote Sens. 60, 419–426.

Kashyap, P.S., Panda, R., 2001. Evaluation of evapotranspiration estimation methods and development of crop-coefficients for potato crop in a sub-humid region. Agricult. Water Manag. 50, 9–25.

Li, C., Gao, S., 2004. Study on the moisture budget of the grasslands in the semiarid regions in North China. Arid Zone Res. 21 (4), 28–32.

Liu, J., Buheaosier, 2000. Study on spatial-temporal feature of modern land use change in China. Quat. Sci. 20 (3), 229–239.

Ma, J., He, J., Qi, S., Zhu, G., Zhao, W., W. Mike, E., Zhao, Y., 2012. Groundwater recharge and evolution in the Dunhuang Basin, northwestern China. Appl. Geochem.

Ma, J., He, J., Qi, S., Zhu, G., Zhao, W., Mike Edmunds, W., Zhao, Y., 2013. Groundwater recharge and evolution in the Dunhuang Basin, northwestern China. Appl. Geochem. 28, 19–31.

National Bureau of Satistics of China, 2009. The New China 60 Years. China Statistics Press, Beijing City, China.

Sado, K., ISLAM, M.M., 1996. Effect of land cover on area evapotranspiration using Landsat TM data with meteorological and height data-the case of Kitami city, Japan. Hydrol. Sci. J. 41, 207–217.

Shi, P., Chen, J., Pan, Y., 2000. Land use change mechanism in Shenzhen City. Acta Geogr. Sin. 55 (2), 151–160.

Song, X., Yang, G., Yan, C., Duan, H., Liu, G., Zhu, Y., 2009. Driving forces behind land use and cover change in the Qinghai-Tibetan Plateau: a case study of the source region of the Yellow River, Qinghai Province, China. Environ. Earth Sci. 59 (4), 793–801.

State Environmental Protection Administration, China, 2006. Ecological Environment Evaluation of Technical Specifications.

Suleiman, A.A., Tojo Soler, C.M., Hoogenboom, G., 2007. Evaluation of FAO-56 crop coefficient procedures for deficit irrigation management of cotton in a humid climate. Agricult. Water Manag. 91, 33–42.

Sun, P., Du, M., Zhao, A., Zhang, X., 2002. Study on water requirement law of some crops and different planting mode in oasis. Agricult. Res. Arid Areas 20 (2), 79–85.

Swenson, S., Famiglietti, J., 2011. Sustainable groundwater management for large aquifer systems: Tracking depletion rates from space. Climate Change Effects on Groundwater Resources: A Global Synthesis of Findings and Recommendations., pp. 367.

Wada, Y., van Beek, L.P., van Kempen, C.M., Reckman, J.W., Vasak, S., Bierkens, M.F., 2010. Global depletion of groundwater resources. Geophys. Res. Lett. 37.

Wang, H., Chen, M., Qing, D., 2003. Rational Allocation and Research of Water Resources Carrying Capacity in Northwest Region. The Yellow River Water Conservancy Press, Henan Province, China, pp. 129–136.

Wang, H., Niu, J., Wang, R., Lv, X., 2011. Impact of climate change on water requirement of main crops in irrigated oasis of Hexi corridor. Acta Pratacult. Sin. 20 (5), 245–251.

Water Resources Department of Gansu Province, 2005. Industry Water Use Quota of Gansu Province.

Yang, G., Qu, Y., Dong, G., 2005. Study on ecology protection in lower reaches area of the Shule River. J. Desert Res. 25 (4), 472–482.

Yang, J., Li, Z., 2011. The dynamic trends and prevention countermeasures of groundwater in Danghe irrigation, Dunhuang basin. Water Resource and Environmental Protection (ISWREP), 2011 International Symposium on. IEEE 4, 3227–3230.

Ye, H.M., Chen, S.H., Sheng, F., Chen, H.W., 2013. Research on dynamic changes of land cover and its correlation with groundwater in the Shule River Basin. J. Hydraul. Eng. 44 (1), 83–90.

Young, J.E., Sánchez-Azofeifa, G.A., Hannon, S.J., Chapman, R., 2006. Trends in land cover change and isolation of protected areas at the interface of the southern boreal mixedwood and aspen parkland in Alberta, Canada. For. Ecol. Manag. 230, 151–161.

Zhang, H.H., Brown, D.F., 2005. Understanding urban residential water use in Beijing and Tianjin, China. Habitat Int. 29 (3), 469–491.

Zhang, M., Zhao, Z., Zeng, Z., 2003. The characteristics of water system and the sustainable utilization of water resources in Dunhuang Basin. J. Arid Land Resour. Environ. 17, 71–76.

Zhou, C., Dong, S., Li, D., Zhang, X., 2007. The characteristics and sustainable utilization of water resources in Dunhuang City of Gansu Province, China. J. Nat. Resour. 22, 4.

Zhuang, D., Liu, J., Liu, M., 1999. Research activities on land-use/cover change in the past ten years in China using space technology. Chin. Geogr. Sci. 9, 330–334.

Zhu, Z., Chen, G., 1998. Land Sandy Desertification in China. Beijing Scientific Press, Beijing City, China, pp. 213.