Environ Earth Sci
DOI 10.1007/s12665-014-3328-0

THEMATIC ISSUE

Model for calculating suitable scales of oases in a continental river basin located in an extremely arid region, China

Yu Lei · Xiangquan Li · Hongbo Ling

Received: 28 August 2013 / Accepted: 25 April 2014

Abstract The Keriya River Basin was chosen as the study site in this paper in order to investigate the suitable scales of natural and artificial oases with a certain water resource quantity. A calculation model was constructed and the suitable scales of natural and artificial oases were analyzed using remote sensing images, water resources, weather and socioeconomic data. The results showed that (1) high- and low-flow variations were apparent for the Keriya River. The mean values for the high-flow period, normal flow period and low-flow period were 9.23×10^8 m^3, 7.177×10^8 m^3 and 5.741×10^8 m^3, respectively. (2) The ecological water demand of natural oasis in the lower reaches of the Keriya River Basin was 2.561×10^8 m^3. (3) In the Tarim Basin, the proportion of natural and artificial oases was 6:4. (4) In the middle reaches, after guaranteeing the unchangeable scale of artificial oases, the most suitable size of a natural oasis was 798–1,157 km^2. Under the reasonable proportion (i.e. proportion of 6:4 for the natural and artificial oases), the respective suitable scales of natural and artificial oases in the middle reaches were 831–1,003 km^2 and 554–669 km^2. This study constructed a model for calculating the suitable scale of an oasis, verified the suitable proportions of natural and artificial oases and discussed the reasonable scales of oases in order to provide a new theoretical basis for determining reasonable development planning in similar river basins located in extremely arid regions.

Keywords Arid region · Tarim Basin · Suitable scale of oasis · Water balance · Climate change

Introduction

Oases are an essential part of arid and semi-arid regions (Su et al. 2007), and their scale, location and development all depend on the temporal-spatial pattern of water resources (Kok and Nel 1996; Wang et al. 2011; Zhang et al. 2011; Moharram et al. 2012; Feng et al. 2012). Oases can be divided into artificial oases and natural oases (Fan et al. 2000; Wang et al. 2011). Artificial oases develop from desert or natural oases and are influenced by long-term human activities. They are the key to human survival and development in arid regions and include an artificial water area, cultivated land, an artificial landscape and an oasis city or town (Fan et al. 2000; Liu et al. 2010). Natural oases can contain desert riparian forest and valley meadow and shrubs. They lie between artificial oases and desert and thus form an important buffer zone that provides the artificial oases with ecosystem stability (Fan et al. 2000; Li et al. 2008). However, as a result of rapid economic development over the past 60 years in China, large-scale artificial oasis expansion has resulted in severe water resource shortages, a reduction in the size of natural oases and an increase in desertification (Pan and Chao 2003; Zhao et al. 2004; Cheng et al. 2006; Wang et al. 2010; Ling et al. 2011a, b). If oasis development is to be sustainable,

Y. Lei
College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing 210098, China

Y. Lei · X. Li
Water Resources Department of Xinjiang Uygur Autonomous Region, Urumqi 830000, China

H. Ling (✉)
Sino-German Joint Research Center for the Management of Ecosystems and Environmental Change in Arid Lands, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS), Urumqi 830011, China
e-mail: linghongbo0929@sina.com; linghongbo0929@163.com

we need to establish the most suitable size for an oasis, based on the carrying capacity of water resources, certain economic and technologic conditions, ecosystem stability and ecological security (Hu et al. 2007; Li et al. 2008).

There have been few studies on the suitable scale of oasis in the continental river basin of arid regions. Of the few studies reported, most of them have focused on the ecological water consumption of an oasis and the watercourse water consumption of rivers (Moran et al. 1994; Maneta et al. 2009; Contreras et al. 2011). In China, a number of studies have provided a theoretical base for calculating the suitable scale of an oasis, such as the ecological landscape types of natural and artificial oases (Fan et al. 2000), or the water consumption in a unit area of irrigated land or of a natural oasis (Lei et al. 2006). There are also models that describe the area of oasis, water utilization (Zhang et al. 2008), oasis stability (Wang et al. 2002; Leng et al. 2011), and oasis water consumption (Tang et al. 2007; Zhao et al. 2010; Contreras et al. 2011). In recent years, some researchers have focused on the suitable scale of an oasis by using water-heat balance (Hu et al. 2007; Huang et al. 2008; Li et al. 2011), but they only considered the development scale of artificial oases under the assumption of a certain water resource quantity and neglected the ecological water demand of natural oases. Therefore their results did not take into account ecosystem stability and the water resource allocation of the whole oasis. In addition, some studies tried to describe the suitable scale of an oasis using the 'certain oases planning mode' (Hu et al. 2007; Huang et al. 2008), but they did not consider the variations in demand of oases water resources and the impact of socio-economic development on artificial oasis. Accordingly, it is vital to determine the suitable development scales of natural and artificial oases if sustainable development of oases is to be achieved.

The Keriya River Basin is situated on the south margin of the Tarim Basin. The Kunlun Mountains are to the south, and the Taklamakan Desert (the largest desert in China) is to the north (Fig. 1). The Keriya River is the longest river in Yutian County and flows from south to north in the Tarim River Basin (Yang et al. 2004). The Daliyaboyi Oasis in the lower reaches of the Keriya River Basin and is a unique, naturally vegetated area that stretches deep into the hinterland of the Taklamakan Desert. The Daliyaboyi Oasis has attracted wide attention because of its desert ecological research, tourism, archaeology and exploration value (Blanc 2011; Yang 2001; Yang et al. 2002; 2006; Baumer 2011; Zhang et al. 2011). However, as a consequence of the rapid expansion of artificial oases in the middle reaches of the Keriya River Basin since the 1950s, the desert ecosystem in the lower reaches is now under threat because the river channel has been cut off and natural vegetation is declining (Ling et al. 2011b). In order to save the natural oases in the lower reaches, we need to investigate the water resource allocation and the most suitable scale of oases in the middle and lower reaches of the Keriya River Basin.

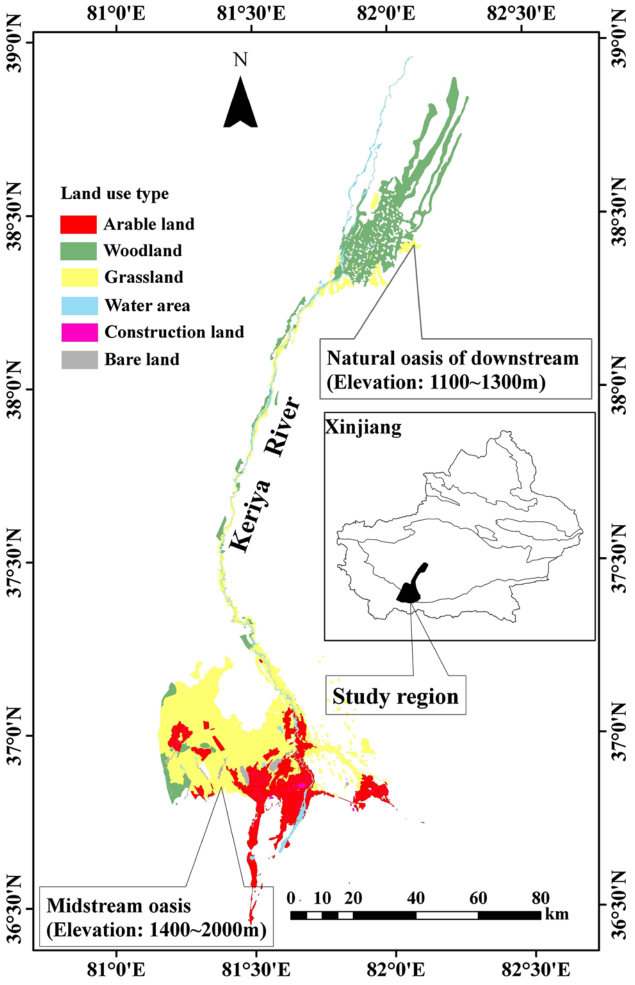

Fig. 1 Sketch map of Keriya River Basin

Therefore, based on water resource data (1957–2009), air temperature and precipitation data (1971–2009), socio-economic data (2009), and ALOS satellite remote sensing images (2010) with the resolution ratio of 2.5 m, this study analyzed the high- and low-flow variations of surface runoff in the Keriya River. The required water resource quantity for maintaining ecosystem stability of a natural oasis in the lower reaches and the socio-economic development of artificial oases in the middle reaches was calculated. Additionally we put forward new development mode for oases based on the optimal size of natural and artificial oasis under the different high- and low-flow variations of the river. The study aimed to provide new ways of investigating the suitable scales of oases in continental river basins located in extremely arid regions (i.e., moist index <0.05) (Ci 1994) and to offer references for determining reasonable oases development management plans.

Study region

With a total length of 740 km and the annual runoff of 7.215×10^8 m^3, the Keriya River begins in the northern Kunlun Mountains and the catchment area covering the mountain pass headstreams is 7,358 km^2, according to the Langan Hydrometric Station. The river basin (35°14′–39°29′N, 81°09′–82°51′E) 466 km long from north to south and 30–120 km wide from east to west (Ling et al. 2011b). The total study region is 3.95×10^4 km^2, the mountain area is 1.24×10^4 km^2, the plain area is 0.57×10^4 km^2, and the desert area is 2.14×10^4 km^2.

The Keriya River Basin lies in the hinterland of Eurasia and belongs to the extreme desert climate of the warm temperate zone. The average annual air temperature is 9.53 °C, the extreme maximum temperature is 43.0 °C, and the extreme minimum temperature is −26.3 °C. The average annual precipitation is 44.7 mm, and the evaporation is 2,239.8 mm. The river basin is one of the regions with a very vulnerable ecosystem and the most serious desertification in western China (Yang 2001; Yang et al. 2006).

Data resources

This study collected ALOS satellite remote sensing images of the Keriya River Basin in July 13, 2010 with a resolution ratio of 2.5 m, and the images were digitalized to obtain the land cover/use data of this river basin (Fig. 1; Table 1). For image processing, firstly, relief maps of two amplitudes with a ratio of 1:100,000 for the research regions were scanned and registered by ArcGIS9.3 (the error precision was below 0.5 pixels), and the digital raster graphic (DRG) was created. Subsequently, the images in 2010 were registered by the digital raster graphic (DRG). Thirty interpretation symbols, such as the crossing points of road and canal systems, and residential centers, were located evenly on the whole image plane. The error precision was below 0.5 pixels in the image registration. In addition, the images in 2010 were further corrected based on field surveys and sampling. The land use types were classified based on the national criteria in the book 'Current Land Use Classification', which was published by the Chinese Government in 2007. According to the classification precision evaluation for the land cover/use of the Keriya River in 2010, the Kappa coefficient (classification precision evaluation index) (Congalton and Green 1999) was 95.8 %, which indicated that it could accurately reflect the land use in the study region.

The socio-economic data came from the Yutian County in the Keriya River Basin yearbook and included the population, crop planting structure, GDP and livestock inventory statistics for 2009. The water resource and weather data covers the measured runoff of the mountain pass of the Keriya River (Langan Hydrometric Station) between 1957 and 2009, underground water and the other surface water resources between 2000 and 2009, and the yearly precipitation and air temperature for Yutian County and Langan Hydrometric Station between 1971 and 2009.

Study methods

The *Z* index was used to analyze the high- and low-flow variations for surface runoff in the river basin. The variation ranges for natural and artificial oases in the river basin were calculated based on the available water resources and a model for calculating a suitable oasis size based on the water quantity balance.

Z index method

The *Z* index can reflect the high- and low-flow variations within a certain period. The specific steps are as follows (Ling et al. 2013).

The annual runoff in a given period obeys the Person-III distribution, and the probability density function is

$$f(x) = \frac{\beta_a}{\Gamma_{(a)}}(x - a_0)^{a-1} e^{-\beta(x-a_0)} (x > a_0) \tag{1}$$

where a, a_0, and β are the three coefficients. The mathematic expectation of the probability density function is:

$$m = \frac{a}{\beta} + a_0 \tag{2}$$

where,

$$a_0 = m\left(1 - \frac{2c_v}{c_s}\right), \tag{3}$$

Table 1 Area ratio of each land type to oasis in the Keriya River Basin

Land use type	Arable land	Woodland	Grassland	Bare land and construction land	Water area
Area ratio of each land type to oasis (%)	14.62	21.460	51.73	4.42	7.77

Table 2 Grade of high- and low-flow index

Grade	Cumulative frequency (%)	High- and low-flow index (*Z*)	High- and low-flow type
1	>70	$Z > 0.5244$	High flow
2	30–70	$-0.5244 < Z \leq 0.5244$	Normal flow
3	<30	$Z \leq -0.5244$	Low flow

$$a = \frac{4}{c_s^2}, \tag{4}$$

$$\beta = \frac{2}{\sigma c_s} \tag{5}$$

C_s is the skewness coefficient and C_v is the variation coefficient. Both are obtained from the runoff data sequence as follows:

$$c_s = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{m\sigma^3}, \tag{6}$$

$$c_v = \frac{\sigma}{\bar{x}} \tag{7}$$

where σ is the standard deviation of the annual runoff sequence and $\bar{x}$ is the mean value of the annual runoff sequence.

Subsequently, the annual runoff x is normalized as follows:

$$x = \frac{a}{\beta}\left[1 - \frac{1}{9a} + z\left(\frac{1}{9a}\right)^{1/2}\right]^3 + a_0. \tag{8}$$

The probability density function is transformed from Person-III distribution to standard normal distribution with Z as the variable. The expression is:

$$z_i = \frac{6}{c_s}\left(\frac{c_s}{2}\varphi_i + 1\right)^{1/3} - \frac{6}{c_s} + \frac{c_s}{6} \tag{9}$$

where z_i is the Z index within the region and φ_i is the standard variable calculated by

$$\varphi_i = \frac{x_i - \bar{x}}{\sigma} \tag{10}$$

According to the normal distribution curve of the Z variable, the limiting value of the Z index is divided into three grades and into high- and low-flow types (Table 2).

Model for calculating the most suitable oasis size

The model for calculating the most suitable oases size was based on the water quantity balance theory.

$$\frac{W - W_0}{(\alpha A_N + \beta A_A + A_W E_{\phi 20}\gamma + A_O E_p)10^{-5}} = 1 \tag{11}$$

where A_N is the area of a natural oasis (km^2), A_A is the irrigated area of an artificial oasis, including farmland, forest land and grassland under artificial irrigation (km^2), A_W is the area of artificial water (km^2) and A_O is the areas of the other land use types in the artificial oasis region, including bare land and construction land (km^2). W is the total available water resource quantity (10^8 m^3), W_0 is the water consumption of non-vegetation, including industrial and domestic water, surface evaporation and the minimum ecological water demand in the river channel (10^8 m^3); α and β are the water demand quotas of the natural and artificial oases. In the Keriya River Basin, these are 400 and 650 mm, respectively (Lei et al. 2006). $E_{\phi 20}$ is the surface water evaporation of the 20 cm general evaporation dish (mm); E_p is the phreatic water evaporation (mm), and γ is the conversion coefficient of surface evaporation, which has a value of 0.61 (Zhou 1999).

The proportion of natural oasis to the total oasis is set as μ.

$$A_N = \mu A \tag{12}$$

$$A_H = A_A + A_W + A_O = (1 - \mu)A \tag{13}$$

where A is the optimal area of a natural oasis in the study region (km^2), and A_H is the optimal area of an artificial oasis (km^2). Equations (12) and (13) were put into Eq. (11), and the calculation model of suitable oasis scale changed to

$$A = \frac{(W - W_0)10^5 + A_W(\beta - E_{\phi 20}\gamma) + A_O(\beta - E_p)}{\alpha\mu + \beta(1 - \mu)} \tag{14}$$

Phreatic evaporation model

This study used a phreatic evaporation model to calculate evaporation from bare land and construction land in an artificial oasis area as follows (Ye et al. 2010):

$$E_p = \omega\left(1 - \frac{H}{H_{\max}}\right)^{\lambda} \times E_{\phi 20} \tag{15}$$

where H is the groundwater depth (mm) and $H_{\max}$ is the critical phreatic water depth (m); ω and λ are the empirical coefficients, which were 0.62 and 2.8 in the Keriya River Basin (Ye et al. 2010). The values of H and $H_{\max}$ are 4.0 and 4.5 m in this river basin (Chen et al. 2005).

Results and analysis

High- and low-flow variations for surface runoff in the Keriya River Basin mountain pass

The high- and low-flow variations for runoff were analyzed using the Z index method (Fig. 2), based on the annual runoff from the Keriya River between 1957 and 2009.

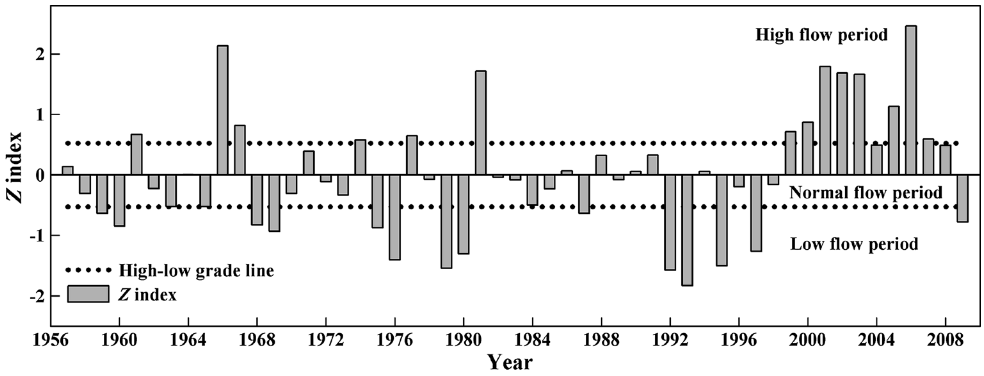

Fig. 2 High- and low-flow variations of runoff in the Keriya River Basin

Figure 2 shows that the runoff in the Keriya River mountain pass headstreams changed from a normal flow period into the low-flow period between 1957 and 1959. Three high-flow years (1961, 1966 and 1967) and three low-flow years (1960, 1968 and 1969) occurred between 1960 and 1969, and the rest were normal flow periods. The runoff had a normal flow period between 1970 and 1973, and then rose to a high-flow period in 1974, but declined to a low flow in the subsequent 2 years. There was then the high-normal-low flows between 1977 and 1979. The flows were mainly normal during the 1980s, except for 1981, which was a high-flow year. Flow was low in 1990, and 1991–1998 had seven alternant changes between high and low flow. The runoff has generally been at the high-flow level since 1999, particularly between 2000–2003 and 2005–2007. However normal flows occurred twice in 2004 and 2008, and a low-flow period occurred once in 2009. According to the above analysis, the Keriya River has apparent high and low-flow variations, so it is feasible to determine the suitable oasis sizes for the Keriya River based on the variations in surface runoff. The mean values for annual runoff in the three flow categories (high, normal and low) between 1957 and 2009 were 9.23×10^8 m^3, 7.177×10^8 m^3 and 5.741×10^8 m^3, respectively. In addition, the average runoff in the study region was 7.34×10^8 m^3, and thus its minimum ecological base flow was 0.734×10^8 m^3 according to the Montana Method (Xia et al. 2006). Moreover, the total available water quantity in the other water systems, spring water and groundwater was 6.424×10^8 m^3. Accordingly, the total available water quantities in the river basin over the three periods were 14.92×10^8 m^3, 12.867×10^8 m^3 and 11.431×10^8 m^3.

Ecological water demand of a natural oasis in the lower reaches of the river and available water resource quantities of oases in the middle reaches of the Keriya River Basin

The natural oasis was impacted less by anthropogenic activities because it was located in the lower reaches of the Keriya River and the hinterland of the Taklamakan Desert (Yang 2001), which meant that the regional industrial and domestic water could be ignored. The natural oasis area in the lower reaches of the river is 640.138 km^2, based on the ALOS satellite remote sensing images from 2010. Its water demand quota is 400 mm, and, therefore, its ecological water demand is 2.561×10^8 m^3. In addition, the area covered by the natural lake and the river channel is 129.93 km^2 and the water surface evaporation is 2239.8 mm. Therefore, the total water consumption is 1.775×10^8 m^3 if the water surface conversion coefficient (0.61) is used. In the Keriya River Basin, if stability in the lower reaches is assumed, then the available water resource quantities of oases in the middle reaches in the high-flow, normal flow and low-flow periods were 10.584×10^8 m^3, 8.531×10^8 m^3, and 7.095×10^8 m^3, respectively.

Water demand of artificial oases in the middle reaches of Keriya River Basin

The land cover/use in 2010 showed that the irrigated area supplied by the artificial oasis in the middle reaches of the Keriya River Basin was 392.54 km^2, and the total water consumption was 2.552×10^8 m^3. Furthermore, the water consumption of the artificial oasis was 1.077×10^8 m^3, and the water consumption of bare land and construction land was 0.003×10^8 m^3. Therefore the total water consumption by the oasis irrigated land, the water area, and the other land use types was 3.632×10^8 m^3.

The populations of the city and village located in the river basin in 2009 were 31,814 and 213,328, respectively, and the water consumption quotas per person per day were 0.096 and 0.08 m^3, respectively (Gu 2006). Therefore, the population water consumption of the river basin was 0.082×10^8 m^3 if the water resource utilization coefficient was 0.9. Furthermore, the regional industrial output in 2009 was $41{,}987 \times 10^4$ yuan. The water consumption quotas for the industrial output of one ten thousand yuan is 210 m^3

Table 3 Areas of natural oasis and total oases in the middle reaches of Keriya River Basin

Grade	Water resource quantity ($10^8 m^3$)	Water demand quota (mm)	Natural oasis (km^2)		Total oasis (km^2)	
			Suitable scale	Actual scale	Suitable scale	Actual scale
High-flow period	6.681	400	1,670	1,325	2,244	1,899
Normal flow period	4.628		1,157		1,731	
Low-flow period	3.192		798		1,372	

Table 4 Suitable scale of oases in the middle reaches of Keriya River Basin under appropriate proportioning

Grade	$W - W_0$ ($10^8 m^3$)	A_W (km^2)	A_O (km^2)	μ	E_p (mm)	Suitable scale (km^2)		
						Total oasis (A)	Natural oasis (A_N)	Artificial oasis (A_H)
High-flow period	10.313	78.86	102.98	60 %	2.96	2,083	1,250	833
Normal flow period	8.260					1,672	1,003	669
Low-flow period	6.824					1,385	831	554

(Gu 2006), and thus the total industrial water consumption was 0.098 × 10^8 m^3 based on a water resource utilization coefficient of 0.9. In addition, the study region had 580,721 adult livestock and 275,511 young livestock at the end of 2009 and the daily consumption quotas of the two livestock were 0.04 and 0.006 m^3 (Gu 2006), so the total water consumption was 0.091 × 10^8 m^3. According to the above calculations, the socioeconomic water consumption of the artificial oasis in the river basin was 0.271 × 10^8 m^3, and the total water consumption of the artificial oasis was 3.903 × 10^8 m^3. Therefore, the respective available water resource quantity of a natural oasis in the middle reaches of the Keriya River Basin was 6.681 × 10^8 m^3, 4.628 × 10^8 m^3 and 3.192 × 10^8 m^3 for the high, normal, and low-flow periods.

Optimal size for an oasis in the middle reaches of Keriya River Basin under different inflow variations

According to the statistical data for Yutian County, the local population was 81,269 in 1949 and had increased threefold by 2009, and the area under cultivation had increased by 294.8 km^2. Therefore, the water demand for irrigation from the Keriya River had significantly increased. As a result, the Keriya River has been able to supply the natural oasis in the lower reaches only during flood periods since the 1980s (Yang 2001). Therefore, if oases are to be sustainably developed, it is important to be able to guarantee the ecosystem stability of natural oasis and to satisfy the normal water demand of artificial oasis in the Keriya River Basin.

Table 3 shows that the optimal size of the natural oasis in the middle reaches should not be below 798 or over 1,670 km^2. If the normal flow period (25 years) and low-flow period (14 years) occupied 74 % of last 53 years, then the optimal area of the natural oasis in the middle reaches is 798–1,157 km^2, and the optimal area covered by all the oases should be 1,372–1,731 km^2. The natural oasis area of middle reaches in 2010 was 1,325 km^2 and its ecological water demand was 5.3 × 10^8 m^3. Accordingly, in the low flow and normal flow periods, the respective ecological water deficits are 2.108 × 10^8 m^3 and 0.672 × 10^8 m^3, respectively, and thus the ecological water demand of the natural oasis was only satisfied during high-flow periods. Figure 2 shows that there were 7 years between 2000 and 2009 belonging to the high-flow period in the Keriya River, so the water quantity of water in the river basin in the past 10 years was able to guarantee the ecosystem stability of the natural oasis in the middle reaches. However, there needs to be further study into whether this ecosystem stability can be maintained in the future.

Calculating the suitable sizes of oases in the middle reaches of the Keriya River Basin under appropriate proportioning

Hu et al. (2007) suggested that the area of a natural oasis should occupy 60 % of the total oases area in any given arid region. Therefore, the optimal size of an oasis in the middle reaches of Keriya River was calculated based on the constructed mathematical model (Eq. 14) in this paper (Table 4).

Table 4 and the calculation show that the respective water consumptions of the natural oasis during the high-flow, normal flow and low-flow periods were 5.0 × 10^8 m^3, 4.012 × 10^8 m^3 and 3.324 × 10^8 m^3, which represented 49 % of the total available water resource (i.e., a high flow of 10.313 × 10^8 m^3, a normal

Table 5 Non-linear fitting between surface runoff and climate factor in Keriya River Basin

Keriya River Basin	Time (year)	Fitting model	*R*	*F*	*P*
Runoff	1971–2009	$R = e^{-2.8098} \cdot P^{0.1511} \cdot T^{1.7491}$	0.604	10.321	0.0003
$E_{\phi 20}$	1971–2009	$E_{\phi 20} = e^{12.9106} \cdot P^{-0.1249} \cdot T^{-1.9312}$	0.643	12.686	<0.0001

Table 6 Suitable scales of oases in the middle reaches of Keriya River Basin in 2020 with appropriate proportioning

Basin	$W - W_0$ ($10^8 m^3$)	A_W (km^2)	A_O (km^2)	μ	E_p (mm)	Suitable scale (km^2)		
						Total oasis (A)	Natural oasis (A_N)	Artificial oasis (A_H)
Keriya River	10.46	78.86	102.98	60 %	2.38	2,386	1,432	954

flow of 8.26 × 10^8 m^3 and low-flow period of 6.824 × 10^8 m^3). Therefore, the allocation of water for the natural and artificial oases in this arid region is consistent with the study result of Qian et al. (2004), and it indicates that the proportion of land occupied by natural and artificial oasis (i.e., natural oasis occupies 60 %, and artificial oasis occupies 40 %) is feasible. Furthermore, the optimal size of a natural oasis in the middle reaches needs to be between 831 and 1,003 km^2 and should not exceed 1,250 km^2. However, the regional natural oasis area has been exceeded by 75 km^2. The actual area covered by artificial oases was 574 km^2 in 2010 for the Keriya River Basin, but this was in the optimal range of 554–669 km^2. Overall, the total area covered by oases in the Keriya River Basin needs to be 1,385–1,672 km^2.

Optimal oasis sizes in the middle reaches of the Keriya River Basin in the future

This study showed that there exists a significant non-linear correlation between surface runoff and climate factor in the Keriya River Basin and that there are close relationships between air temperature, precipitation and evaporation (Ling et al. 2011b). Consequently, a correlation model runoff was constructed, based on relevant data from the Keriya River Basin, such as surface runoff, air temperature, precipitation and evaporation in the headstreams and oasis area (Table 5).

Table 5 shows that the correlation coefficients among runoff and three climate factors (evaporation, air temperature and precipitation) were all extremely significant at the 0.01 level, so these three fitting models all had better fitting precision. According to Xu et al. (2008), the average annual air temperature for Xinjiang between 2011 and 2020 will be higher than between 2001 and 2010 by 0.4 °C, whereas precipitation will not change. Therefore, the air temperature and precipitation in the Keriya River headstreams will be 11.7 °C and 95.9 mm and will be 12.8 °C and 49.9 mm, respectively in the oasis areas. Table 5 shows that the surface runoff would be 8.862 × 10^8 m^3 and the evaporation will be 1,805.8 mm in the Keriya River Basin in 2020.

The total water resource of the Keriya River Basin will be 15.286 × 10^8 m^3 in 2020. If the water consumption of the natural oasis in the lower reaches 2.561 × 10^8 m^3, then the minimum ecological base flow demand of the river channel will be 0.734 × 10^8 m^3, water surface evaporation of the natural water area will be 1.431 × 10^8 m^3, the socio-economic water consumption will be 0.1 × 10^8 m^3 (Zhu 2000) and the available water resource quantity of oases in the middle reaches of the river will be 10.46 × 10^8 m^3 (Table 6). As suggested by the Hu et al. (2007), the water demand quota for artificial oases in this river basin is 500 mm under the implement of water-save measures. Table 6 shows that as climate change and irrigation technology advance, the respective upper limits of natural and artificial oasis areas in the middle reaches of the river basin in 2020 could be 1,432 and 954 km^2, which is greater than the area of each by 107 and 380 km^2, respectively, so the oases in the study region have a development potential in the future. However, it is worth noting that the water quantity of the river basin could not satisfy the water consumption demand for all of the oases in the middle reaches in 2010. Consequently, a series of efficiency measures, such as regulating oasis development, enhancing water utilization efficiency and strengthening water resources allocation are still necessary if the coordinated development of natural and artificial oases is to be achieved.

Discussions

Calculation of the optimal size of oases in arid region

Small oases usually restrain human production and daily living because it is difficult to fully utilize the regional natural resources in arid regions. However oversized oases will lead to environmental deterioration due to a shortage of water resources, which will then threaten oasis survival and development. Overall, oasis development needs to be controlled. According to Li et al. (2008), oases of 90 % have no appropriate proportion of artificial and natural oases in arid regions of China, and artificial oases covering of 59 % cannot be maintained. For this reason, the determinations of suitable oases sizes should been further investigated. There have been few studies into the optimal size of oases in arid regions. Domestic studies have only focused on the optimal size of artificial oases (Hu et al. 2007; Huang et al. 2008; Li et al. 2011). However, the above studies have not considered the regional water resource changes and have not calculated the ecological water demand of natural oases. Therefore, this paper utilized GIS technology and field survey techniques to analyze natural and artificial and confirmed the optimal size of natural and artificial oases. Furthermore, the model for calculating the optimal size of natural and artificial oasis in the continental river basins of extremely arid regions has been constructed for the first time.

In this arid region, the optimal oasis size mainly depends on the total water quantity (Li et al. 2011). This paper took the change in water recourses as the primary factor and determined the optimal oasis size for an artificial oasis and for reasonable proportion of two oases. In addition, in the continental river basin of an extreme arid region, the local water resources are mainly supplied by glacial meltwater and precipitation in the headstream mountain area, so the water recourses are sensitive to the regional climate change (Ling et al. 2011b) This paper forecasts the development direction of oases in the future and supports the sustainable development of oases in the arid regions.

Measures to ensure the sustainable oasis development

1. There is a need to change oases development. Formerly, the development of artificial oases mainly relied on the shrinkage of natural oases (Yang 2001). This led to a weaker ecosystem in arid regions and a reduction in the long term survival and development of artificial oases. Therefore, the development of artificial oases should depend on productivity enhancement rather than expansion. Local managers should reduce the water consumption from artificial oases by a series of measures, such as enhancing water utilization efficiency, strengthening cyclic utilization of municipal and industrial sewage and adopting advanced irrigation technology. In the Keriya River Basin, the upper limits of natural and artificial oases should exceed 1,432 and 954 km^2 in 2020, respectively. Compared with 2010, the two oases in 2020 have expansion potential to expand by 107 and 380 km^2, respectively. However, if the natural and artificial oases in river basin were to remain at their 2010 levels there would be a surplus water quantity of 2.328×10^8 m^3 in 2020; but most importantly, the surplus water could be used to enhance the output value of water resources (for example, for industrial development around artificial oases) and replacing the expansion of the artificial oasis area.
2. Reasonable water resources allocation needs to be determined according to the high and low-flow variation in surface runoff. The surface runoff usually shows high and low-flow variation in the continental river basin of this arid region (Ling et al. 2011a, b), so local managers should avoid expanding artificial oases during the high-flow period and reducing ecological water supply to the natural oasis during a low-flow period. For example, the Keriya River was dominated by normal flow and low flow in the middle of the 1980s to the late 1990s, thus the expansion of artificial oasis before the 1980s led to the shrinkage of the natural oasis and no flow in the river channel during the low-flow periods (Yang 2001; Ling et al. 2011b).
3. We need to build and improve water conservancy projects in the middle reaches of Keriya River Basin. There are eight plain reservoirs in the middle reaches that have a designed total capacity of 0.3×10^8 m^3 and have an actual total capacity of 0.18×10^8 m^3. However, these reservoirs are old and suffer from severe leakage losses. Moreover, the total spillage of spring water from the river basin is 2.8×10^8 m^3, but the reservoirs have a much smaller capacity and have limited regulation, and thus the utilization degree of the spring water is not high. Therefore, it is urgent to build and improve water conservancy projects in the middle reaches of the Keriya River Basin.
4. Establishing a mountain reservoir will improve flood storage and management. The annual runoff of the Keriya River has an uneven distribution and the water quantity between May and September represents 80.4 % of the annual runoff. It is necessary to allocate water resources reasonably and scientifically by building the mountainous reservoir in order to make up for the lack of oasis water in the lower and middle reaches.

Conclusions

The Keriya River Basin, which is in an in the extremely arid region of China was chosen as the study area. Based on the data of water resources, weather, socio-economy and remote sensing image data, the suitable scales sizes of oases under different high and low-flow variations were analyzed by using the *Z* index and by creating a model that could calculate an appropriate oases size. The following conclusions were obtained:

1. The Keriya River has high- and low-flow variations. During the high, normal and low-flow periods, the total available water from the river basin was 14.92×10^8 m^3, 12.867×10^8 m^3 and 11.431×10^8 m^3, respectively.
2. The ecological water demand of the natural oasis was 2.561×10^8 m^3 in the lower reaches of the Keriya River. The respective development scales in the natural oasis in the middle reaches of the river during the high-, normal- and low-flow periods were 1,670, 1,157 and 798 km^2, respectively, and the optimal size was 798–1,157 km^2.
3. The optimal proportion of the natural to artificial oases was 6:4 (i.e., natural oasis occupies 60 % of the whole oasis, and the artificial oasis is 40 %.). Using this proportion, the size of the natural oasis in the middle reaches should be 831–1,003 km^2, and the size of the artificial oasis should be 554–669 km^2. If climate change is taken into account, the increase of basin water quantity and the advance of science and technology, then the respective upper limit of natural and artificial oases in the middle reaches in 2020 will approach 1,432 and 954 km^2, respectively.
4. With climate change and provisions for sustainability, the oases in the middle reaches of Keriya River Basin have substantial development potential. However, the study region has obvious high and low-flow variations in surface runoff, so we need to limit the size of oases because the oases may not be supplied during low-flow periods. However, as technology advances, we may be able to enhance the productivity of artificial oases.

Acknowledgments This work was supported by the Science and technology plan projects of the xinjiang uygur autonomous region (201230117-01-02), National Natural Science Foundation of China (51209223, 31370551, 41171427 and 30970549).

References

Baumer C (2011) The Ayala Mazar-Xiaohe culture: new archaeological discoveries in the Taklamakan desert, China. Asian Aff 42:49–69. doi:10.1080/03068374.2011.539323

Blanc D (2011) Keriya, memoirs of a river: archaeology and civilization in the Taklamaakan Oasis, China. Oeil Mag Int D Art 523:32

Chen R, Deng XZ, Zhan JY, Wang YL, Li D, Niu WY (2005) Estimation model and application of the amount of eco-water demand: a case study on Keriya River Basin. Geogra Res 24:725–731 (in Chinese)

Cheng WM, Zhou CH, Liu HJ, Zhang Y, Jiang Y, Zhang YC, Yao YH (2006) The oasis expansion and eco-environment change over the last 50 years in Manas River Valley, Xinjiang. Sci China Ser D 49:163–175. doi:10.1007/s11430-004-5348-1

Ci LJ (1994) The impact of global change on desertification in China. J Nat Resour 9:289–303 (in Chinese)

Congalton RG, Green K (1999) Assessing the accuracy of remotely sensed data: principals and practices. CRC Press, London, pp 137–145

Contreras S, Jobbagy EG, Villagra PE, Nosetto MD, Puigdefabregas J (2011) Remote sensing estimates of supplementary water consumption by arid ecosystems of centual Argentina. J Hrdrol 397:10–22. doi:10.1016/j.jhydrol.2010.11.014

Fan ZL, Ma YJ, Wang RH, Ji F, Zhang LY (2000) Ecosystem types in the continental river watershed of arid area and the managemental approaches. J Desert Res 12:293–296 (in Chinese)

Feng Q, Peng JZ, Li JG, Xi HY, Si JH (2012) Using the concept of ecological groundwater level to evaluate shallow groundwater resources in hyperarid desert regions. J Arid Land 4:378–389. doi:10.3724/SP.J.1227.2012.00378

Gu LN (2006) Study on carrying capacity of water resources of Keriya River Valley based on the sustainable development theory. Xinjiang University, Xinjiang, China, pp 36–44 (in Chinese)

Hu SJ, Song YD, Tian CY, Li YT, Li XC, Chen XB (2007) Suitable scale of Weigan River plain oasis. Sci China Ser D 50:56–64. doi:10.1007/s11430-007-8021-7

Huang LM, Shen B, Zhang GF (2008) Study on the suitable scale for Hotan oasis, Xinjiang. J Arid Land Resour Environ 22:1–4 (in Chinese)

Kok OB, Nel JAJ (1996) The Kuiseb River as a linear oasis in the Namib desert. Afr J Ecol 34:39–47. doi:10.1111/j.1365-2028.1996.tb00592.x

Lei ZD, Hu HP, Yang SX, Tian FQ (2006) Analysis on water consumption in oases of the Tarim Basin. J Hyd Eng 37:1470–1475 (in Chinese)

Leng C, Chen YN, Li XG, Sun YX (2011) Evaluation of oasis stability in the lower reaches of the Tarim River. J Arid Land 3:123–131. doi:10.3724/SP.J.1227.2011.00123

Li JL, Feng Q, Guo QL (2008) Fractal study of sustainable proportions of natural and artificial oases. Environ Geol 55:1389–1396. doi:10.1007/s00254-007-1089-8

Li WH, Li F, Chen ZS, Wang Y, Li BM (2011) Analysis of driving force of water consumption in plain and suitable scale of oasis in Hotan River Basin. J Glac Geocryol 33:1161–1168 (in Chinese)

Ling HB, Xu HL, Shi W, Zhang QQ (2011a) Regional climate change and its effects on the runoff of Manas River, Xinjiang, China. Environ Earth Sci 64:2203–2213. doi:10.1007/s12665-011-1048-2

Ling HB, Xu HL, Zhang QQ, Shi W (2011b) Runoff variation law and its response to climate change in the headstream area of the Keriya River Basin, Xinjiang. J Earth Sci 22:780–791. doi:10.1007/s12583-011-0227-0

Ling HB, Xu HL, Fu JY (2013) High- and low-flow variations in annual runoff and their response to climate change in the headstreams of the Tarim River, Xinjiang, China. Hydrol Process 27:975–988. doi:10.1002/hyp.9274

Liu YX, Zhang XL, Lei J, Zhu L (2010) Urban expansion of oasis cities between 1990 and 2007 in Xinjiang, China. Int J Sust Dev World 17:253–262. doi:10.1080/13504501003764421

Maneta MP, Torres M, Wallender WW, Vosti S, Kirby M, Bassoi LH, Rodrigues LN (2009) Water demand and flows in the Sao Francisco River Basin (Brazil) with increased irrigation. Agr Water Manag 96:1191–1200. doi:10.1016/j.agwat.2009.03.008

Moharram SH, Gad MI, Saafan TA, Allah SK (2012) Optimal groundwater management using genetic algorithm in El-Farafra oasis, Western Desert, Egypt. Water Resour Manag 26:927–948. doi:10.1007/s11269-011-9865-3

Moran MS, Clarke TR, Inoue Y, Vidal A (1994) Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index. Remote Sens Environ 49:246–263. doi:10.1016/0034-4257(94)90020-5

Pan XL, Chao JP (2003) Theory of stability and regulation and control of ecological in oasis. Glob Planet Change 37:287–295. doi:10.1016/S0921-8181(02)00201-1

Qian ZY, Shen GF, Pan JZ (2004) Research of configuration of water resources for ecological environment construction and sustainable development strategy in Northwest Region. Science Press, Beijing (in Chinese)

Su YZ, Zhao WZ, Su PX, Zhang ZH, Wang T, Ram R (2007) Ecological effects of desertification control and desertified land reclamation in an oasis-desert ecotone in a region: a case study in Hexi Corridor, northwest China. Ecol Eng 29:117–124. doi:10.1016/j.ecoleng.2005.10.015

Tang QH, Hu HP, Oki TK, Tian FQ (2007) Water balance within intensively cultivated alluvial plain in an arid environment. Water Resour Manage 21:1703–1715. doi:10.1007/s11269-006-9121-4

Wang ZJ, Wang HF, Lei ZD (2002) Stability analysis of oasis in arid region. J Hyd Eng 5:26–30 (in Chinese)

Wang GY, Shen YP, Zhang JG, Wang SD, Mao WY (2010) The effects of human activities on oasis climate change and hydrologic environment in the Aksu River Basin, Xinjiang, China. Environ Earth Sci 59:1759–1769. doi:10.1007/s11269-007-9218-4

Wang YB, Feng Q, Si JH, Su YH, Chang ZQ, Xi HY (2011) The changes of vegetation cover in Ejina oasis based on water resources redistribution in Heihe River. Environ Earth Sci 64:1965–1973. doi:10.1007/s12665-011-1013-0

Xia J, Feng HL, Zhan CS, Niu CW (2006) Determination of a reasonable percentage for ecological water-use in the Haihe River Basin, China. Pedosphere 16:33–42. doi:10.1016/S1002-0160(06)60023-4

Xu CH, Xu Y, Luo Y (2008) Climate change of the 21st century in Xinjiang with Sres Scenarios. Desert Oasis Meteorol 3:1–7 (in Chinese)

Yang X (2001) The oases along the Keriya River in the Taklamakan Desert, Chian, and their evolution since the end of the last glaciation. Environ Geol 41:314–320. doi:10.1007/s002540100388

Yang XP, Zhu ZD, Jaekel D, Owen LA, Han JM (2002) Late Quaternary palaeoenvironment change and landscape evolution along the Keriya River, Xinjiang, China: the relationship between high mountain glaciation and landscape evolution in foreland desert regions. Quat Int 97:155–166. doi:10.1016/S1040-6182(02)00061-7

Yang B, Shi YF, Braeuning A, Wang JX (2004) Evidence for a warm-humid climate in arid northwestern China during 40–30 ka BP. Quat Sci Rev 23:2537–2548. doi:10.1016/j.quascirev.2004.06.010

Yang X, Liu Z, Mang F, White PD, Wang X (2006) Hydrological changes and land degradation in the southern and eastern Tarim Basin, Xinjiang, China. Land Degrad Dev 17:381–392. doi:10.1002/ldr.744

Ye ZX, Chen YN, Li WH (2010) Ecological water demand of natural vegetation in the lower Tarim River. J Geogra Sci 20:261–272. doi:10.1007/s11442-010-0261-3

Zhang Q, Yu YX, Zhang J (2008) Characteristics of water cycle in the Qilian Mountains and the Oases in Hexi Inland River Basins. J Glac Geocryol 30:907–913 (in Chinese)

Zhang F, Wang T, Yimit H, Shi QD, Ruan QR, Sun ZQ, Li F (2011) Hydrological changes and settlement migrations in the Keriya River delta in central Tarim Basin ca. 2.7–1.6 ka BP: inferred from (14)C and OSL chronology. Sci China Ser D 54:1971–1980. doi:10.1007/s11430-011-4206-1

Zhao WZ, Chang XL, He ZB (2004) Responses of distribution patterns of desert riparian forests to hydrologic process in Ejina oasis. Sci China Ser D 47:21–31. doi:10.1360/04zd0003

Zhao WZ, Niu ZR, Chang XL, Li SB (2010) Water consumption in artificial desert oasis based on net primary productivity. Sci China Ser D 53:1358–1364. doi:10.1007/s11430-010-4028-6

Zhou YC (1999) Hydrology and water resources of rivers in Xinjiang. Xinjiang Technology Health Press, Xinjiang, China, p 31 (in Chinese)

Zhu BQ (2000) The calculation and analysis on the capacitance of the water resource in Keriya River. Xinjiang University, Xinjiang, China, p 53 (in Chinese)