Suitable oasis scales under a government plan in the Kaidu-Konqi River Basin of northwest arid region, China

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Abstract

The Kaidu-Konqi River Basin was chosen as the study site in this paper in order to investigate suitable scales of natural and artificial oases with a specified water resource and water quantity planned by the local government. Combined with remote-sensing images in 2013, water resources in 2013, 2020 and 2030, and weather and socioeconomic data, suitable scales of oases were analyzed. The results showed that: (1) The total available water quantities in the Yanqi Basin and the Konqi River Basin without river base flow, and the input of water into Bosten Lake and Tarim River, over high-, normal and low-flow periods, in 2020 and 2030, were $19.04\times10^8m^3$, $10.52\times10^8m^3$, $4.95\times10^8m^3$, $9.95\times10^8m^3$ and $9.95\times10^8m^3$, as well as $21.77\times10^8m^3$, $13.95\times10^8m^3$, $10.11\times10^8m^3$, $12.50\times10^8m^3$, and $9.74\times10^8m^3$. (2) The water demand of the natural oasis in the Yanqi Basin and the Konqi River Basin was $5.33\times10^8m^3$, and $5.91\times10^8m^3$, respectively. (3) The total water consumption of the artificial oasis in 2013, 2020, and 2030 were $18.16\times10^8m^3$, $17.63\times10^8m^3$ and $17.63\times10^8m^3$ in the Yanqi Basin, respectively, and $17.11\times10^8m^3$, $16.54\times10^8m^3$ and $16.54\times10^8m^3$ in the Konqi River Basin, respectively. (4) Under government planning, the optimal area in 2020 and 2030 should be 3198.98 km^2 in the Yanqi Basin oases, and 3858.87 km^2 and 3081.17 km^2 in the Konqi River Basin oases, respectively, under the different inflow variations, and 3129.07 km^2 in the Yanqi Basin oases, and 3834.58 km^2 and 3061.78 km^2 in the konqi River Basin oases, respectively, under the appropriate proportion. (5) The natural and artificial oases in these basins should be greatly decreased in the future due to limited water resources.

Keywords: available water quantity; inflow variations; water balance; water demand of oasis; government planning

Highlights:

- The total available water quantities and water demand of the natural and artificial oases in the Yanqi Basin and Konqi River Basin, China were calculated.
- The actual oases area in 2013 is in the range of optimal area under the different inflow variations.
- Under government planning, the natural and artificial oases need to be decreased more in 2020 and 2030 compared to 2013.

1 Introduction

Mountain-oasis-desert is the main topographic feature of inland river basin in China (Sun, Wang & Yang, 2007). Oases, a major human activities and economic development zone, exist in a desert background, and constitute an essential part of arid and semi-arid regions (Su et al., 2007). Their scale, location, and development depend on the carrying capacity of water resources (Wang et al., 2011; Moharram et al., 2012). Water resource originates from the mountain area located in the upper reaches of basin, and is mainly composed of mountain precipitation and ice snow melt water (Chen et al., 2016). Flow at mountain-pass supplies water consumption of natural and artificial oases (Huang et al., 2011). Therefore, river runoff is one of very important factors affecting oasis development (Li et al, 2015). However, mountain precipitation, ice snow melt water, and river runoff are affected by the climate change and variability (Coppola, Raffaele & Giorgi, 2016; Ling et al., 2011). It has been reported that the climate warming has led to the declination of mountain solid precipitation, the increase of ice snow melt water and the temporary increase of river runoff (Piao et al., 2010; Chen et al., 2016), but the water resource in the mountain area exists a decrease trend in a long run if the temperature continues to rise (Piao et al., 2010; Chen et al., 2016). The decrease of water resources will seriously affect the oasis development (Piao et al., 2010), even intensify the shortage of water resources and the contradiction between supply and demand because of the increase of population, which results in the unsustainable development of oasis. Therefore, for realizing the stable and sustainable of oasis, the local government has planned the supply of water resources in the future based on the status of river runoff and the development scale of oasis in order to relief the shortage of water resources and make sure the healthy development of oasis (Crabbe and Robin, 2006). What scale of oasis can be met to develop by the supply quantities of water resources planned by the local government in the future is a critical issue to be answered at present.

The suitable scale of oases has recently attracted the attention of researchers (Lei et al., 2006; Fan et al., 2000; Maneta et al., 2009; Contreras et al., 2011), but studies focusing on continental river basins of arid regions remain scarce in China. Of the few studies reported, most have focused on calculating the suitable scale of oases in the present year on the basis of runoff, ecological water demand of natural oases, and water demand of artificial oases (Lei, Li & Ling, 2015; Guo et al., 2016; Huang, Shen & Zhang, 2008; Cao et al., 2012; Ling et al., 2012; Zheng et al., 2011; Hu et al., 2006). However, the extant literature has rarely involved prediction of suitable scales of oases in the future, especially when the allocation and use of water resources is planned by local governments. Only Lei, Li & Ling (2015) predicted the suitable size of the Keriya River Basin, Xinjiang, in 2020, according to fitting models between surface runoff and climate factors; however, the regulatory role of the government was not taken into account. Government planning of water resource supply and demand constitutes an essential factor in arid regions, especially in arid areas where water resources are limited and water conflicts are prominent. Because government limitations on the supply and demand of water resources seriously constrain oasis development, it is very important to investigate the impact of government planning on oasis development. This type of investigation would provide a scientific basis for policy-makers to coordinate the development scale of different departments and ecological, economic, and social water use in

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oases.

The Kaidu-Konqi River Basin (40.00-43.20N，82.55-90.15E) is located in the central section of the Xinjiang Uygur Autonomous Region, China, in the north portion of the Tarim Basin. The total area of the Kaidu-Konqi River Basin is 122,200 km^2 and encompasses the Kaidu River, Bosten Lake, and the Konqi River. The Kaidu River originates in the south of the middle Tianshan Mountains and flows through Bosten Lake into the Konqi River. The administrative divisions comprises six counties (cities) (i.e., Yanqi, Hejing, Heshuo, Bohu, Kuerl, and Yuli), 11 military regiment production-construction farms, four state farms, and oil enterprises belonging to the Mongolia Autonomous Prefecture of Bayinguoleng. Kaidu River is a river mixed with snow, ice, and rainwater with an annual mean runoff of $35.05\times10^8 m^3$. There is abundant surface and ground water resources, with total mean available water resources of $42.00\times10^8 m^3$. However, as a consequence of the rapid expansion of artificial oases since the 1950s, water consumption in artificial oases has mostly increased, which has greatly crowded-out ecological water so that desert riparian forests have substantially declined. To alleviate the contradiction between supply and demand of water resources, and ensure the healthy development of oasis, lake and desert ecosystems, the local government formulated plans for the supply and demand of water resources in the Kaidu-Konqi River Basin in 2020 and 2030. Based on this government plan, determining precisely how water resources can be optimally allocated and the most suitable scale of oases in these basins need to be elucidated.

Based on previous research, the present study took into account the government plan for the limitation of the supply and demand of oasis water resources, including collected water resource data (1958-2013), air temperature, precipitation and solar short radiation data (1958-2013), socio-economic data (2013), and ALOS satellite remote-sensing images (2013) on land cover/use with the resolution ratio of 30 m, to analyze high- and low-flow variations of surface runoff in the Kaidu River and the Konqi River. The required quantities of water resources were calculated for maintaining the socioeconomic development of artificial oases in the Kaidu-Konqi River Basin. We calculated the required ecological water quantities of natural vegetation. On the basis of the above analysis, we also discussed the suitable scale of natural and artificial oasis in 2013, as well as in 2020 and 2030 under the government plan. This study aimed to provide a sound theoretical basis for determining reasonable oasis development management plans.

2 Materials & Methods

2.1 Study region

The Kaidu-Konqi River Basin is located in the Northeastern Tarim River and the Northeastern margin of the Taklimakan Desert. The total area of the Kaidu-Konqi River Basin is 77,000 km^2, with a mountainous area of 34,660 km^2 and a plain area of 42,600 km^2. The Kaidu River originates in the Yilianhabierga Mountains in the central of the south of the Tianshan Mountains, with a length of 560 km. It flows through the Yanqi Basin and flows into Bosten Lake. The outflow of Bosten Lake is called the Konqi River. The Kaidu River consists of ice and snow melt, with a length of 560 km and an average annual runoff of $35.05\times10^8 m^3$. The Konqi River originates from Bosten Lake, with a length of 942 km and an average annual

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runoff of $13.34\times10^8 m^3$.

The Kaidu-Konqi River Basin lies in the hinterland of Eurasia, and experiences an extreme desert climate of a warm temperate zone. This basin encompasses a typical mountain-oasis-desert ecosystem in an arid region. The climate varies with the gradually decreasing of elevation from mountains, plain oasis, to desert. The mountainous area has an average annual temperature of -4.3 ℃, average sunshine hours of 2789.5 h, average annual precipitation of 275 mm, and evaporation of 680 mm. The oasis in Yanqi Basin has an average annual temperature of 8.3 ℃, average sunshine hours of 3047.6 h, average relative humidity of 57%, average annual precipitation of 76.3 mm, and average annual evaporation of 1073 mm. The climate in the Konqi River Basin Oasis is drier than the Yanqi Basin Oasis, with an average annual temperature of 11.0 ℃, average annual precipitation of 45.9 mm, average annual evaporation of 1429 mm, and average sunshine hours of 2987 h.

In this study, the Yanqi Basin and the Konqi River Oasis were chosen as the study area (Fig. 1). Figure 1 presents land use/cover in 2013 in the study areas. The mountainous area of the higher reaches of the Kaidu River Basin cannot be taken into consideration because water resources originated from the mountains, and mountain-pass water resources cannot be used by mountain vegetation. Therefore, mountain vegetation is not considered in the present study. However, desert vegetation in the lower reaches of the Konqi River was included because vegetation growth depends on mountain-pass water.

2.2 Data collection

2.2.1 Land cover/use data

The present study collected United States Geological Survey (USGS) satellite remote-sensing images of the Kaidu-Konqi River Basin with the Digital Elevation Model (DEM) and land cover/use in 2013 with a resolution ratio of 30 m (Fig. 1). These digitalized images can provide land cover/use data of the study area. For image processing, firstly, 50 Digital Elevation Models (DEMs) covering the entire Xinjiang, ranging from N40°-44 °and E 82°-91°, were downloaded from http://www.gscloud.cn/. These DEMs were merged and cropped according to land cover/use image boundaries of the Kaidu-Konqi River Basin in order to obtain the Kaidu-Konqi River Basin DEM. Watersheds with more 100,000 m^3 flows in DEM were extracted by spatial analyst tools, including slope, aspect, fill, flow accumulation, flow direction, stream link, and watershed of Arcgis 12.2.2. Watershed boundaries, including the Yanqi Basin and the Konqi River Basin (the study area of this paper, Fig. 1), were manually extracted with Arcgis 12.2.2. Combined with land cover/use image and extracted watershed boundary images of the study area, land cover/use in the study area was registered by watershed boundary images. Seven different colors represent the different land use types, including forest land, grassland, water, ice, residence site, unused land, and cultivated land. The area of the different land uses can be calculated by checking the attribute table and resolution ratio on land cover/use images. Forest land and grassland are taken as natural oases, while residence sites and cultivated land represent artificial oases. There is no ice in this study area. Water includes rivers, Bosten Lake, and other small water systems. Unused land cannot be considered because a tract of unused land does not consume water

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resources in oases.

2.2.2 Available water resource quantity

In this study, total available water resource quantity is determined by the runoff of the Kaidu River and the Konqi River. The runoff data from 1958 to 2013 in the Kaidu River are derived from the Dashankou Hydrologic Station located in the mountain pass of the headstream of the Kaidu River (Fig. 1). Regarding the Konqi River, runoff data are from the Tashidian Hydrologic Station (Fig. 1) located in the region that flows out from Bosten Lake. Runoff data in the Konqi River are missing in 1966 to 1974 due to the influence of the Cultural Revolution. Runoff data in 2020 and 2030 have been provided by the book titled by "Comprehensive Planning in the Tarim River Basin in Xinjiang" (the Xinjiang Uygur Autonomous Region Water Conservancy and the Hydropower Survey Design and Research Institute, 2012). The runoff in 2020 and 2030 in the Kaidu River was set to $33.43\times10^8 m^3$ and $33.43\times10^8 m^3$, respectively, which is slightly less than normal flow. The runoff in 2020 and 2030 in the Konqi River was set to $7.76\times10^8 m^3$ and $5.00\times10^8 m^3$, respectively, both of which are slightly less than normal flow. The local government plans to control the quantity of available water resources in the Kaidu-Konqi River Basin to a normal flow level in the future in order to meet ecological, economic, and social needs for water resources in the study area.

2.2.3 Current natural and artificial oases area

In the present study, the year of 2013 is regarded as the current year. Areas of natural oases, artificial oases, and bodies of water in the Yanqi Basin and the Konqi River Basin were obtained by DEM and land cover/use image in 2013. Water mainly includes rivers and lakes. However, when the water area in the Yanqi Basin was calculated, Bosten Lake was not included because the water evaporation of Bosten Lake is not affected by the quantity of available water resources in the Yanqi Basin. Therefore, the water area in the Yanqi Basin was calculated by the total water area provided by land cover/use images subtracted by the Bosten Lake water area of 800 km^2. It is assumed that the areas of natural oases, artificial oases, and water are unchangeable in 2020 and 2030, and the same as in 2013.

2.2.4 Groundwater depth

Groundwater depth and maximum groundwater depth can be utilized to calculate phreatic evaporation (E_p). They were collected by consulting the relevant literature (Guo et al., 2013). It is also assumed that the groundwater depth is constant from 2013 to 2030.

2.2.5 Surface water evaporation of the 20-cm general evaporation dish ($E_{\Phi 20}$)

The daily $E_{\Phi 20}$ from weather stations in Yanqi, Hejing, Heshuo, Bohu and Yuli counties, and Korla city were collected by the China Meteorological Science Data Sharing Service Network (http://data.cma.cn). Yanqi, Hejing, Heshuo, and Bohu counties were chosen as the Yanqi Basin. Korla city and Yuli county represent the Konqi River Basin. The daily $E_{\Phi 20}$ in 2013 in the Yanqi Basin and the Konqi River Basin was summed up, respectively. $E_{\Phi 20}$ in 2020 and 2030 are the same as in 2013.

2.2.6 Social-economy data

Population, livestock, and industrial output need to be collected in this study. These data were obtained from Chen (2014). Although the Konqi River Basin only occupies one part of Yuli county, most industrial and agricultural production, and people's lives depend on the Konqi River, with very little use of water from the Tarim River. Social-economy data in Yuli county belong to the Konqi River Basin. In this study, the total social-economy data in Korla and Yuli county were used to represent the data in the Konqi River Basin. It is assumed that these social-economy data in 2020 and 2030 are the same as those in 2013.

2.3 Methods

2.3.1 Z index method

The Z index was utilized to analyze high- and low-flow variations for surface runoff within a certain period in the river basin (Ling, Xu & Fu, 2013). The annual runoff of the Kaidu River and the Konqi River for 1958-2013 follows a Person-III distribution, and the formula for calculating the Z index is:

$$Z = \frac{6}{C_s} \times \left(\frac{C_s}{2} \times \varphi_i + 1 \right)^{1/3} - \frac{6}{C_s} + \frac{C_s}{6} \quad (1)$$

$$C_s = \frac{\sum_{i=1}^{n} \left(R_i - \overline{R} \right)^3}{n \times \sigma^3} \quad (2)$$

$$\varphi_i = \frac{R_i - \overline{R}}{\sigma} \quad (3)$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(R_i - \overline{R} \right)^2} \quad (4)$$

$$\overline{R} = \frac{1}{n} \times \sum_{i=1}^{n} R_i \quad (5)$$

where Z is the Z index; C_s is the skewness coefficient; φ_i is the standard variable; R_i is the annual runoff; n is the sample number; and $\overline{R}$ is the mean value of the annual runoff

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sequence.

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 (Guo et al., 2016).

2.3.2 Natural vegetation ecological water demand

Natural vegetation ecological water demand was calculated using the area quota method. This method has been widely employed to study well-investigated areas. Although it is simple to use, the method requires a reasonable determination of the ecological water quota of different types of vegetation. Its calculation formula is:

$$W_p = \sum_{i=1}^{n} W_{pi} = A_i m_{pi} \quad (6)$$

where p is vegetation water demand guarantee rate; A_i is the vegetation area of the type i; m_{pi} is the water quota for the corresponding vegetation guaranteed rate; and n is the number of vegetation types.

According to Zhang et al. (2011), the water quota in the Yanqi Basin is 3000 m^3 hm^{-2} for woodland, 1500 m^3 hm^{-2} for sparse woodland ground (with less than half shrub land), and 2250 m^3 hm^{-2} for all lawn. Because the areas of different types of vegetation are difficult to obtain, the water quota of natural vegetation in the Yanqi Basin was considered as the average of that of the above three types of vegetation, i.e., 2250 m^3 hm^{-2}, and the same as in 2020 and 2030.

2.3.3 Water demand of artificial oasis

In artificial oases, water consumption of cultivated areas, residences, industries, and livestock were considered. They were calculated by using the same method, i.e., the quota method. Specifically, the cultivated areas, the populations of non-agricultural residents and agricultural residents, the regional industrial output and livestock amounts, respectively, multiply their respective daily water consumption quotas (Fu et al., 2017). The irrigation water quota in 2013, 2020 and 2030 was $90\times10^4 m^3/km^2$, $87\times10^4 m^3/km^2$ and $87\times10^4 m^3/km^2$, respectively (Guo et al., 2013). In addition, coefficients of irrigation water use in these two regions were 0.725 and 0.795, respectively (Guo et al., 2013). According to the survey, daily water consumption of non-agricultural residents and agricultural residents was 185.52 L day^{-1} per capita and 165.87 L day^{-1} per capita, respectively (Zhang et al., 2011). The water quota for standard livestock in these two regions was 16 L/capita day, and 85 m^3 $million^{-1}$ $yuan^{-1}$for industries (Li et al., 2011). It has been assumed that the amount and water consumption quota of residents, standard livestock, and industry in 2020 and 2030 are the same as in 2013.

2.3.4 Model for calculating the most suitable oasis size

Based on the water balance in the Kaidu-Konqi River Basin, the following model was utilized for calculating the most suitable oasis size in arid regions (Lei, Li & Ling, 2015):

$$\frac{W - W_0}{(\alpha A_N + \beta A_A + A_W E_{\varphi 20} \gamma + A_0 E_p)^{10^{-5}}} = 1 \quad (7)$$

where A_N is the area of a natural oasis (km^2); A_A is the area of an artificial oasis (km^2); A_w is the area of artificial water (km^2); A_0 is the area of construction land in the artificial oasis region (km^2); W is the total quantity of available water resources (10^8m^3); W_0 is non-vegetation water consumption, including industrial and domestic water uses, as well as surface evaporation and the minimum ecological water demand in the river channel (10^8m^3); α and β are the water demand quotas of the natural and artificial oases, which are 400 and 650 mm (Lei et al., 2006) in the Kaidu-Konqi River Basin, respectively; $E_{\varphi 20}$ is the surface water evaporation capacity of a 20 cm general evaporation dish (mm); E_p is the phreatic evaporation (mm) from construction land in an artificial oasis, calculated by formula (11). In the formula, the value of H is 3.5 m in this river basin (Guo et al., 2013); and γ is the conversion coefficient of surface evaporation, which has a value of 0.61 (Zhou, 1999).

2.3.5 Optimal area of natural oases

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

$$A_N = \mu A \tag{8}$$

$$A_H = A_A + A_W + A_o = (1-\mu)A \tag{9}$$

where A is the optimal area of an oasis in the study region (km^2); and A_H is the optimal area of an artificial oasis (km^2). Equations (8) and (9) were put into Eq. (7), and the calculation model of the suitable oasis scale changes to:

$$A = \frac{(W - W_o)10^5 + A_W(\beta - E_{\varphi 20}\gamma) + A_o(\beta - E_p)}{\alpha\mu + \beta(1-\mu)} \tag{10}$$

2.3.6 Phreatic evaporation model

This study used a phreatic evaporation model to calculate evaporation from construction land in an artificial oasis area as follows (Ye, Chen & Li, 2007):

$$E_p = a(1 - H/H_{\max})^b E_{\Phi 20} \tag{11}$$

where E_p is the phreatic evaporation intensity (mm); $E_{\Phi 20}$ is the surface water evaporation of the 20 cm general evaporation dish (mm); H is the groundwater depth (mm); $H_{\max}$ is the critical phreatic water depth (m), which is 5 m in the study (Guo et al., 2013); a and b are the empirical coefficients and taken as $a = 0.62$ and $b = 2.8$ in these two regions, because of widely distributed meadow sand (Shi, 2009; Ye, Chen & Li, 2007).

3 Results

3.1 High- and low-flow variations for surface runoff in the Kaidu-Konqi River

High- and low-flow variations for surface runoff were analyzed using the Z index method (Fig. 2), based on annual runoff from the Kaidu-Konqi River from 1958 to 2013, as well as 2020 and 2030.

Figure 2 shows that the runoff in the Kaidu River pass headstreams changed from a high- and normal-flow period into a low-flow period between 1958 and 1962. Four normal-flow years (1963-1966) occurred followed by two low-flow years (1967 and 1968). Two high-flow years (1970-1971) and 10 low-flow years (1974-1975, 1977-1979, 1981, 1983-1986) occurred between 1970 and 1989, and the rest were normal-flow periods. Runoff had a normal-flow period between 1990 and 1992, declined to a low-flow period in 1993 and 1995, and then increased to a high-flow period in 1994 and 1996. After 1996, the flows were mainly high, except 1997, 2003-2005, 2009 and 2012, which were normal-flow years.

From Fig. 2b, it can be seen that the runoff in the Konqi River had a normal-flow year in 1958, rose to a high-flow period in 1959, and then declined to a normal-flow year in 1960. After 1960, the flow entered a low-flow period between 1961 and 1963. Flows returned to a normal condition in 1964 and 1965. Flow conditions from 1966 to 1974 cannot be determined because of missing data. Runoff has generally been at a low-flow level since 1975, particularly between 1975-1981, 1983-1986, and 1989-1992, and the rest were normal-flow periods until 1999. Runoff has been at a high-flow level from 2000 to 2004, 2006, 2009 and 2013, and the rest were normal flow. The runoff of Kaidu and Konqi Rivers in 2020 and 2030 planned by the local government were all near the normal-flow level.

According to the above analysis, since the Kaidu River and the Konqi River have apparent high- and low-flow variations, it is feasible to determine suitable oasis sizes for the Kaidu-Konqi River Basin based on variations in surface runoff. The mean values for annual runoff in the three flow categories (high, normal, and low) between 1958 and 2013 in the Kaidu River and the Konqi River were $42.99\times10^8 m^3$, $34.48\times10^8 m^3$ and $28.91\times10^8 m^3$, as well as $22.25\times10^8 m^3$, $14.43\times10^8 m^3$ and $10.59\times10^8 m^3$, respectively. The local government has planned a runoff of $33.90\times10^8 m^3$ in the Kaidu River and a runoff of $15.55\times10^8 m^3$ and $12.79\times10^8 m^3$ in the Konqi River in 2020 and 2030 when the water inflow rate was 50%, respectively (Xinjiang Uygur Autonomous Region Water Conservancy and Hydropower Survey Design and Research Institute, 2012). In addition, the average runoff in the Kaidu River and the Konqi River was $35.05\times10^8 m^3$ and $13.34\times10^8 m^3$, respectively (Guo et al., 2013), and thus their minimum ecological base flow was $3.505\times10^8 m^3$ and $1.334\times10^8 m^3$ according to the Tennant method, respectively (Ye et al., 2007),. Moreover, the average available water quantity in the other water systems and groundwater in the Kaidu River and the Konqi River was $6.54\times10^8 m^3$ and $3.48\times10^8 m^3$ in 2013, respectively (Xinjiang Uygur Autonomous Region Water Conservancy and Hydropower Survey Design and Research Institute, 2012). The Kaidu

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River needs to provide $26.99\times10^8m^3$ to Bosten Lake in order to maintain the ecological security of Bosten Lake (Guo et al., 2013). In addition, the Konqi River needs to provide $2.63\times10^8m^3$ in 2013 and $4.50\times10^8m^3$ in 2020 and 2030, respectively, to the Tarim River annually in order to ensure delivery of water to the lower reaches of the Tarim River (Guo et al., 2013). The total available water quantity of groundwater in the Konqi River planned by the government in 2020 and 2030 was $2.78\times10^8m^3$ (Xinjiang Uygur Autonomous Region Water Conservancy and Hydropower Survey Design and Research Institute, 2012). Regarding the Kaidu River, the total available water quantity in groundwater and other water systems in 2020 and 2030 are unchangeable, and the same as in 2013. Accordingly, the total available water quantities after eliminating the river base flow and the input of water into Bosten Lake from the Kaidu River over the three periods, in 2020 and 2030 were $19.04\times10^8m^3$, $10.52\times10^8m^3$, $4.95\times10^8m^3$, $9.95\times10^8m^3$, and $9.95\times10^8m^3$. The total available water quantities after eliminating the river base flow and the input of water into the Tarim River in the Konqi River over the three periods, in 2020 and 2030 were $21.77\times10^8m^3$, $13.95\times10^8m^3$, $10.11\times10^8m^3$, $12.50\times10^8m^3$, and $9.74\times10^8m^3$.

3.2 Ecological water demand of a natural oasis

The natural oasis is impacted less by anthropogenic activities because it is located at the periphery of cultivated land and the lower reaches of the Konqi River Basin. The natural oasis mainly comprises forest and grassland in this region. The natural oasis area in the Yanqi Basin and the Konqi River Basin was 2367.43 km^2 and 2628.18 km^2, respectively, based on ALOS satellite remote-sensing images from 2013. Their water demand quota were all $22.5\times10^4m^3/km^2$, and therefore their ecological water demand was $5.33\times10^8m^3$ and $5.91\times10^8m^3$, respectively. In addition, the water surface evaporation of the natural lake (Bosten Lake) was neglected because the evaporation capacity of Bosten Lake cannot be affected by the total quantity of available water resources in the Yanqi Basin. The area covered by the river channel and other water systems, except Bosten Lake, was 9.36 km^2 (997.36 km^2-988 km^2 of Bosten Lake in 2013) and 37.52 km^2, and water surface evaporation ($E_{\Phi20}$) in the whole year of 2013 is 1162.7 mm and 1460.2 mm in the Yanqi Basin and the Konqi River Basin, respectively. Therefore, the total water consumption was $0.07\times10^8m^3$ and $0.34\times10^8m^3$ in these two regions, respectively, if the water surface conversion coefficient (0.61) is used. It was assumed that the ecological water demand of natural vegetation and the water surface evaporation of the river course are the same in 2020 and 2030, as in 2013. In the Yanqi Basin and the Konqi River Basin, if river course stability is assumed, then the available water resource quantities of oases in the Yanqi Basin in the high-flow, normal flow, and low-flow periods, 2020 and 2030 were $13.64\times10^8m^3$, $5.12\times10^8m^3$, $-0.45\times10^8m^3$, $4.55\times10^8m^3$, and $4.55\times10^8m^3$. The total available water quantities in the Konqi River over the three periods, 2020 and 2030 were $15.52\times10^8m^3$, $7.70\times10^8m^3$, $3.86\times10^8m^3$, $6.25\times10^8m^3$, and $3.49\times10^8m^3$. It can be concluded that the remaining water resources, not including river base flow, river evaporation and inflow into Bosten Lake in the low-flow period in the Yanqi Basin oasis cannot meet the needs of natural vegetation for water.

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3.3 Water demand of artificial oases

Land cover/use in 2013 showed that the cultivated area supplied by the artificial oasis in the Yanqi Basin and the Konqi River Basin was 2447.41 km^2 and 2376.91 km^2, respectively. The water consumption of the cultivated area was $15.97\times10^8m^3$ and $17.01\times10^8m^3$ in the Yanqi Basin and the Konqi River Basin, respectively. Furthermore, the water consumption of the other land use types, such as construction land, was $2.18\times10^8m^3$ and $0.07\times10^8m^3$ in these two regions, respectively, based on calculated phreatic evaporation intensity (E_p).

The agricultural and non-agricultural populations in 2013 were 301,100 and 270,600 in the Yanqi Basin, and 197,700 and 409,300 in the Konqi River Basin, respectively, and the water consumption quotas per person per day were 0.166 m^3 and 0.186m^3, respectively. Therefore, the population water consumption of the Yanqi Basin and the Konqi River Basin was $0.000903\times10^8m^3$ and $0.000981\times10^8m^3$, respectively, if the water resource utilization coefficient was 0.9. Furthermore, the regional industrial output in the Yanqi Basin and the Konqi River Basin in 2013 was 1326,147 104 yuan and 6600,403 104 yuan, respectively. The water consumption quotas for the industrial output of one million yuan is 45 m^3, and thus the total industrial water consumption was $0.00537\times10^8m^3$ and $0.027\times10^8m^3$ in the Yanqi Basin and the Konqi River Basin, respectively. In addition, the Yanqi Basin and the Konqi River Basin had 1726,100 and 767600 livestock, respectively, at the end of 2013, and the daily consumption quotas of the livestock per capita per day was 0.01 m^3, and thus the total water consumption in these two regions was $0.00017\times10^8m^3$ and $0.000076\times10^8m^3$, respectively. According to the above calculations, the socioeconomic water consumption of the artificial oasis in these two regions was $0.0064\times10^8m^3$ and $0.028\times10^8m^3$, respectively, and the total water consumption of the artificial oasis was $18.16\times10^8m^3$ in the Yanqi Basin and $17.11\times10^8m^3$ in the Konqi River Basin, which were more than $9.95\times10^8m^3$and $12.12\times10^8m^3$ calculated by Chen, Du & Chen (2013). This is because the cultivated area in the Kaidu-Konqi River Basin predicted by Chen, Du & Chen (2013) was only 2023 km^2 in 2015, which is much less than the 5116.91 km^2 derived from satellite images in 2013. Therefore, the results predicted by Chen, Du & Chen (2013) were smaller than the results in this paper. It was assumed that the cultivated area, population, industrial output, and livestock in 2020 and 2030 are the same as 2013, except that irrigation water quotas in 2020 and 2030 decreased to $87\times10^4m^3/km^2$ (Guo et al., 2013). Then, the total water consumption of the artificial oasis in 2020 and 2030 was $17.63\times10^8m^3$ in the Yanqi Basin and $16.54\times10^8m^3$ in the Konqi River Basin. Therefore, the respective available water resource quantity of the Yanqi Basin was $-4.52\times10^8m^3$, $-13.04\times10^8m^3$, $-18.61\times10^8m^3$, $-13.08\times10^8m^3$ and $-13.08\times10^8m^3$ for the high-, normal-, low-flow periods, in 2020 and 2030. The water shortage quantity of the Konqi River Basin was $-1.59\times10^8m^3$, $-9.41\times10^8m^3$, $-13.25\times10^8m^3$, $-10.29\times10^8m^3$ and $-13.05\times10^8m^3$ for the high-, normal-, and low-flow periods, in 2020 and 2030. It can be concluded that, at present, available water resources not including river base flow, river evaporation and water requirement of natural oases, cannot meet the needs of artificial oases for water. If the cultivated area is not reduced in 2020 and 2030, water resource planning by the local government cannot meet the needs of artificial oases, and thus expansion or reducing the area of the artificial oases and determining the suitable development scale of oases are currently

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critical.

3.4 Optimal size for an oasis under different inflow variations

Table 1 shows that the optimal size of the natural oasis in the Yanqi Basin and the Konqi River Basin should not be below 1170.66 km^2 and over 4525.11 km^2, respectively. If the normal flow period (23 years in the Yanqi Basin and 29 years in the Konqi River Basin) and low-flow period (16 years in the Yanqi Basin and 18 years in the Konqi River Basin) occupied 70% and 84% of the last 56 years, then the optimal area of the natural oasis in these two regions is 1170.66-3841.75 km^2 and 2227.57-4525.11 km^2, and the optimal area covered by all the oases should be 1767.70-5801.05 km^2 and 3185.43-6470.91 km^2, respectively. The actual natural oasis area of these two regions in 2013 was 2367.43 km^2 between the suitable scales and 2628.18 km^2 less than the suitable scale, and their ecological water demand was $5.33\times10^8m^3$ and $5.91\times10^8m^3$, respectively. Therefore, low flow cannot meet the needs of natural oases for water resources in the Yanqi Basin, in which the respective ecological water deficits are $0.39\times10^8m^3$, except for high flow and normal flow,. However, the ecological water demand of the natural oasis in the Konqi River Basin was satisfied during high-, normal-, and low-flow periods.

As shown in Table 1, the suitable scale of artificial oasis in the Yanqi Basin is lower than the actual area, which indicates that the artificial oasis needs to be decreased by 659.28-2021.53 km^2 in high-, low-, and normal-flow runoff. Nevertheless, the artificial oasis area needs to be decreased rapidly by 1031.16-2019.10 km^2 in high-, low-, and normal-flow runoff due to the severe shortage of water resources in the Konqi River Basin.

The local government has planned the quantity of available water resources in the Kaidu-Konqi River Basin to be slightly less than the normal-flow level in 2020 and 2030 (Table 1). It has been calculated that the suitable scale of the natural oasis is 2118.53 km^2 and 2118.53 km^2 in 2020 and 2030, respectively, in the Yanqi Basin, and 2698.51 km^2 in 2020 and 2154.66 km^2 in 2030, respectively, in the Konqi River Basin. Compared to the actual scale of the natural oasis in 2013, the natural oasis needs to be reduced by 248.90 km^2 and 473.52 km^2 till 2030 in the Yanqi Basin and the Konqi River Basin, respectively, by abandoning the survival and growth of forest and grass due to a great lack of water. The artificial oasis needs to be decreased even more, by 1538.12 km^2 in the Yanqi Basin and 1816.59-2050.44 km^2 in the Konqi River Basin, respectively, in 2020 and 2030.

3.5 Calculating suitable sizes of oases under appropriate proportioning

Hu et al. (2006) suggested that the area of a natural oasis should comprise 60% of the total oases area in any given arid region. Lei, Li & Ling (2015) also reported that the proportion of land occupied by natural and artificial oasis (i.e., natural oasis occupies 60%, and artificial oasis occupies 40%) is feasible in the Keriya River Basin. Therefore, the optimal sizes of an oasis under 60% of the occupation rate of the natural oasis in the Yanqi Basin and the Konqi River Basin were calculated based on the constructed mathematical model (Eq. 10) in this paper (Table 2).

From Table 2, it can be seen that compared to 49% of the oasis occupation rate in the Yanqi

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Basin (Guo et al., 2016), the suitable scales of natural oasis calculated according to 60% of the oasis occupation rate increased by 64.39-211.30 km^2 and suitable scales of artificial oasis decreased by 103.02-338.07 km^2. Thus, the suitable scales of total oasis decreased by 38.63-126.78 km^2, which indicates that natural oasis needs to be increased slightly, and artificial oasis needs to be decreased in order to improve the natural oasis occupation rate to 60%. In 2020 and 2030, the suitable scale of natural oasis increased by 116.52 km^2, but the artificial oasis suitable scale decreased by 186.43 km^2. Thus, the suitable scale of the total oasis decreased by 69.91 km^2.

In the Konqi River Basin, when the natural oasis occupation rate changes from 57% to 60%, the suitable scale of natural oasis only needs to be increased by 33.41-67.87 km^2 in high-, normal-, and low-flow periods. Artificial oasis decreased by 53.47-108.60 km^2, and thus the suitable scale of total oasis decreased by 20.06-40.73 km^2, which indicates that the scale of oasis changes non-significantly when the natural oasis occupation rate changes from 57% to 60%. This is likely because the natural oasis occupation rate at present in the Konqi River Basin is 57%, which is closer to 60% than 49% in the Yanqi Basin. Therefore, the change of the oasis scale in the Konqi River Basin is not obvious as the natural oasis occupation rate ranging from 57% to 60% than in the Yanqi Basin. The suitable scale of natural oasis increased by 40.47 km^2 and 32.32 km^2 in 2020 and 2030, respectively, and the suitable scale of artificial oasis decreased by 64.77 km^2 and 51.72 km^2, respectively. Thus, the suitable scale of the total oasis decreased by 24.29 km^2 and 19.39 km^2 in 2020 and 2030, respectively, in the Konqi River Basin.

4 Discussion

According to Li, Feng & Guo (2008), oases of 90% have no appropriate proportion of artificial and natural oases in arid regions of China, and artificial oases covering 59% cannot be maintained. At present, artificial oases in the Yanqi Basin and the Konqi River Basin comprise 51% and 42% of the total oases, respectively. Although they are all less than 59%, these oases still cannot be maintained. For this reason, the determinants of suitable oases sizes should be further investigated. There have been few studies investigating the optimal sizes of oases in arid regions. Some studies have focused on the optimal size of artificial oases (Hu et al., 2006; Huang, Shen & Zhang, 2008; Li et al., 2011) and natural oases (Lei, Li & Ling, 2015; Guo et al., 2016). A few studies have considered regional water resource changes and the ecological water demand of natural oases (Lei, Li & Ling, 2015; Guo et al., 2016). However, these studies only calculated the suitable oases scales at present, and did not consider suitable size changes in the future under government planning for water resource allocation. Therefore, this paper utilized GIS technology and field survey techniques to analyze the changes of water resources, and natural and artificial oases, and confirmed the optimal size of natural and artificial oases at present and in 2020 and 2030 impacted by the local government planning.

As in Lei et al. (2015) and Guo et al. (2016), this paper regarded the change in water resources as the primary factor because total water quantity determines the development scale of oases in arid regions (Li et al., 2011). In the current study, runoff variation in the past 56 years in the Yanqi Basin and Konqi River Basin was analyzed, and it was found that runoff was mainly in normal- and low-flow periods. It was also determined that the available water quantity cannot meet the water demand of artificial oases in the Yanqi Basin and the Konqi River Basin. Therefore, compared with 2013, the entire oasis in the Yanqi Basin needs to be decreased by 1787.02 km^2 and 1787.02 km^2 in 2020 and 2030, respectively. The Konqi River Basin needs to be reduced by 1746.26 km^2 and 2523.96 km^2 in 2020 and 2030, respectively, compared with 2013. The artificial oases should be decreased by 1538.12 km^2 and 1816.59-2050.44 km^2 until 2030 in the Yanqi Basin and the Konqi River Basin, respectively. In addition, the decrease scope of the suitable oasis sizes in this region is much more than 487 km^2 of the Keriya River Basin (Lei, Li & Ling, 2015) and 148 km^2 of the Hotan River Basin (Guo et al., 2016).

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%). Natural oasis did not occupy 60% of the whole oasis in the Kaidu-Konqi River Basin in 2013, i.e., only 49% and 58%. In this paper, the suitable oases scale was calculated again when assuming 60% of natural oases in all of the oases. The result showed that the natural oases area needs to be increased slightly compared to the proportion of original oases, whereas the artificial oases area needs to be decreased to a greater extent. Therefore, the deficient natural oases area and redundant artificial oases area at present cannot maintain a healthy ecosystem because consuming too much water for artificial oases would seriously crowd-out ecological water leading to serious water shortage. To solve this problem, the local government has decided to adjust available surface water and the amount of groundwater exploitation, and established that the total quantity of available water resources in 2020 and 2030 would be slightly more than that of the normal-flow period in 2013 in the Yanqi Basin, but slightly less than that of the normal-flow and the low-flow periods, respectively, in the Konqi River Basin. Based on these planned data, suitable oasis sizes were calculated, and it was found that the natural and artificial oasis scales in the Yanqi Basin and the Konqi River Basin need to be greatly decreased in the future.

5 Conclusions

The Yanqi Basin and Konqi River Basin, which are in an extremely arid region of China, were chosen as the study area. Based on water resource, weather, socio-economic and remote sensing image data, and government plan reports, suitable scales of oases under different high-, low- and normal-flow variations and the government plan for available water resources were analyzed by using the Z index and the water balance method. The following conclusions were obtained:

(1) The Kaidu River and the Konqi River have high- and low-flow variations. The local government has planned water resources quantity in 2020 and 2030. The total available water quantities after eliminating the river base flow and the input of water into Bosten Lake and the Tarim River in the Kaidu-Konqi River over the three periods, in 2020 and 2030 were $19.04\times10^8m^3$, $10.52\times10^8m^3$, $4.95\times10^8m^3$, $9.95\times10^8m^3$ and $9.95\times10^8m^3$, as well as $21.77\times10^8m^3$, $13.95\times10^8m^3$, $10.11\times10^8m^3$, $12.50\times10^8m^3$, and $9.74\times10^8m^3$.

(2) The ecological water demand of the natural oases was $5.33\times10^8m^3$ and $5.91\times10^8m^3$ in the Yanqi Basin and the Konqi River Basin, respectively. The respective development scales

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in the natural oasis during the high-, normal- and low-flow periods, in 2020 and 2030 were 3841.75 km^2, 2226.59 km^2, 1170.66 km^2, 2118.53 km^2 and 2118.53 km^2 in the Yanqi Basin, and 4525.11 km^2, 2984.22 km^2, 2227.57 km^2, 2698.51 km^2 and 2154.66 km^2 in the Konqi River Basin. The suitable scales only in high-flow periods in the Yanqi Basin and in high- and normal-flow periods in the Konqi River Basin were more than 2367.43 km^2 and 2628.18 km^2 , respectively, of the actual oasis areas. However, the runoff was mainly between normal- and low-flow, which indicated that oases need to be decreased more in the future.

(3) The total water consumption of the artificial oasis was $18.16\times10^8 m^3$, $17.63\times10^8 m^3$ and $17.63\times10^8 m^3$ in the Yanqi Basin, and $17.11\times10^8 m^3$, $16.54\times10^8 m^3$ and $16.54\times10^8 m^3$ in the Konqi River Basin in 2013, 2020, and 2030. The total available water cannot meet the needs of the artificial oasis in the Yanqi Basin and the Konqi River Basin. The respective development scales of the artificial oases during the high-, normal- and low-flow periods, in 2020 and 2030 were 1959.29 km^2, 1135.56 km^2, 597.04 km^2, 1080.45 km^2 and 1080.45 km^2 in the Yanqi Basin, and 1945.79 km^2, 1283.22 km^2, 957.86 km^2, 1160.36 km^2 and 926.51 km^2 in the Konqi River Basin. All suitable scales calculated were less than 2618.57 km^2 and 2976.95 km^2 of the actual oasis area, respectively, which indicated that artificial oases in the Yanqi Basin and the Konqi River Basin need to be reduced more in the future.

(4) Using 6:4 as the proportion of the natural to artificial oases, the size of the natural oasis in the Yanqi Basin and the Konqi River Basin should be 1235.05-4053.05 km^2 and 2260.98-4592.98 km^2, respectively, and the size of the artificial oasis should be 494.02-1621.22 km^2 and 904.39-1837.19 km^2, respectively. The suitable total oases scale under the 6:4 proportion of the natural to artificial oases in the Yanqi Basin and the Konqi River Basin will decrease by 69.91 km^2 and 19.39-24.29 km^2, respectively, in 2020 and 2030, compared to the original proportion. Therefore, the suitable scale of artificial oases will decrease by 186.43 km^2 and 51.72-64.77 km^2 until 2030 in the Yanqi Basin and the Konqi River Basin, respectively.

(5) The natural and artificial oases in the Yanqi Basin and the Konqi River Basin tend to decrease due to limited water resources. Consequently, a substantial amount of farmland should be returned to forest land or grassland in these basins.

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Table 1

Basin	Periods of the different Grade	Water resource quantity ($10^8 m^3$)	Water demand quota (mm)	Natural oasis (A_N) (km^2)		Artificial oasis (A_H) (km^2)		Total oases (A) (km^2)	
				Suitable scale	Actual scale	Suitable scale	Actual scale	Suitable scale	Actual scale
Yanqi Basin	High-flow period	19.03	400	3841.75	2367.43	1959.29	2618.57	5801.05	4986
	Normal-flow period	10.51		2226.59		1135.55		3362.15	
	Low-flow period	4.94		1170.66		597.04		1767.70	
	2020	14.34		2118.53		1080.45		3198.98	
	2030	15.34		2118.53		1080.45		3198.98	
Konqi River Basin	High-flow period	21.74		4525.11	2628.18	1945.79	2976.95	6470.91	5605.13
	Normal-flow period	13.92		2984.22		1283.22		4267.44	
	Low-flow period	10.08		2227.57		957.85		3185.43	
	2020	12.47		2698.51		1160.36		3858.87	
	2030	9.71		2154.66		926.51		3081.17	

Notes: A_N is the optimal area of a natural oasis (km^2); A_H is the optimal area of an artificial oasis (km^2); A is the optimal area of an oasis in the study area (km^2);

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Table 2

Basin	Periods of the different Grade	$W-W_0$ (10^8 m^3)	A_W (km^2)	A_0 (km^2)	μ(%)	E_P (mm)	Suitable scale (km^2)		
							Total oases (A) (km^2)	Natural oasis (A_N)(km^2)	Artificial oasis (A_H) (km^2)
Yanqi Basin	High-flow period	19.03	6.02	197.56	60	24.76	5674.27	4053.05	1621.22
	Normal-flow period	10.51					3288.67	2349.05	939.62
	Low-flow period	4.94					1729.07	1235.05	494.02
	2020	14.34					3129.07	2235.05	894.02
	2030	15.34					3129.07	2235.05	894.02
Konqi River Basin	High-flow period	21.74	55.75	219.28	60	31.10	6430.18	4592.98	1837.19
	Normal-flow period	13.92					4240.58	3028.98	1211.59
	Low-flow period	10.08					3165.38	2260.98	904.39
	2020	12.47					3834.58	2738.98	1095.59
	2030	9.71					3061.78	2186.98	874.79

Notes: A_w is the area of artificial water (km^2); A_N is the optimal area of a natural oasis (km^2); A_H is the optimal area of an artificial oasis (km^2); A is the optimal area of an oasis in the study area (km^2); A_0 is the area of construction land in the artificial oasis region (km^2); W is the total quantity of available water resources (10^8m^3); W_0 is non-vegetation water consumption, including industrial and domestic water uses, as well as surface evaporation and the minimum ecological water demand in the river channel (10^8m^3); E_p is the phreatic evaporation (mm) from construction land in an artificial oasis; μ is the proportion of natural oasis to the total oasis.

Figure Legends

Figure 1. Location of the study region in Xinjiang, China. The study region includes the Yanqi Basin and the Konqi River Basin without the mountainous area of the Kaidu-Konqi River Basin

Figure 2. High- and low-flow variations of runoff in the Kaidu-Konqi River Basin. Lines of 0.54 and -0.54 represent judgment boundary on grades of low-, normal- and high-flow index.

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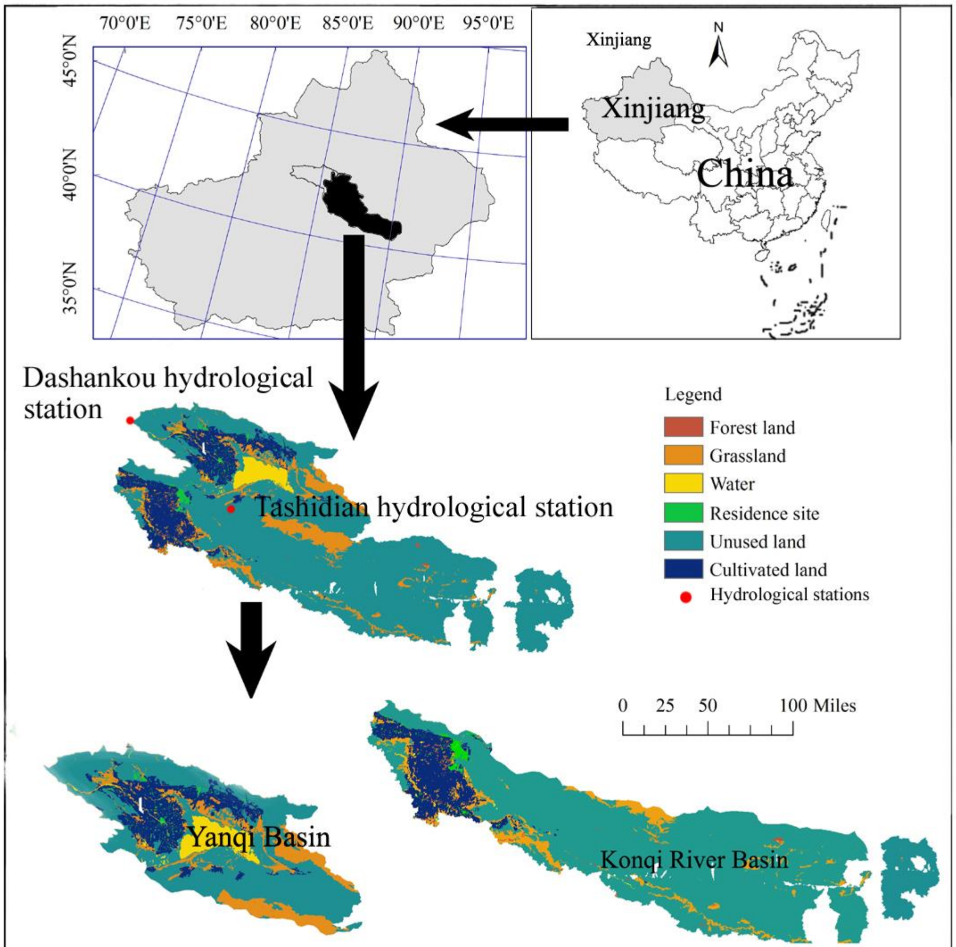
70°0'E
75°0'E
80°0'E
85°0'E
90°0'E
95°0'E
45°0'N
40°0'N
35°0'N
Xinjiang
N
Xinjiang
China
Dashankou hydrological station
Tashidian hydrological station
Legend
Forest land
Grassland
Water
Residence site
Unused land
Cultivated land
Hydrological stations
0 25 50 100 Miles
Yanqi Basin
Konqi River Basin

Figure 1

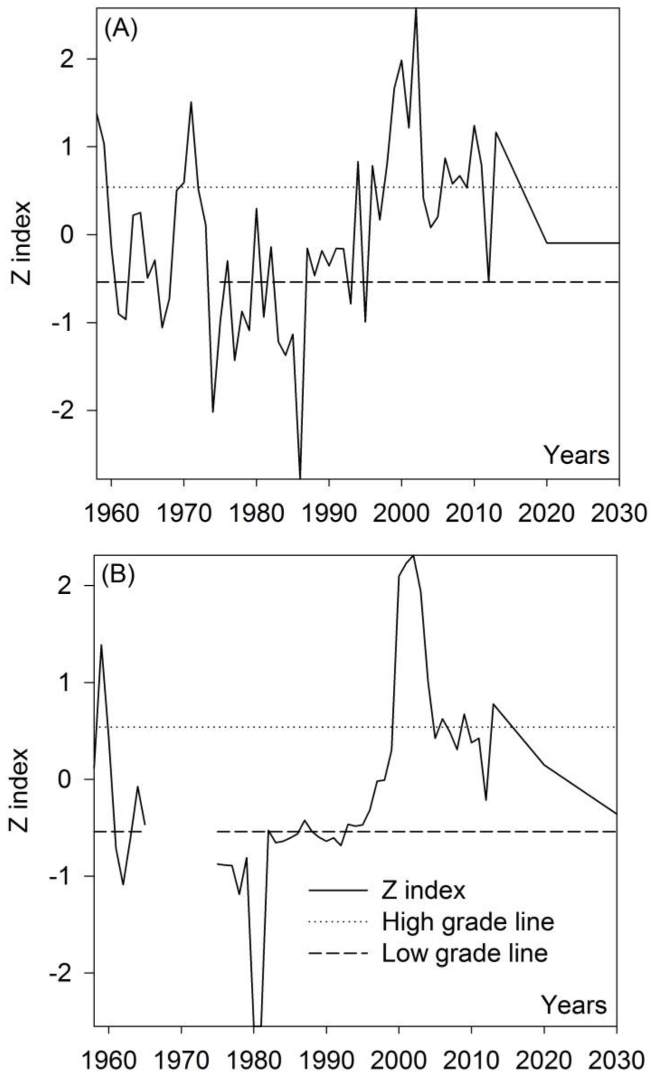
(A)
Z index
Years
1960 1970 1980 1990 2000 2010 2020 2030
2
1
0
-1
-2
(B)
Z index
Years
Z index
High grade line
Low grade line

Figure 2