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IMPACT OF CLIMATE CHANGE AND HUMAN ACTIVITIES ON THE SUSTAINABLE DEVELOPMENT OF XINJIANG AKSU OASIS (CHINA)

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ABSTRACT

Aim of the study

The aim of this study is to show that the Oasis in Xinjiang, China is facing serious sustainable development challenges due to the climate change and human activities, especially for the drought stress.

Material and methods

Linear trend method, also known as linear trend forecasting method and linear fitting, is the most studied and popular quantitative forecasting method so far.

Based on the time series data during the observation period, it is assumed that the predicted variables have a linear function relationship with time, and is fitted into a straight line, so that the straight line can reflect the changing trend of the variables themselves, namely, a linear regression model.

Results and conclusions

From 1961 to 2016, the Aksu Oasis climate in general showed a „warm and wet" trend. From 1991 to 2016, the oasis area continued to expand, and the desert area showed a decreasing trend, and land use changed significantly.

The regional water resources have obviously changed, and the average groundwater depth in the oasis area was between 3.55 and 4.35 meters, showing an increasing trend, while the groundwater level was decreasing. Water resources shortage is the most fundamental reason to restrict the expansion of oasis scale.

The suitable oasis scale of the Aksu Oasis in 1991, 2001 and 2016 is 12,611.30, 15,949.95 and 16,631.59 km^2, respectively, but the actual area of the oasis in the three periods is larger.

Keywords: Aksu oasis, suitable scale of oasis, sustainable development, Hydrothermal equilibrium model

INTRODUCTION

The Oasis in Xinjiang, China is facing serious sustainable development challenges due to the climate change and human activities, especially for the drought stress (Pritchard, 2019; Sorg et. al., 2012). In recent years, the oasis area of Xinjiang has experienced a large-scale water diversion and famine process, with its land use pattern and surrounding ecological environment changing dramatically. Artificial ecosystems replaced the corresponding original natural ecosystems, including farmland, in the following way: artificial forest

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land replaced the natural woodland and grassland, artificial reservoirs replaced the natural lakes. However, the expansion of the oasis and the rapid growth of the population have made the ecological environment of the oasis more fragile, and the conflict between the people and the land became more and more acute, and a series of ecological environment problems was caused. Therefore, the development of oasis is not unlimited, oasis scale should be within the appropriate scope in order to maintain its long-term stability and development (Sobota and Jawecki, 2021). Many scholars in China have carried out a lot of research on this: Han (Han, 1992) calculated that the amount of water resources needed for each 1 hm^2 of oasis is 5,415 m^3; Chen (Chen, 1995) calculated the suitable area of oasis and suitable farmland area by analyzing the total amount of water resources and oasis water demand in the various river basins of the Hexi Corridor, and analyzed the stability of the existing oasis; Wang (Wang and Wang, 2002) proposed the concept of "Greenness" and calculated and evaluated the appropriate scale and stability of the Hexi Corridor oasis. It can be found that under certain climatic conditions, a certain amount of water resources can only breed oasis of a certain area. However, oases of different regions have their own characteristics, so there is no uniform calculation mode and standard for a quantitative calculation of the suitable scale of oasis. While the moderate scale of oasis mainly depends on two factors, one being the amount of water resources and its spatial and temporal distribution, the other is the type of vegetation in the oasis and its water demand.

In the past 25 years, the area of the Aksu Oasis has expanded rapidly, and land use has undergone great changes. In particular, the area of cultivated land has increased significantly, which has gradually broken the natural balance of the oasis, and the function and structure of the oasis have gradually become unstable. In addition, ecological and environmental problems such as secondary salinization of the land and desertification around the oasis are becoming more and more serious. Therefore, it is necessary to accurately calculate the appropriate scale of the Aksu Oasis at this stage, to clarify the use of oasis water and soil resources and the potential for future development under the constraints of water resources. In this paper, the suitable development scale and arable land area of the Aksu Oasis was studied. It is based on the analysis of soil and water resources change, and according to amount of available water resources, combined with the development of oasis. The paper provides scientific reference for local decision makers in the development of oasis water and soil resources, agricultural development, water resources utilization and ecological construction.

GENERAL INFORMATION ON THE AKSU OASIS

Aksu Oasis is located in the southern foothills of the Tianshan Mountains in the west of Xinjiang. The oasis is located along the Aksu River and its source, the terrain is tilted from northwest to southeast, and the geomorphology is mountainous, with plain oasis, river corridor and desert from north to south. The Aksu River is has the largest flow of trails in south of Xinjiang, located on the upper reaches of Tarim River, and the amount of water supplied to the Tarim River accounts for more than 70% of its total runoff. The river basin has a watershed range of 75°35′~80°59′E, 40°17′~42°27′N, and the area is about 5.6 × 104 km^2, of which the domestic area is 3.7 × 104 km^2, and the foreign area is 1.9 × 104 km^2. The oasis is mainly divided into five administrative regions (see: Fig. 1) of Wensu County, Wushi County, Kalpin County, Awat County and Aksu City (including Alaer City) in the middle and lower reaches of the Aksu River. Aksu Oasis is located deep in the Eurasian continent, with the Tianshan block in the north, and affected by the vast desert in the south. Its climate is warm temperate continental climate. The climate here is characterized by dryness and low rainfall, with an average annual precipitation of 75.6 mm. The sunshine duration is long, and the annual sunshine hours are nearly 3000 h, then the heat quantity is abundant, and the annual evaporation capacity is large, reaching about 1540–2860 mm. The frost-free period is long and averages 190 to 251 days per year, and the temperature difference between day and night is large. What is more, the spring is dry and windy, the summer is hot, and the winter is quite cold.

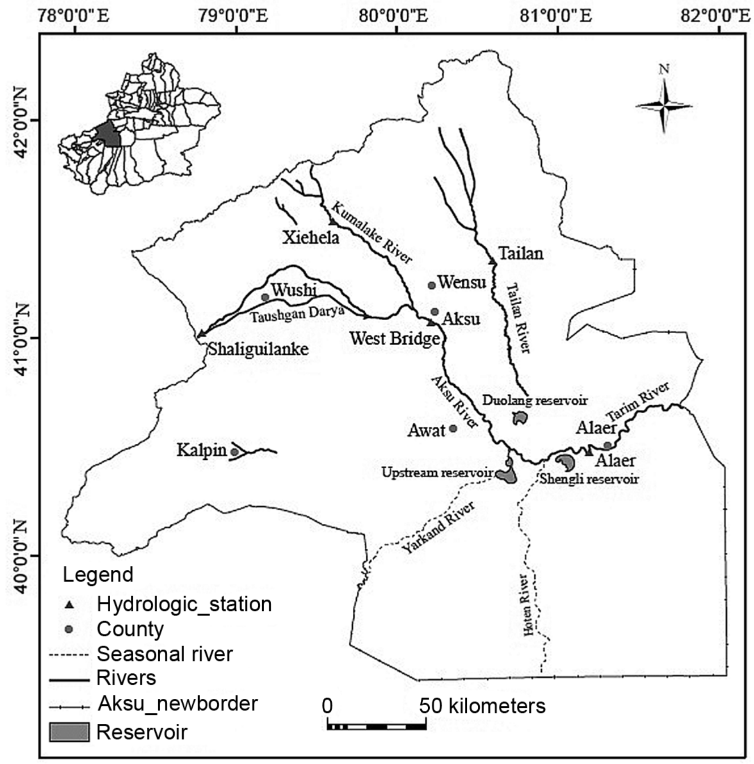

Fig. 1. Sketch map of the Aksu Oasis (*Source*: Resources and Environmental Science Data Center)

DATA SOURCE AND METHOD

Data source

The meteorological data used included daily observations of meteorological elements (temperature, precipitation, sunshine hours, wind speed, relative humidity, etc.) from 1961 to 2016 of three national meteorological stations (Aksu, Kalpin and Alaer) in the study area. The hydrological data includes monthly runoff data from 1957 to 2014 of the exit hydrological stations (Kumalik River and Taushgan Darya, the two major streams of the Aksu River, and the Tailan River) and the two related hydrological stations in the oasis.

The land use data was extracted from three-phase remote sensing images of the study area in 1991, 2001 and 2016, and the remote sensing images were derived from the geospatial data cloud (http://www.gscloud.cn).

In order to analyze the water consumption of the population, agriculture and industry, the 1992–2016 Xinjiang Statistical Yearbook was used. Population, number of livestock, planted area and industrial output value of 5 cities and counties in Aksu during 1991–2015 years were obtained in order to calculate the water use.

METHOD

Linear trend method

Linear trend method, also known as linear trend forecasting method and linear fitting, is the most studied and popular quantitative forecasting method so far. Based on the time series data during the observation period, it is assumed that the predicted variables have a linear function relationship with time, and is fitted into a straight line, so that the straight line can reflect the changing trend of the variables themselves, namely, a linear regression model with one variable:

$$Y = a_0 + bx \tag{1}$$

Where y is the dependent variable, that is, the sequence of elements required; x is the independent variable, mostly time series; b is the slope of the linear equation, the characterization of linear change tendency and rate, positive (negative) b represents the trend of increase (decrease), *b* value of zero indicates no change trend, and b × 10a will be defined as climate tendency rate; a_0 is the regression constant, which can be obtained by least square method.

Hydrothermal equilibrium model

Sustainable development is very important for farm land (Prus, 2008). The evolution of an oasis can be regarded as the evolution of the oasis vegetation ecosystem in a certain sense, and the regional hydrothermal equilibrium state determines the evolution of the vegetation ecosystem. Based on the principle of hydrothermal equilibrium, proposed by Wang (Wang and Wang, 2002) and other scholars, to evaluate the indicator of hydrothermal equilibrium of oasis – Greenness (H_0), the formula is as follows:

$$H_o \frac{W - W_1 + A_n \cdot \mathrm{r}}{ET_o \cdot A_n} \tag{2}$$

where W is the annual net foreign water resource of the oasis, which is the foreign water limit (100 million m³) allocated to the oasis in the sense of water resources planning; W_1 (million m³) is the annual average net water consumption of industry, population and livestock in the oasis, which does not contribute to the growth of its vegetation. It should be deduced from the hydrothermal equilibrium; A_n is the actual scale of oasis (km²); ET_0 i.e., Reference Crop Evapotranspiration (mm), calculated according to the Penman Monteith equation; *r* is the annual precipitation (mm) in the oasis.

H_0 reflects the stability degree of the oasis ecology and is a small and medium scale index reflecting the relationship of hydrothermal equilibrium. According to the previous research results (Duan et al., 2010), combined with the characteristics of oasis ecological environment in arid and semi-arid areas, the stability of oasis can be divided as shown in Table 1. The larger H_0, the higher the stability of the oasis.

In this paper, combined with the previous research results and the current water resources allocation in Tarim River, and based on the principle of hydrothermal equilibrium, a model algorithm suitable for appropriate scale of the Aksu Oasis is constructed. In addition, the role of groundwater in maintaining the scale of Oasis has been added.

$$A = \frac{W - W_1 - W_2 + W_3 - W_4 + W_5 - W_6}{100\,000\left(ET_o - R\right) \times K_p \times H_o^*} \tag{3}$$

Here W_2 is the planned outward water transport volume of the oasis area (100 million m³); W_3 is the amount of water transport volume from the outside of oasis area to its interior; W_4 is the water ecological requirement of the desert vegetation in the downstream

Table 1. Oasis stability as dependent on environment and human activity

Evaluation	H_0	Oasis ecology	Ecological landscape that can be maintained normally	Evaluation of development and utilization of oasis
Unstable status	< 0.50	Degeneration	Steppe	Size of oasis must be reduced to maintain local stability.
Transition status	0.50~0.75	Beginning of degeneration	Steppe and sparse forest grasslands	Oasis needs higher investment to stay stable.
Stable status	0.75~1.00	In balance	Forest steppe or grassland	Oasis area can be expanded appropriately with reliable measures.
Ultra-stable status	> 1.00	Heterogeneity will increase	Lakes, large wetlands and forests	Oasis area can be expanded.

of the river; R is the annual precipitation (mm) of the oasis district; W_5 is the annual groundwater utilization in the oasis area; W_6 is the water loss of the plain reservoir, the meanings of A, W, W_1, ET_0, K_p, H_0*, A_c, K_t are the same as before.

The water consumption of the Aksu Oasis includes mainly the total amount of water consumption, such as habitation, industrial and agricultural production, ecological water uses in oasis, as well as evapotranspiration and infiltration, seepage, etc. of the underlying surface of vegetation and waters. Among them, industrial and agricultural production, habitation and ecological water use in the oasis area are collectively referred to as social and economic water use.

The main economic activity of the Aksu Oasis is agricultural production. Agricultural irrigation water is the main source of water consumption accounting for more than 90% of social and economic water, mainly from Aksu River and its tributary water system. The total amount of water coming from the upstream of Aksu River minus the amount of water discharge is the total amount of water used for surface runoff in the oasis. Due to the dry climate in the study area, the rainfall is scarce, so the precipitation factor is not considered in this paper. The industrial water consumption can be calculated according to the industrial water quota (m^3/10,000 yuan per unit of industrial GDP) and the industrial output value (ten thousand yuan). The amount of habitation water is calculated based on the water quota and the population, including the urban and rural population, and the amount of water used by livestock.

ANALYSIS OF CHANGE OF REGIONAL CLIMATE AND WATER RESOURCES

Climate change

In recent 60 years, the temperature, precipitation, wind speed and relative humidity of the study area have changed significantly (see: Fig. 2). It was found

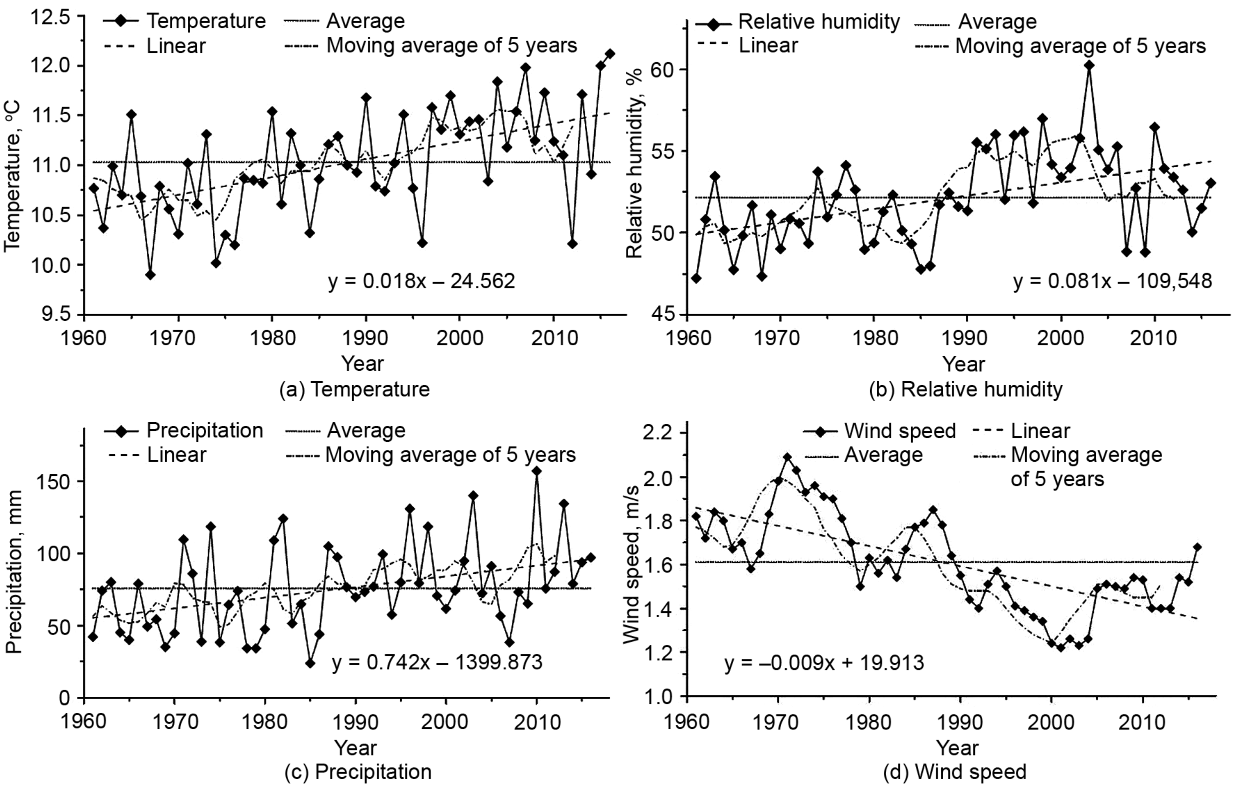

Fig. 2. Change trends of meteorological factors in the Aksu region (a. $R^2 = 0.29$, b. $R^2 = 0.21$, c. $R^2 = 0.14$, d. $R^2 = 0.47$)

that the average annual temperature in the Aksu oasis was 11~, which is higher than the year-round average from the 1950s to 1980s, and it shows an upward trend with the rate of 0.18~/10 a and synchronized with the trend of global temperature change. Starting in the late 1980s, temperatures began to be significantly higher, and the upward trend in temperature was evident. The Aksu Oasis is located in the southern foothills of the Tianshan Mountains and is affected by their presence. The annual wind speed is low and the average annual speed is 1.61 $m \cdot s^{-1}$. During the period of 1961 to 2016, the annual average wind speed showed a downward trend with the rate of –0.092 $m \cdot s^{-1}$/10 a, and its speed decreased more significantly. In the past 60 years it has decreased by 0.5 $m \cdot s^{-1}$.

In the past 60 years, there has been an obvious trend of humidification in the Aksu Oasis. According to the measured data on precipitation, its annual average was 75.6 mm, with the change tendency of 7.42 mm/10 a. The highest amount of precipitation in 2010 was 157 mm and the lowest in 1985 (23.8 mm). The average annual precipitation after the 1990s was 87.6 mm, an increase of 34.6% compared to the measurements from before the 1990s. The relative humidity also showed an increasing trend. The relative humidity was 52.8% from 1961 to 2016, and the growth tendency was 0.81%/10 a, and it passed the significance test of $\alpha = 0.05$ level. In particular, the relative humidity increased significantly from 1991 to 2006, and the growth rate was 8.3%, but there was a slight downward trend after 2007.

REGIONAL WATER RESOURCE CHANGES

Change characteristics of surface water resources

The global warming and humidification directly affects the change in the surface runoff in the Aksu Oasis. The Kumailik river, one of the main sources of the Aksu River, originates from the glaciers in the Jengish Chokusu area of the Tianshan mountains. In the context of global warming, the glaciers in the Jengish Chokusu area are rapidly melting (Li and Li, 2010) the area of 483 glaciers has decreased from 2267.71 km^2 in 1984 to 2067.41 km^2 in 2003, the withdrawal amplitude was 8.8%. With the rapid melting of the snow and ice in Tianshan Mountains, glacier retreat and ice melting began to increase (Zeng et al., 2011) which brought considerable water resources. The runoff of the Aksu River, which is dominated by glaciers and snowmelt, is generally increasing (see: Fig. 3). For the two source streams, the trend rates of the runoff of Kumailik River (Xiehela hydrological station) and Taushgan Darya (Shaliguilanke hydrological station) were $1.72 \times 10^8\ m^3$/10 a and $2.65 \times 10^8\ m^3$/10 a, respectively, the increase trend being significant. 69.7% of the runoff composition of Tailan River comes from glacial meltwater, and its runoff also showed increasing trend in the late 1980s, with change tendency rate of $0.36 \times 10^8\ m^3$. According to relevant statistics (Shen et al., 2003) – the melting of glaciers caused by rising temperatures in the past 44 years is equivalent to $1.24 \times 10^8\ m^3$ per year of runoff to Tailan River, accounting for 15% of the annual runoff of the river.

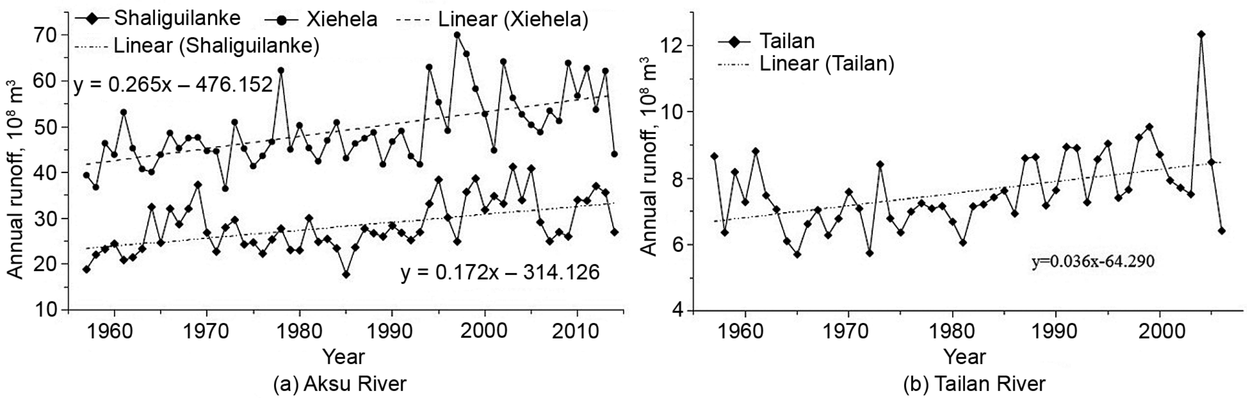

Fig. 3 Changes in the annual runoff at main hydrological stations in the study region (Shaliguilanke. $R^2 = 0.26$, Xiehela. $R^2 = 0.33$, Tailan. $R^2 = 0.19$)

Figure 4 shows the characteristics of the high flow and low flow cycles of runoff of the two source rivers of Aksu and Tailan. The two source rivers of the Aksu River had a tendency to increase its runoff in the 1960s, but in the late 1970s there was a decrease in this volatility. For the 37 years from 1957 to 1993 only 1968 was a partial year with abundance of water and the dry years, including partial one, lasted 16 years, while the other years were normal years. However, since the 1990s the two source rivers of the Aksu River entered the wet seasons. The runoff of Kumailik River and Taushgan Darya increased by 10.39×10^8 m^3 and 10.72×10^8 m^3, respectively, compared with 1950s, and the increase rate reached 23.4% and 50.1%. Between 1994 and 2014, there were 6 normal years, the remaining staying with abundance of water. During the 30 years from 1957 to 1986 the Tailan River had a partial year with abundance of water for 3 years (1957, 1961, 1973), 11 years with shortage of water (including partial dry year) and the rest were normal years. However, during the 20 years from 1987 to 2006, only 2006 was a partial dry year, and 11 years were years with abundance of water (including the partial year) and the remaining 8 years were normal years. It can be found that the Tailan River entered the wet seasons in 1987. The annual runoff of wet seasons, partial wet seasons, normal-water periods, partial withered water periods and withered water period of the Aksu Oasis mountain-pass runoff from 1957 to 2014 was average over the years, and the amount of water available for the oasis in each phase of the inflow scenario can be obtained, which are 92.16×10^8, 85.23×10^8, 70.22×10^8, 60.6×10^8 and 53.03×10^8 m^3, respectively.

The runoff of the Aksu Oasis enters the plain oasis area after leaving the mountain pass, and with the rapid development of society and economy in the oasis area, the area and the amount of water diversion of the oasis agricultural land irrigation area increased continuously, but the discharge water of the Aksu River to the main stream of the downstream Tarim River did not appear to increase obviously, there was even some decline after 2000 (see: Fig. 5). In the 1950s, the amount of water that the Aksu River remitted into the main stream of the Tarim River was 34.4×10^8 m^3, which dropped to 31.3×10^8 m^3 in the 2000s. However, in the same period, the water consumption of surface runoff in the oasis showed an increasing trend. Especially after the 1990s, the area of the oasis agricultural land increased significantly, and the water consumption of the oasis increased significantly. The water consumption of the 2000s increased by 16.4% compared to the 1990s, and increased by 55.6% compared with the 1950s. The proportion of water consumption to water inflow into the oasis also showed an increasing trend. And in the 1950s, the proportion of water consumption to water inflow was 65%. After 2000, the proportion of water consumption to water inflow rose to 67.9%. The proportion of the Aksu River discharge water in the 1950s was about 35%. In the 1970s and 1980s, the proportion increased, but after the 1990s, it showed a significant decrease trend. After 2000, the proportion of discharged water to the water inflow dropped to

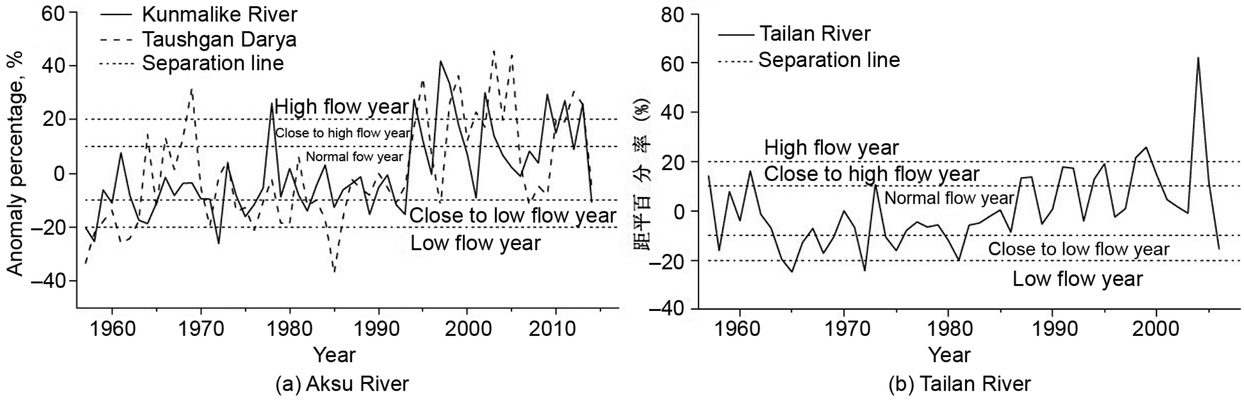

Fig. 4 High flow and low flow cycles of the runoff to the Aksu Oasis mountain-pass

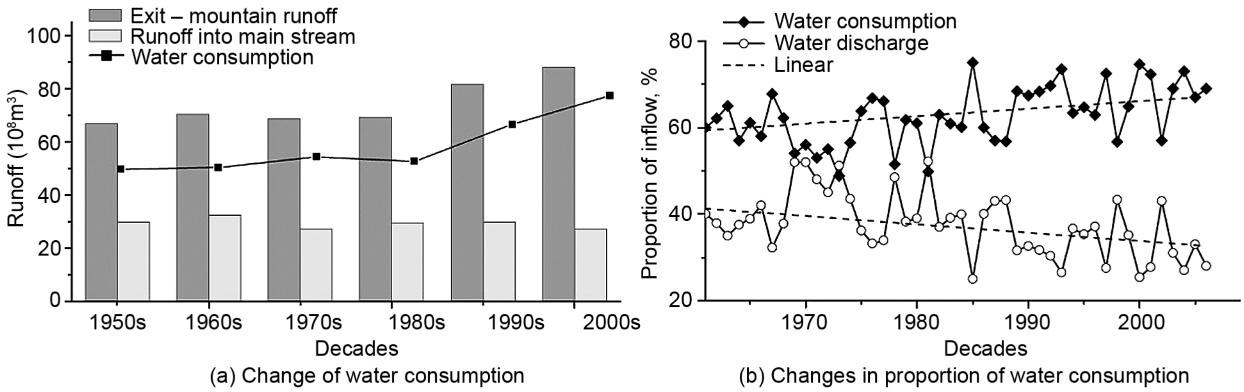

Fig. 5. Changes in consumption and outflow of water resources and proportions to annual inflow

31.6%. The proportion of water in the main stream of the Tarim River recharged by the Aksu River is decreasing in the oasis.

Groundwater depth change

For the agricultural water use of the Aksu Oasis, in addition to the surface runoff of Aksu River and its tributaries, the groundwater is also an important source of water for the social and economic development. According to the relevant statistics (Liu, 2016), the amount of groundwater resources in the Aksu River basin is about 4.535 billion m^3, but large-scale agricultural development and the continuous expansion of the oasis have affected the formation and recharge of groundwater in the study area to a certain extent in recent years, and obvious changes have taken place in groundwater resources. According to the monitoring data of the observation well of groundwater in the study area from 2000 to 2015 (Zhang, 2003), there is a change in the groundwater depth in the study area (see: Fig. 6). During this period the average groundwater depth in the Aksu Oasis area was between 3.55 and 4.35 meters, showing an overall increasing trend, and the groundwater level continued to decline, dropping by about 0.8 meters in 16 years. Because of the different situation of surface water recharge, land use and agricultural structure in different regions, the depth of groundwater shows great differences. Aksu and Awat are located in the alluvial plains of the middle reaches of the Aksu River and are the main industrial and agricultural production areas. Their water consumption increased significantly, and the groundwater exploitation and utilization degree are relatively large, which results in an increase in the embedded depth of groundwater. From 2000 to 2015, the groundwater depth in the two regions increased by 1.91 meters and 0.89 meters respectively, and the groundwater depth in other regions did not change much.

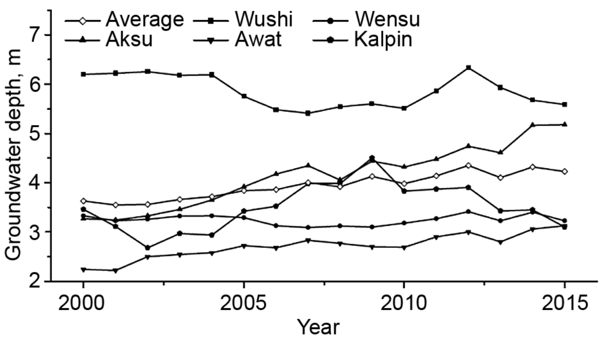

Fig. 6. Annual mean variation of groundwater depth of the Aksu oasis during 2000 to 2015

The increase of groundwater depth can reduce the moisture content of cultivated soil layer and increase the surface water irrigation and number of crops. The increase of groundwater depth indicates that the natural ecology of the Aksu Oasis is degenerative. According to the variation of groundwater depth in the Aksu Oasis from 2000 to 2001 and from 2014 to 2015, it is estimated that the utilization of groundwater resources in 2001 was about 953 million m^3, and that in 2016 it was about 1.247 billion m^3. Considering the phenomenon of disorderly exploitation of groundwater resources in the study area, the depth of groundwater has increased significantly in recent years, so the low value of available groundwater resources is about 953 million m^3.

Analysis of land use change in the Aksu Oasis

The pattern distribution of land use/cover space in the Aksu Oasis is showed in Figure 7, and it can be found that more than 50% of the land is unused, including wilderness, desert, Gobi, saline-alkali land, bare land, and so on, which is distributed around the oasis and away from rivers. Glaciers in the high mountain, meandering rivers, lakes and reservoirs are the life source of the oasis, an important factor of the whole desert oasis ecosystem development, and it also determines the basic pattern of desert oasis development. The

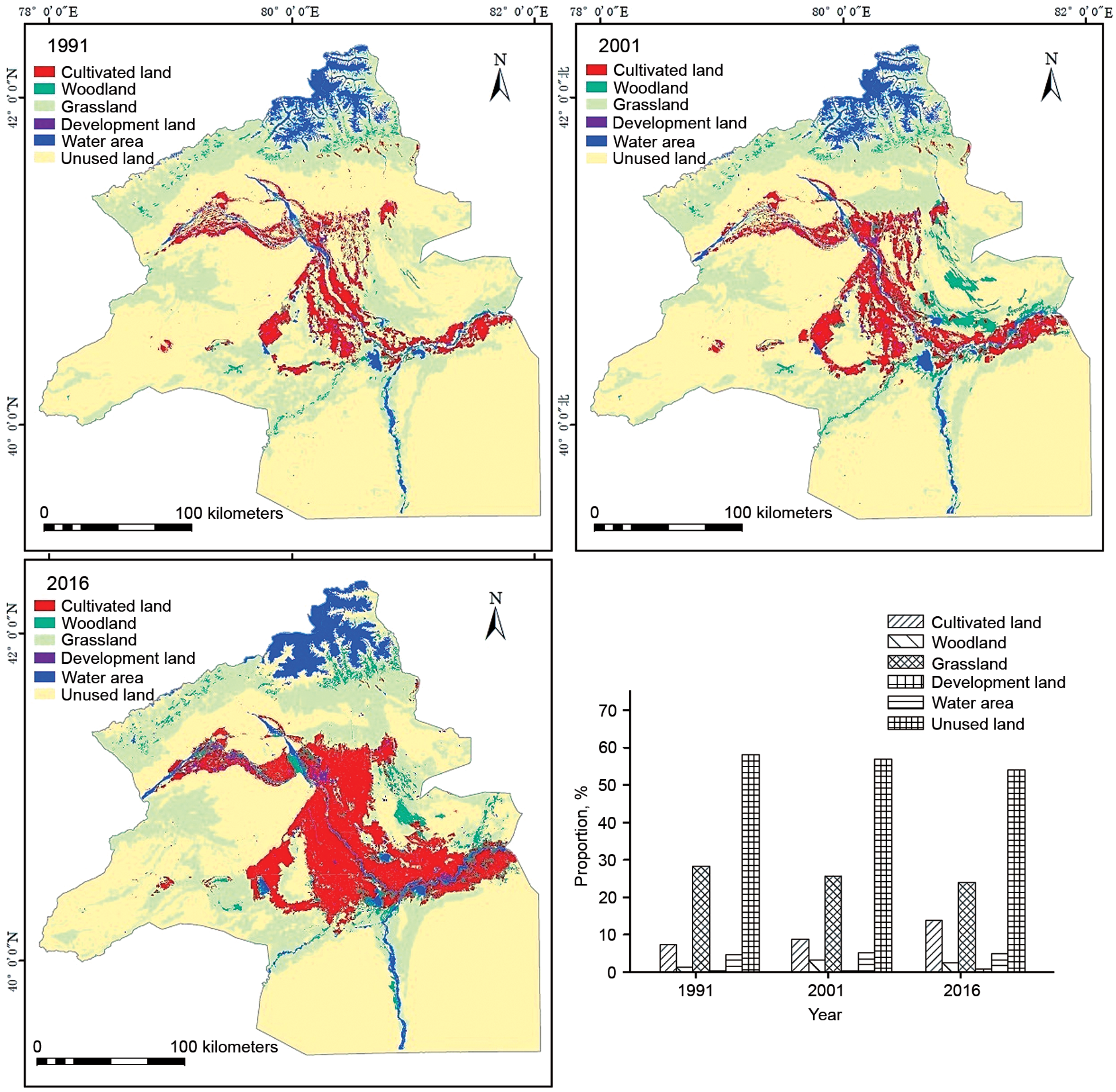

Fig. 7. Spatial variation of land use/cover in the Aksu Oasis from 1991 to 2016 (*Source*: Geospatial Data Cloud)

main types of land in the oasis area are cultivated land and grassland, which accounted for 84.6% of the study area in 1991 and 82.03% in 2016. Among them, the proportion of cultivated land area was on the rise, while the proportion of grassland decreased. According to statistics, the area of the cultivated land in the oasis in 1991 was 4650.74 km^2, accounting for 7.36% of the study area, and it increased to 8759.74 km^2 in 2016, accounting for 13.87% of the area. In the past 25 years, the area of cultivated land has nearly doubled, with an average annual increase of 164 km^2. Woodland is mainly distributed in the periphery of the mountain and rivers, and grassland is found in foothills, the surrounding plains and the edge of the oasis and the desert, while water area and the development land area account for a relatively small proportion. The area of development land increased significantly from 2001 to 2016 but the proportion was only 0.81%. What is more, both grassland and unused land area showed a decreasing trend.

The transfer matrices of land use types of the oasis in the period from 1991 to 2001 and from 2001 to 2016 are shown in Tables 1 and 2, from which the way magnitude and direction of the mutual transformation between land use/land cover can be explained quantitatively. As Table 2 shows, during the period of 1991–2001, the area of cultivated land in the study area increased by 883.46 km^2, while the newly added area mainly came from the conversion of grassland (1054.83 km^2) and unused land (308.548 km^2). In addition, the area of woodland also increased significantly, and the newly added woodland mainly came from grassland (783.12 km^2) and unused land (369.01 km^2); the grassland area was reduced, and a large part of grassland was degraded into unused land (1669.04 km^2), or was changed into cultivated land (1054.83 km^2). The main reason is that grassland on the edge of the oasis area became cultivated land through land reclamation due to water source conditions. In addition, some grassland (783.12 km^2) was converted into woodland because of abundant water resources; The water area increased slightly by 180.33 km^2, mainly converted from grassland (232.36 km^2) and unused land (58.82 km^2). Similarly, the development land also increased slightly during this period, and the transfer-in area is roughly the same as the transfer-out area. Its main use is the mutual and frequent conversion from cultivated land. The unused land is mainly converted into grassland (1854.62 km^2), which is slightly larger than the grassland conversion area of 1669.04 km^2, showing a slight decrease trend.

Table 3 shows that during the period from 2001 to 2016, the cultivated land in the study area showed a substantial increase, and the area increased from 5534.2 km^2 to 8759.74 km^2, as well as the growth rate reached 58.3%. The area of development land has nearly doubled from the original 266.31 km^2 to 509.41 km^2, which shows that the urbanization process accelerated significantly during this period. However, the newly added area of 279.37 km^2 of development land was derived from cultivated land, which shows that the city occupied a large area of cultivated land in the process of its expansion. The area of grassland and unused land continued to decrease, with a decrease of 1170.15 km^2 and 1797.80 km^2, respectively, and with a change range of 7.76% and 5.27%. The area

Table 2. Transfer matrix of land use changes in the Aksu Oasis from 1991 to 2001 (unit/km^2)

	Land use types Cultivated land	2001						Total
		Wood land	Grass land	Water area	Developed land	Unused land		
1991	Cultivated land	4038.82	111.44	282.34	31.73	83.20	103.21	4650.74
	Forestland	35.12	749.42	17.26	16.92	2.13	19.90	840.75
	Grassland	1054.83	783.12	14033.11	232.36	8.37	1669.04	17780.83
	Water area	15.61	27.51	58.95	2829.27	0.06	58.33	2989.74
	Development land	81.27	6.85	6.03	0.98	166.86	2.60	264.61
	Unused land	308.54	369.01	1854.62	58.82	5.38	34047.61	36644.28
	Total	5534.20	2047.35	16252.31	3170.07	266.31	35900.69	63170.94

Table 3. Transfer matrix of land use changes in the Aksu Oasis from 2001 to 2016 (unit/km^2)

Land use types Cultivated land		2016						Total
		Wood land	Grass land	Water area	Development land	Unused land		
2001	Cultivated land	4762.42	254.17	151.67	48.34	279.37	37.36	5533.32
	Forestland	701.76	356.71	601.95	93.92	32.86	260.04	2047.24
	Grassland	1816.40	574.19	9744.62	363.62	53.56	3702.50	16254.89
	Water area	157.56	128.73	222.81	2208.52	8.27	443.88	3169.76
	Development land	182.31	5.24	8.09	1.19	67.37	2.11	266.31
	Unused land	1139.30	337.28	4355.60	343.50	68.00	29655.75	35899.43
	Total	8759.74	1656.32	15084.74	3059.09	509.41	34101.63	63170.94

of woodland was reduced by 390.92 km^2, which was mainly converted into cultivated land and grassland. The area of the water area changed little, decreasing by 110.67 km^2.

DISCUSSION

Analysis of the utilization change of water resources in the oasis

Aksu is a typical agricultural oasis, and its agricultural water use accounts for a large proportion in the water consumption. The 2015 Aksu Oasis water use (see: Fig. 9(a)) was employed to analyze the agricultural and industrial water use and its proportion to water use of the oasis. Figure8(a) shows that the total water consumption in 2015 was 4.931 billion m^3 · among which agricultural water accounted for the largest proportion (91.3%), while industrial and habitation water for 6.7% and 2.0%, respectively. According to the regional distribution, Aksu City, Wensu County and Awat County are located in the plain oasis area of the Aksu River, where the population is dense and the area of the cultivated land is large · therefore, water use accounts for a large proportion – 28.5%, 25.1% and 32.2% of the total oasis water consumption, respectively. Relatively speaking, Wushi and Kalpin use less water, making 10.7% and 3.5% of the total oasis water use. Except for Aksu's agricultural water use ratio of 78.3%, the proportion of agricultural water use in the other four counties is above 90%. Among them, Aksu has the highest proportion of agricultural water use, reaching 97.9%. It shows that the agricultural water use in the Aksu Oasis is still dominant, and the rational control of agricultural water use is essential for the water allocation of the oasis.

From 2010 to 2015, water consumption of the Aksu Oasis increased year by year. From 2010 to 2012, it increased by 780 million m^3, 220 million m^3 and 14 million m^3, respectively. The increase range of water consumption for habitation was the smallest (15.8%), while water use for agriculture and industry increased by 20.9% and 199.1%, respectively. However, the proportion of agricultural water use was on a downward trend (see: Fig. 8 (b)), and in 2009, the proportion of agricultural water consumption was 95%. By 2015, it dropped to 91.3%, but industrial water consumption had increased significantly, and the proportion of water used for habitation had not changed much.

Appropriate scale analysis of the oasis

Aksu Oasis is located in an arid area, and its size should be determined according to the amount of water resources. If the availability of water resources is not taken into account, excessive development of land resources will lead to desertification. According to the appropriate scale calculation model, combined with data for water resources available in different years, calculated above, the proper area of the oasis in 1991, 2001 and 2016 and the proper area of cultivated land were calculated, as shown in Table 4. The annual average of the observed years was taken as the precipitation in the table; ET_0 was calculated according to the

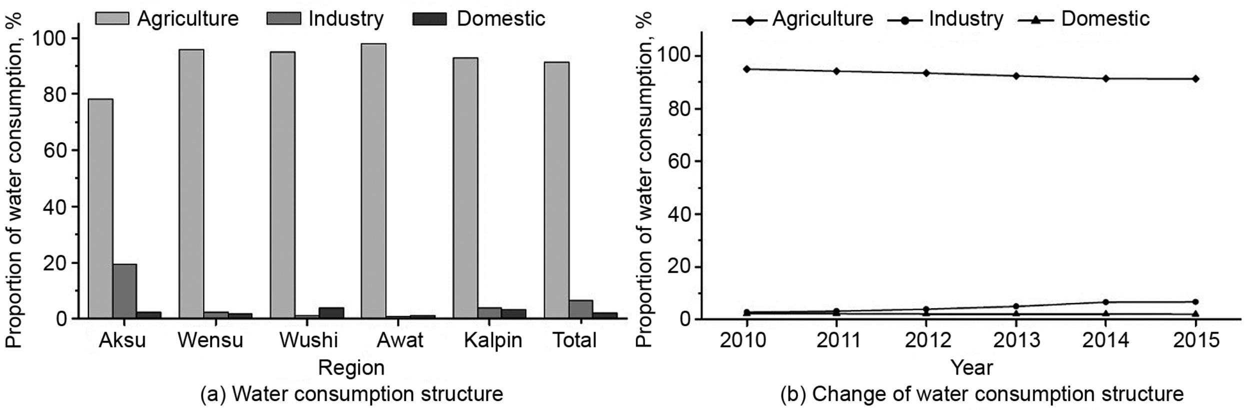

Fig. 8. Structure and change of water use in the Aksu Oasis

Penman formula, and the comprehensive plant coefficient of the main plants in oasis was 0.7. As the oasis is surrounded by desert, the natural environment is bad, from the point of view of maintaining its existence, the value of green degree was 0.75~1. Cultivated land should not exceed 70% accounts for the proportion of total oasis area (cultivated land rate), so the cultivated land rate of 40% is suitable for this paper, and greenness 0.75 is selected to calculate.

In recent years, the rising temperature in the Aksu area has led to glacier retreat, and the glacier meltwater continues to increase, especially after 1990 (Wang et al. 2008). At the same time, precipitation also increased significantly. Table 4 shows that the surface runoff of the oasis area increased after 2000. In 1991, the amount of water coming to the Aksu River was 7.29 billion m^3; in 2001, the amount of water coming was 8.7 billion m^3, and in 2016, the amount of water coming was 8.65 billion m^3, which was an increase of 9.4% and 8.7%, respectively, over 1991. The water resources available in the Oasis District increased. Therefore, in 2001 and 2016, the appropriate scale of the oasis in the study area and the appropriate scale of cultivated land tended to expand. The three periods of suitable scales of the Aksu oasis were 12611.30km^2, 15949.95km^2 and 16631.59 km^2, respectively. However, the actual area of the oasis was greater than that in the same period. In 1991, the area was exceeded by 3746.11km^2, in 2001 by 1081.25 km^2, and in 2016 3160.42 km^2. From 1991 to 2001, the oasis agriculture was still in its infancy and the actual cultivated land area in these two years was 4650.74 km^2 and 5534.20 km^2 respectively, which was 393.78 km^2 and 845.78 km^2 lower than the appropriate area. This analysis shows that the oasis still has a potential to increase cultivated land at that time. However, the population pressure in the study area increased rapidly after 2001, and the water resources were utilized in an unplanned fashion while the cultivated land area increased significantly. In 2016, the cultivated land area of the study area reached 8759.74 km^2, exceeding the suitable cultivated area by 2107.10 km^2. Too much cultivated land increased the pressure on the oasis and accelerated its degradation. It can also be found from the stability index H_0 that the water volume has increased significantly since 1991, and the stability of the oasis has increased from 0.66 in 1991 to 0.77 in 2001. However, due to a significant area increase of the oasis from 2001 to 2016 and a decrease in the amount of water resources in the oasis, the stability of the oasis has dropped to 0.62 in 2016. The oasis is already in a metastable state, and some areas have even shown signs of degradation. Overdevelopment has threatened the stable structure within the oasis, and it needs higher investment to maintain its current stability.

The water available in the Aksu Oasis comes mainly from the mountainous area, accounting for more than 85% of the total amount of available water. Therefore, the changes of the water coming from the mountains will directly affect its development. Therefore, it is necessary to consider the conditions

Table 4. Optimum scales for oasis and farmland in the Aksu Oasis

Year	incoming flow /$10^8 m^3$	R/mm	ET_0/mm	Suitable area/km²		Actual area/km²		
				Oasis	Cultivated land	Oasis	Cultivated land	H_0
1991	72.90	73.14	1044	12611.30	5044.52	16357.41	4650.74	0.66
2001	87.01	68.81	1020	15949.95	6379.98	17031.20	5534.20	0.77
2016	86.47	89.98	1104	16631.59	6652.64	19792.01	8759.74	0.62

of abundance or scarcity of mountain water and to define the appropriate scale of the oasis. According to the calculation, the total amount of industrial and habitation water used in the oasis area in the year of 2016 is 136 million m³. Between Xiehela and Haliguilanke and West Bridge Hydrological Station of the Aksu River, the annual runoff in the control area without station is about 608 million m³, then the amount of water resources available in the interval is 315 million m³, (Chen, 1995) excluding the invalid consumption of 353 million m³. The availability of groundwater resources in the study area was about 1.552 billion m³, and the downstream amount of water flowing in and out of the region takes a multi-year average of 848 million m³. In the Outline of Comprehensive Management Plan for the Tarim River Basin, it is pointed out that the water loss of the Aksu River plain reservoir is about 420 million m³, and the reservoir area changes little over the years. Aksu River provides water to the main stream of the Tarim River every year, with an average annual input of about 3.42 billion m³. The proportion of ecological water consumption in the Aksu oasis is very small, and the annual ecological water consumption is about 40 million m³. Based on the above data analysis, with 2016 as the current year, the appropriate scale of oasis in different water resources scenarios such as wet seasons, we calculated a normal water period and low water period of the Aksu Oasis (see: Table 5).

As can be found in Table 5, the suitable size of the oasis in the partial year with abundance of water is 12183.02~162244.03 km². In 2016, the available water resource was at the level of partially abundant. The actual area of the oasis was 19792.01 km², which is 3547.98 km² higher than the suitable area. And its stability index is 0.62, which is a transition status, which indicates that the amount of water resource in the partial abundance period can still guarantee the water consumption in the oasis, but the oasis is in a declining trend and needs high investment to maintain its current stable status, which is consistent with its current status. However, the present oasis area, if it is in the normal-water level, has a stability index of 0.51, which has reached the critical value of the transi-

Table 5. Stability and suitable scale of the Aksu oasis under different water resources scenarios

Abundant and dry level	Available water resources/$10^8 m^3$	ET_0/mm	R/mm	Suitable area for Oasis /km²			Current Oasis/km²	
				$H_0 = 0.5$	$H_0 = 0.75$	$H_0 = 1$	area	H_0
Year of abundant water	92.16	1075	75.6	26347.24	17564.83	13173.62	19792.01	0.67
Year of partial abundant water	85.23	1075	75.6	24366.05	16244.03	12183.02	19792.01	0.62
Normal water year	70.22	1075	75.6	20074.90	13383.27	10037.45	19792.01	0.51
Partial low water year	60.6	1075	75.6	17324.68	11549.79	8662.34	19792.01	0.44
Low water year	53.03	1075	75.6	15160.52	10107.02	7580.26	19792.01	0.38

Note: The range of suitable scale for oasis, H0 value of 0.75 ~ 1.

tion status. The suitable area of oasis in normal-water year ranges from 10037.45 km^2 to 13383.27 km^2, and the current annual oasis area is larger than the critical area of 6408.74 km^2. What is more significant is when the stability index falls to 0.44 and 0.38 in the current oasis area during partial dry season and dry season. The current oasis area is much higher than the critical value of the suitable area in these two periods. Therefore, in the normal and low period, the amount of available water resources in the Aksu oasis will not be able to sustain further development and expansion of the oasis.

The size of the oasis should be controlled within a certain range. If the scale is too small, the water and soil resources of the oasis cannot be fully utilized. On the contrary, if the area is too large, the heterogeneity of the oasis will increase, and the ecological environment will deteriorate inside and outside the oasis (Polat et al. 2021; Zubaida et al. 2018). Considering that the number of years in normal water period (27 years) and the wet season (including the partial wet season: 16 years) accounted for 74.1% of the total number of years (58 years), especially after the 1990s the number of years in normal-water period and wet seasons accounted for 87.5% years of the total number of years (24 years), in which wet seasons accounts for 58.3%. Therefore, the most suitable area of the Aksu Oasis under these water resource conditions should be controlled within 10037.45~16244.03 km^2, and the maximum value should not exceed 20074.90 km^2.

CONCLUSIONS

(1) From 1961 to 2016, the Aksu Oasis climate in general showed a „warm and wet" trend. The annual average temperature increased at a linear tendency rate of 0.18%/10 a, and the annual precipitation increased by a tendency of 7.42 mm/10 a, then the annual average relative humidity increased at a tendency rate of 0.81%/10 a. However, the annual average wind speed was significantly reduced by a tendency of –0.092 ms-1/10 a, and the annual average wind speed in the last 60 years has been reduced by 0.5m · s^{-1}.

(2) From 1991 to 2016, the oasis area continued to expand, and the desert area showed a decreasing trend, and land use changed significantly. The area of cultivated land increased significantly from 4650.74 km^2 in 1991 to 8759.74 km^2 in 2016, so the cultivated land area has nearly doubled in 25 years.

(3) The regional water resources have obviously changed, and the average groundwater depth in the oasis area was between 3.55 and 4.35 meters, showing an increasing trend, while the groundwater level was decreasing. The surface runoff varied in recent 58 years and the mountain runoff increased significantly in the last 25 years. During the 21 years from 1994 to 2014 the Aksu River had 6 years of normality, with water abundance in the rest of years. However, the consumption of water resources in the oasis areas also showed an increasing trend. In particular, after the 1990s the area of cultivated land increased significantly and the water consumption of the oasis evidently increased. The water consumption in 2000 increased by 16.4% which is more than in the 1990s and increased by 55.6% in the 1950s, which is less than in the 1950s.

(4) Water resources shortage is the most fundamental reason to restrict the expansion of the scale of the oasis. The suitable oasis scale of the Aksu oasis in 1991, 2001 and 2016 is 12611.30, 15949.95 and 16631.59 km^2, respectively, but the actual area of the oasis in the three periods was larger. The actual area of agricultural land in 1991 and 2001 is smaller than the suitable area of the land, and the oasis still has some potential of agricultural land development. But in 2016 the actual agricultural land area exceeded the suitable agricultural land area by 2107.10 km^2, and the oasis stability index fell to 0.62. The current year 2016 is partial year with abundance of water, and the actual oasis size and cultivated land size were 19792.01 and 8759.74 km^2, respectively. Under the present condition of oasis, if the incoming water in the oasis is that of a normal and dry year, the oasis stability index will decrease to 0.51 and 0.37. In light of the recent condition of water income to the oasis, the most suitable area of the Aksu oasis should be kept within 10037.45-16244.03 km^2 and the maximum area should not exceed 20074.90 km^2.

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REFERENCES

Chen, C. (1995). Actual quantity of water resources and the suitable area for oasis and farmland in the Hexi corridor, Gansu Province. Journal of Arid Land Resources and Environment, 3, 122–128. [in Chinese].

Duan, J., Liu, X., Gou, S., Gao, Q., Wang, S. (2010). The surface water resources and its available in the non-controlled area in the Aksu River basin. Journal of Glaciology and Geocryology, 32(3), 609–618. [in Chinese].

Han, D. (1992). The oasis system and oasis geographic construction. Arid Land Geography, 15 (sup.), 5–11[in Chinese].

Li, Z., Li, K., Wang L. (2010). Study on recent glacier changes and their impact on water resources in Xinjiang, north western China, Quaternary Sciences. 30(1), 96–106. [in Chinese].

Liu, X. (2016). Temporal evolution characteristics of groundwater burial depth in Aksu irrigation area. China Water Transport, 16(8), 173–174. [in Chinese].

Muhtar, P., Xia, J., Muyibul, Z., Zihriya, B., Abliz, A., Zhang, M. (2021). Evaluating the evolution of oasis water metabolism using ecological network analysis: A synthesis of structural and functional properties, Journal of Cleaner Production, 280, 124422.

Pritchard, H.D. (2019). Asia's shrinking glaciers protect large populations from drought stress. Nature, 569, 649–654.

Prus, P. (2008). Sustainable development of individual farms based on chosen groups of farmers. Electronic Journal of Polish Agricultural Universities, 11(3).

Shen, Y., Liu, S., Ding, Y., Wang S. (2013). Glacier mass balance change in Tailanhe River watersheds on the south slope of the Tianshan Mountains and its impact on water resources. Journal of Glaciology and Geocryology, 25(2), 124–129. [in Chinese].

Sobota, M., Jawecki, B., Li F. (2021). Charges for water services: legal and systemic concepts in the European Union (the example of Poland) and China. Journal of Water Law, 27(1), 13–19.

Sorg, A., Bolch, T., Stoffel, M., Solomina, O., Beniston, M. (2012). Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nature Climate Change. 2, 725–731.

Wang, G., Shen, Y., Su, H., Wang, J., Mao, W., Gao, Q., Wang, S. (2008). Runoff changes in Aksu River Basin during 1956-2006 and their impacts on water availability for Tarim River. Journal of Glaciology and Geocryology, 30(4), 562–568. [in Chinese].

Wang, Z., Wang, H. (2002). Stability analysis of oasis in arid region, Journal of Hydraulic Engineering, 33(5), 0026–0031. [in Chinese].

Zhang, G., Wu, S., Wang, Z. (2003). The signal of climatic shift in Northwest China deduced from river runoff change in Xinjiang region. Journal of Glaciology and Geocryology, 23(2), 183–186.[in Chinese].

Zheng, S., Abdirahman, H. (2011). Study on suitable scale of Qiemo Oasis, Research of Soil and Water Conservation, 18(6), 240–244. [in Chinese].

Zubaida, M., Xia, J., Polat, M., Shi, Q.D., Zhang, R. (2018). Spatiotemporal changes of land use/cover from 1995 to 2015 in an oasis in the middle reaches of the Keriya River, southern Tarim Basin, Northwest China. Catena, 171, 416–425.

WPŁYW ZMIAN KLIMATYCZNYCH ORAZ DZIAŁALNOŚCI CZŁOWIEKA NA ZRÓWNOWAŻONY ROZWÓJ TERENÓW OAZY AKSU W XINJIANG W CHINACH

ABSTRAKT

Cel badania

Celem tego badania jest wykazanie, że tereny oazy Aksu w Xinjiang w Chinach stoją w obliczu poważnych wyzwań związanych ze zrównoważonym rozwojem ze względu na zmiany klimatyczne i działalność człowieka.

Materiał i metody

Metoda trendu liniowego, znana również jako metoda prognozowania trendu liniowego i dopasowanie liniowe, jest jak dotąd najlepiej zbadaną i popularną metodą prognozowania ilościowego.

Na podstawie szeregu danych czasowych w okresie obserwacji zakłada się, że przewidywane zmienne mają związek funkcji liniowej z czasem i są wpasowane w linię prostą, tak aby linia prosta mogła odzwierciedlać zmieniający się trend samych zmiennych, czyli model regresji liniowej.

Wyniki i wnioski
Od 1961 do 2016 roku klimat Aksu Oasis ogólnie wykazywał trend „ciepło i mokro". W latach 1991–2016 obszar oaz nadal się powiększał, obszar pustynny wykazywał tendencję spadkową, a użytkowanie gruntów znacznie się zmieniło.
Zmieniły się oczywiście regionalne zasoby wodne, a średnia głębokość wód gruntowych w obszarze oazy wynosiła od 3,55 do 4,35 m, wykazując tendencję wzrostową, podczas gdy poziom wód gruntowych spadał. Niedobór zasobów wodnych jest najistotniejszym powodem ograniczania ekspansji skali oaz.
Odpowiednia skala oazowa Aksu Oasis w latach 1991, 2001 i 2016 wynosi odpowiednio 12 611,30, 15 949,95 i 16 631,59 km^2, ale faktyczna powierzchnia oazy w tych trzech okresach jest większa.

Słowa kluczowe: oaza Aksu Xinjiang, zrównoważony rozwój, model równowagi hydrotermalnej