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Evaluation of the Stability and Suitable Scale of an Oasis Irrigation District in Northwest China

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Abstract: Oases support human activities in arid and semiarid regions, and their stability is important for regional sustainable development and water resource management. Water consumption is the major factor affecting the stability of oases. On the basis of remote sensing images, evaporation and socioeconomic data, this study first evaluates the stability of the Dunhuang Oasis against the expansion of an oasis irrigation district and planting structure changes from 1987 to 2015. Next, it calculates a suitable area of the oasis irrigation district using water–energy balance theory. The results are as follows: (1) During the 1987–2015 period, with the expansion in the oasis irrigation area, the planting structure underwent a marked transformation from food crops to cash crops to orchards. Water consumption pattern likewise changed considerably. (2) The stability of the Dunhuang Oasis continued to weaken from 0.54 in 1987 until it reached a dangerously unstable level of 0.17 in 2010. With the implementation of water-saving measures and a water-transfer project, the stability of the Dunhuang Oasis irrigation district increased to a metastable level of 0.22 in 2015. (3) Setting the stability are 0.5 of a stable level and 0.75 of an extremely stable level, and the oasis irrigation district should be impractical and reduced by 168 and 241 km^2 to attain a suitable oasis ecosystem scale. Hence, at present, the water-transfer project is the most practical way to increase allocated water resource to the oasis irrigation district for improving its stability.

Keywords: oasis irrigation district; stability evaluation; suitable scale

1. Introduction

The mountain–oasis–desert unit is the main topographic feature of inland river watersheds in China [1]. For watersheds in this arid region, water from melted snow and glacier in the mountain flows through an oasis similar to a water tower, thereby providing fresh water to people and nature before disappearing into the desert. Through this morphotectonic pattern, as an important landscape, oases support human activities and economic development in arid regions [2] but are generally water deficient [3]. Its stability is directly related to the sustainable development of regional economy and ecological security [2].

In recent decades, the expansion of the irrigation district, population growth, and economic development in the middle-stream oasis of the inland river basin has considerably modified hydrological cycles and reduced surface runoffs to downstream reaches. Consequently, this situation has led to dried-up rivers, reduced outflows to terminal lakes, and the deterioration of the ecosystem in downstream areas [4–7]. These effects have manifested in dried-up inland lakes, such as the Aral Sea in Central Asia [8,9], Lake Urmia in Iran [10,11], and the Shiyang River in Northwestern China [12]. Thus, assessing whether an oasis is stable under the present development pattern is important in the pursuit of sustainable development. Moreover, evaluating a suitable oasis scale is crucial to the government development plan.

Several studies on stability evaluation and suitable oasis scales have focused on the Endorheic Basin in Northwest of China, specifically, the Keriya River Basin [13], the Manas River Basin [2], the Tarim River Basin [14], the Weigan River [15], and the Heihe River Basin [16]. Research methods in stability evaluation and suitable scales have continuously progressed owing to the rapid development of ecological hydrology. In the past, suitable oasis cropland areas were calculated by establishing a regression equation using the total amount of runoff water resources and the cropland area of the oasis [17]. Wang et al. [18] applied contrastive analysis to different oasis landscapes and their homologous water–energy balance relationship and proposed the concept of the "green degree" to assess stability evaluation and suitable oasis scales. In addition, a suitable farmland scale model had been established from the perspective of crop water footprint and water resources available in an oasis city [19]. Recently, Hao et al. [16] developed an approach for calculating oasis and cultivated land scales by combining water–energy balance and wind–sand dynamic theories with ecological health assessments in the Heihe River Basin.

Agricultural irrigation consumes the largest proportion of the water supply of an oasis, and the suitability of a cropland scale can directly affect the stability of an oasis. Previous research on stability evaluation and suitable oasis scales has generally neglected the impact of changes in planting structure and agricultural water consumption. Additionally, no relevant studies have been conducted on the Shule River Basin, which is adjacent to the Heihe River Basin. The Dunhuang Oasis, which is the study area of this research, is located west of the Shule River Basin and an important region along the Silk Road.

Similar to the case of the middle reaches of the Heihe River Basin, the Dunhuang Oasis also has a sharp contradiction of the water resource issue between the economy and the ecosystem. In the past decade, planting structures constantly changed with the expansion in oasis irrigation areas. Moreover, water exploitation and utilization rates reached nearly 100% in the oasis, in which agricultural water consumption accounted for nearly 90% of total available resources [20]. Hence, natural oasis ecosystems are unable to receive necessary water resources. Dunhuang City has proposed a water resource plan, namely, the "Comprehensive Planning of the Rational Use of Water Resource and Protection of Ecosystem Services in the Dunhuang Basin" [21] to improve the ecological environment of its natural oasis. The main purpose of this plan is to allocate large amounts of water resources to the natural oasis in the lower reaches of the Dunhuang Basin and leave only a limited amount of water for the irrigation district of the Dunhuang Oasis.

The objective of this study is to propose a novel research idea to evaluate the stability of the oasis and calculate the suitable oasis scale by combining water–energy balance with altered planting structures. First, this study evaluates stability during the long-term expansion process of the Dunhuang Oasis from 1987 to 2015. Next, it calculates a suitable oasis scale to a certain stability degree. Finally, it discusses to what extent the current water plan can improve the stability of the oasis and provides a scientific reference for the sustainable development of the oasis.

2. Materials and Methods

2.1. Study Area

The Dunhuang Oasis irrigation district is located east of Dunhuang City (92°13′–95°30′ N, 39°40′–41°40′ E) in Northwest China, with a total area less than 5% of that of the entire city (Figure 1). The Dunhuang Oasis irrigation district lies between the Mingsha Mountain (Echoing-sand Mountain) and the Sanwei Mountain in the southeast and the Mazong Mountain in the north and spreads into the

Gobi Desert in the west, thereby earning the name the “Gobi Desert Oasis”. The world famous Mogao Grottoes are located southwest of the Dunhuang Oasis. The elevation of the oasis ranges from 800 to 1500 m and is high in the south and low in the north. The oasis experiences the strong sunshine with the annual solar radiation reaches to 6418.4 MJ/m^2, and mean maximum and minimum temperatures are −28.6–43.6 °C. The oasis also experiences high evaporation, with the annual potential evaporation reaches 2486.0 mm, but the annual precipitation is only 39.2 mm. The Danghe River, which originates from the Qilian Mountain, provides the water resources for the oasis, and the Danghe River alluvial fan developed the oasis. The oasis consists mainly of gray brown desert, alkali saline, and irrigation desert soil (China soil science database, http://vdb3.soil.csdb.cn). According to the Dunhuang City National Economic Statistics Yearbook (1987–2015), spring wheat, melon, cotton, and grapes are the main crops planted in this area [22].

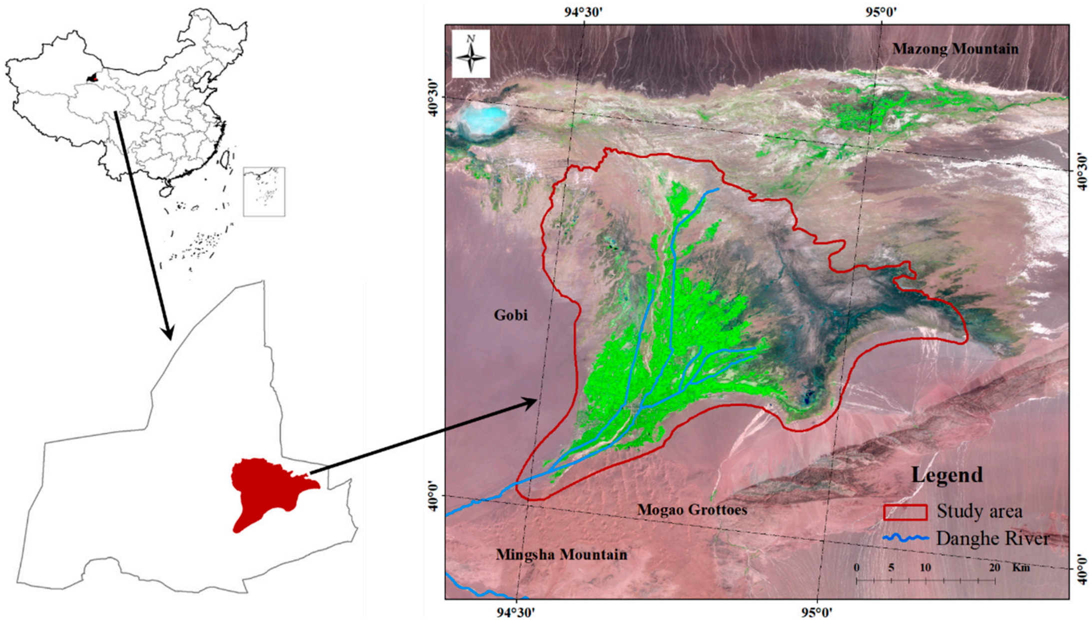

Figure 1. Study area derived by Landsat TM imagery (Bands 5-4-3).

2.2. Remote Sensing Image Data Processing

The high-quality remote images with a 30 m spatial resolution from Landsat TM (Thematic Mapper) were taken in low cloud covers during high biomass season, and all mage data were acquired from http://glovis.usgs.gov/ and http://www.radi.ac.cn/. We selected 1987, 1990, 1996, 2001, 2007, 2010, and 2015 to identify the actual irrigation district of the oasis using the software of ERDAS 9.1 and ArcGIS 10.3. Based on a 1:250,000 topographic map of the Dunhuang Oasis, all images were processed under the common universal transverse mercator coordinate system. A total of 50 uniformly distributed ground control points (e.g., roads and rivers) were used for geometric correction and georeferencing, and we used the quadratic polynomial transformation and nearest-neighbor resampling methods to identify ground control points in image-to-map rectification, the root mean square error of the geometrical rectification was less than one pixel. When the images were all ready, we divided the land use types into eight classes according to visual interpretation, namely, cropland, water, high-density grassland, medium-density grassland, low-density grassland, shrub land, urban construction land, and barren land. For verifying the result of visual interpretation, the field investigation points and corresponding interpretation results were compared, and the overall interpretation accuracy of land use classification in the 1987, 1990, 1996, 2001, 2007, 2010, and 2015 images was 80.91%, 84.96%, 79.85%, 79.69%, 84.98%, 85.79%, and 89.45%, respectively, which met the minimum accuracy requirement of 70% [23]. In this study, we used only the results of the cropland in the interpretation, as the scale of the oasis was mainly affected by the changes in the cropland. On the basis of the interpreted cropland data, we calculated the actual crop areas of crop food, cash food, and orchards by multiplying the crop food, cash food, and orchard area ratios in the Dunhuang City statistical yearbook [22] to determine the water consumption of each crop and orchard.

2.3. Water Consumption Data Analyses

In this study, water consumption denoted crop, domestic, and industrial water consumption.

2.3.1. Crop Water Consumption

The Food and Agricultural Organization (FAO)–Penman–Monteith methods were used to estimate reference crop evapotranspiration (ET_0), and multiplying by the crop coefficient (Kc) can get actual evapotranspiration (ET) as crop water consumption [24]:

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

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

Based on the above principle, ET_0 is computed using the CropWat 8.0 [25] tool after the monthly averages of minimum temperature, maximum temperature, humidity, wind speed, and sunshine hours are inputted.

The values of Kc vary with the crop development stages, and values of monthly Kc were adopted from FAO-56 [24] for spring wheat, cotton and grape. Adjustments to Kc mid in climates where RH_{min} differs from 45% or wher U_2 is larger or smaller than 2.0 m/s, were made by following the guidelines of Allen et al. [24]:

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

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

$K_{cmid(Tab)}$ is the tabulated Kc values in the mid-seasonof Table VI-12 of Allen et al. [24];
$K_{cend(Tab)}$ is the tabulated Kc values in the late-season of Table VI-12 of Allen et al. [24];
U_2 is wind speed at 2 m height over grass, the range is 1 m/ s ≤ U_2 ≤ 6 m m/s;
RH_{min} is daily minimum relative humidity, the range is 20% ≤ RH_{min} ≤ 80%;
H is mean plant height, the range is 0.1 m ≤ h ≤ 10 m.

This research considered the water consumption of vines. Figure 2 shows the adjusted K_C of wheat, cotton and grape. Compared with wheat and cotton, the K_C of grape is more complicated, and the values of the germination, growing season with shoots, flowering, and berry growing periods as well as berry and tendril maturation were 0.80, 1.09, 1.13, 1.07, 1.03, and 0.82, respectively.

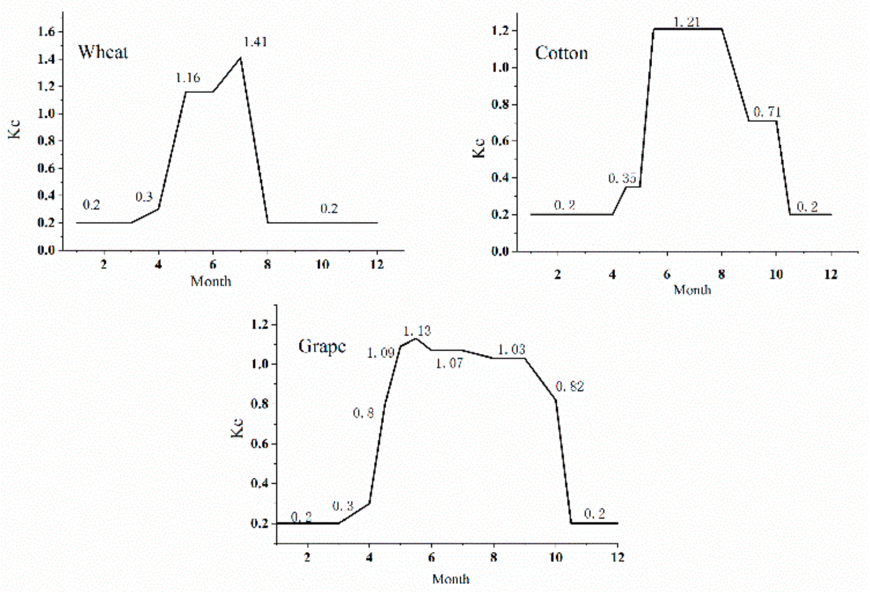

Figure 2. Crop evapotranspiration coefficients.

Actual ET rates of food crops and cash crops are estimated by Allen et al. [24]

$$\mathrm{ET} = \mathrm{ET}_0 \times \mathrm{K}_\mathrm{C} \tag{4}$$

2.3.2. Domestic Water Consumption

Domestic water consumption represented the water consumption of urban and rural populations, tourists, and livestock, which was positively correlated with living standards. It is defined as follows:

$$\mathrm{D} = (\mathrm{P}_1 \times \mathrm{C}_1 + \mathrm{P}_2 \times \mathrm{C}_2 + \mathrm{P}_3 \times \mathrm{C}_3 + \mathrm{P}_4 \times \mathrm{C}_4) \times 365 \times 10^{-8} \tag{5}$$

D is the total domestic water consumption (10^8 m^3);
P_1 is the amount urban population (10^8 m^3);
P_2 is the amount rural population (10^8 m^3);
P_3 is the amount tourists population (10^8 m^3);
P_4 is the amount livestock number (10^8 m^3, sheep unit);
C_1 is the average per capital water use coefficient of urban (L/day);
C_2 is the average per capital water use coefficient of rural (L/day);
C_3 is the average per capital water use coefficient of tourist (L/day);
C_4 is the average per capital water use coefficient of livestock (L/day);

The values for C_1, C_2, C_3 and C_4 (Table 1) are obtained from the literature for the four periods with different living standards: 1987–1990, 1991–2000, 2001–2007, and 2008–2015 [26].

Table 1. Water use coefficient.

Item	Coefficient				Unit
	1987–1990	1991–2000	2001–2007	2008–2015	
Urban resident water-use coefficient (C_1)	80	95	110	120	L/day
Rural resident water-use coefficient (C_2)	25	45	60	80	L/day
Tourist water-use coefficient (C_3)	100	250	400	400	L/day
Livestock water-use coefficient (C_4)	15	15	20	20	L/day
Industrial water-use coefficient (C_5)	215	205	185	180	m^3/10^4 RMB

2.3.3. Industrial Water Consumption

Industrial water consumption was affected by industrial output, technology, processes, and the amount of water used to create RMB 10,000 (Chinese currency) worth of industrial output. It is defined as follows:

$$P = \mathrm{Indo} \times C_5 \times 10^{-8} \quad (6)$$

P is the industry water use (10^8 m^3);
Indo is the industrial output (RMB);
C_5 is the amount of water used to create 10,000 RMB worth of industrial output ($m^3/10^4$ RMB).

The value for C_5 (Table 1) was also determined separately for the four periods with different living standards for the period of 1987–1990, 1991–2000, 2001–2007, and 2008–2015, respectively [26].

2.4. Oasis Stability and Suitable Oasis Scale Model

In this study, a stability index (H_0), which is based on the theory of ecological water–energy balance, was used to estimate the stability degree of the oasis under certain water resource conditions [18]. H_0 is the relative equilibrium analysis between water and energy conditions of the oasis, which can not only reflect ecological evolution and degradation from the internal perspective of the oasis but also the "green degree" or "stability degree" from the overall regional view point. The greater the H_0, the less affected the water stress and the higher the oasis stability, and vice versa. The formula is as follows:

$$H_0 = \frac{W_1 - W_2 + P \times \sum A_i}{ET_0 \times \sum A_i} \quad (7)$$

where A_i is the area of the land type (I = food crops, cash crops, and grapes; km^2), W_1 is the total available water volume of the river basin (10^8 m^3), W_2 is the annual average agricultural, industrial, and domestic water consumption, ET_0 is the reference crop evapotranspiration, and P is the annual average precipitation. The H_0 of the oasis was classified on the basis of the characteristics of the natural environment (Table 2).

Table 2. Classification of oasis stability.

H_0	Type	Evaluation of Exploration and Utilization
>0.75	Extremely stable	Has potential
0.50–0.75	Stable	Safeguarded; the oasis has limited developmental potential
0.20–0.50	Metastable	Does not have developmental potential
<0.20	Unstable	Reduced oasis scale

Based on the previous section, the calculation model of the suitable oasis scale (A) is

$$A = \frac{W_1 - W_2}{(ET_0 - P) \times k_p \times H_0^*} \quad (8)$$

where k_p is the comprehensive coefficient of plants in the oasis, which includes planting crops, trees, and grass. H_0^* is used to estimate the suitable oasis scale.

3. Results

3.1. Land Use/Land Cover Changes between 1987 and 2015

Figures 3 and 4 show changes in land use/land cover between 1987 and 2015. From Figure 3, we can deduce that the cropland area exhibited an expanding pattern, and the interpretation results demonstrate the total cropland area in the oasis was 272.69, 276.41, 295.33, 327.08, 371.40, 380.47, and

389.41 km^2 in 1987, 1990, 1996, 2000, 2007, 2010, and 2015, respectively. In terms of the temporal characteristics of land use/land cover changes, incremental rates from 1996 to 2007 more than doubled from 1987 to 1996 and from 2007 to 2015. With regard to spatial pattern, the cropland increased by 116.72 km^2. Growth is mainly attributed to its transformation from a grassland and a barren land in the fringe of the oasis [27] and to the continuously expanding urban construction land within the oasis.

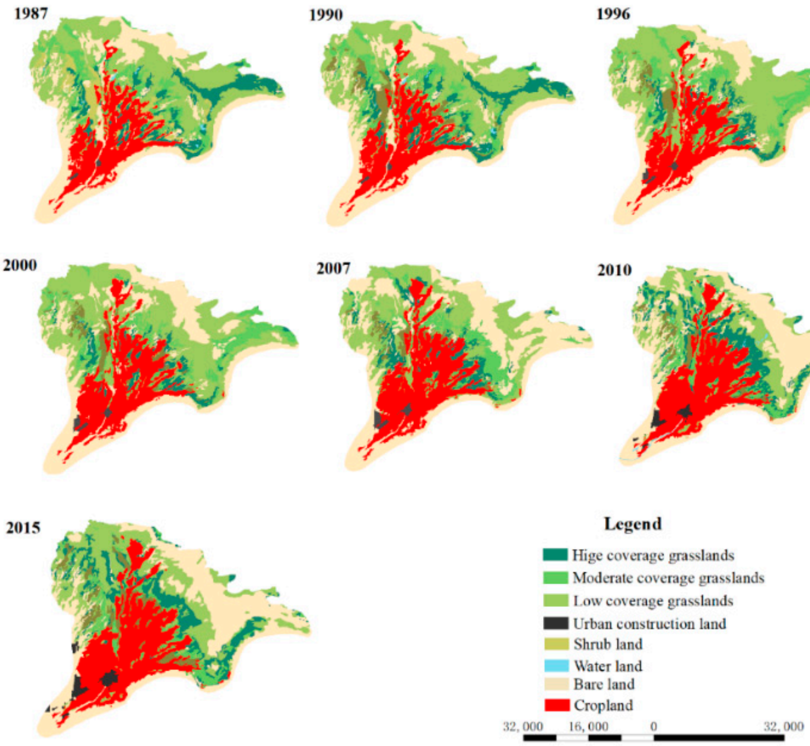

Figure 3. Land use/land cover spatial pattern from 1987 to 2015 in the Dunhuang Oasis.

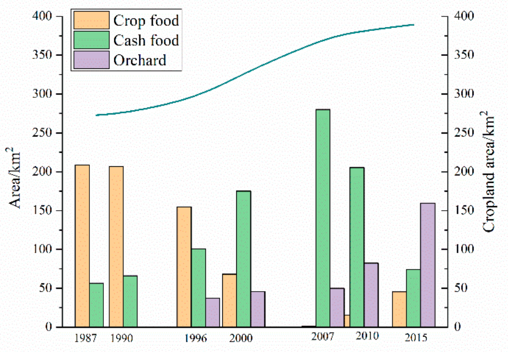

Figure 4. Planting structure changes in the Dunhuang Oasis.

The three different-colored bar charts in Figure 4 represent the crop areas of crop food, cash food, and orchards. The planting structure exhibited marked changes and even transformed during the 1987–2015 period. Specifically, (1) the crop food area decreased continuously from 1987 to 2007, and the crop food area in 2007 was only 1.61km^2, making it too small to display. Meanwhile, cotton was the main cash crop, which experienced a substantial increase owing to its high value. A distinct transformation in the food and cash crops from 1996 to 2000 can be observed, as the crop area of the cash crops gradually became larger than that of the food crops. In addition, the trial planting of grapes in the sandy soil region began in 1996. (2) In 2010, cotton areas gradually decreased, and grape orchards increasingly involved large-scale cultivation.

3.2. Water Consumption

3.2.1. Agricultural Water Consumption

Agricultural water consumption comprises the core section of the suitability evaluation of the oasis. In the Dunhuang Oasis, agricultural water consumption includes food crops, cash crops, and orchards. From 1987 to 2015, total water consumption increased initially from 2.293 × 10^8 m^3 in 1987 to 3.513 × 10^8 m^3 in 2007, then decreased to 2.902 × 10^8 m^3 in 2015 (Table 3). Listed individually in Table 3, food crop water consumption decreased sharply by 1.334 × 10^8 m^3 from 1987 to 2015. Meanwhile the water consumption of cash crops with high economic benefits progressively increased by 2.374 × 10^8 m^3 from 1987 to 2007 then began to decrease to 2.207 × 10^8 m^3 in 2010 and eventually decrease to a very low value of 0.774 × 10^8 m^3 in 2015. This trend in cash crop water consumption is closely related to that of grapes, which increased slowly before 2010 before rising rapidly.

Table 3. Agricultural water consumption in 1987–2015 (10^8 m^3).

Year	Food Crop	Cash Crop	Grape/Orchard	Sum
1987	1.727	0.566	0	2.293
1990	1.754	0.668	0	2.422
1996	1.300	0.984	0.389	2.673
2000	0.585	1.780	0.489	2.854
2007	0.015	2.940	0.558	3.513
2010	0.139	2.207	0.915	3.261
2015	0.393	0.774	1.735	2.902

3.2.2. Domestic and Industrial Water Consumption

Domestic and industrial water consumption should not be neglected in the suitability evaluation of the oasis. During the 1987–2015 period, the total population of the Dunhuang Oasis increased from 108,373 to 142,558, in which the rural population accounted for nearly 70% to 80%. Rural livestock increased from 349,820 sheep units in 1987 to 486,816 in 2015. In addition, the number of tourists increased from less than 100,000 in 1987 to 6,603,914 in 2015. Furthermore, industrial output increased by 84.6 × 10^8 RMB [22]. Thus, we can calculate overall domestic and industrial water consumption under increasing populations and the booming tourism industry. Table 4 shows that overall domestic and industrial water consumption rapidly increased from 0.038 × 10^8 to 0.219 × 10^8 m^3. The percentage of domestic and industrial water consumption in overall water consumption is very small.

Table 4. Domestic and industrial water consumption in 1987–2015 (10^8 m^3).

Year	Domestic	Industrial	Sum
1987	0.034	0.004	0.038
1990	0.036	0.007	0.043
1996	0.050	0.026	0.076
2000	0.045	0.045	0.09
2007	0.064	0.117	0.181
2010	0.075	0.116	0.192
2015	0.102	0.117	0.219

3.3. Oasis Stability Evaluation

In this study, the total available water volume originates from the Danghe River; thus, we use its perennial mean runoff, that is, 4.13 × 10^8 m^3, as W_1. From the above data, total available water quantity for the oasis in 1987, 1990, 1996, 2000, 2007, 2010, and 2015 was 1.79 × 10^8, 1.66 × 10^8, 1.37 × 10^8, 1.78 × 10^8, 0.43 × 10^8, 0.67 × 10^8, and 1.00 × 10^8 m^3, respectively. From the oasis stability evaluation, as shown in Equation (7), the H_0 of the Dunhuang Oasis were 0.54, 0.51, 0.41, 0.39, 0.15, 0.19, and 0.22 from 1987 to 2015 (Table 5).

Table 5. Stability of Dunhuang Oasis.

Year	P/(mm)	ET_0/(mm)	W_1-W_2 (10^8 m^3)	H_0
1987	43.80	1300	1.79	0.54
1990	45.60	1279	1.66	0.51
1996	40.20	1288	1.37	0.41
2000	36.70	1357	1.78	0.39
2007	87.40	1355	0.43	0.15
2010	50.90	1322	0.67	0.17
2015	31.40	1299	1.00	0.22

3.4. Suitable Oasis Irrigation District Scale

We take 2015 as an example and use Equation (8) to derive a suitable oasis irrigation district scale. Crops and natural vegetation are considered as having a common effect on kp, which is 0.72 [18], and the H_0^* is set as two values, namely, 0.5 for the stable level and 0.75 for the extremely stable level.

Table 6 shows that the suitable oasis irrigation district scale was smaller than the actual area in 2015. According to the water–energy balance model, the current oasis irrigation district scale should be reduced by 168 and 241 km^2 to attain stable to extremely stable levels, respectively.

Table 6. Suitable oasis irrigation district scales/km^2.

Year	H_0^* (0.5–0.75)	Status Quo 2015	Suitable Scale(A)/Km^2
2015	0.5 0.75	389	221 148

4. Discussion

The planting structure exhibited two marked changes. The first planting structure change happens between crop food and cotton. Except for cotton's high value and cultivation suitability, the rapidly increasing cotton lands, which were mainly attributed to farmers, had autonomy in terms of land use activities since the early 1980s under China's economic reform policy. Against this background, farmers envisioned market economy ideas, and production activities were closely associated with market demands. In addition, the trial planting of grapes in the sandy soil region began in 1996. The second planting structure change happens between cotton and grape; this is because of successful grape trial experiments in the sandy soil region, and from then on, a large number of farmers began to install grape trellises in fields previously planted with cotton or wheat. Hence, the planting structure of the oasis changed once again.

Although the total cropland area increased by 18.01 km^2 from 2007 to 2015, agricultural water consumption decreased by 0.611×10^8 m^3. This result may be beneficial to the transformation of crop patterns and water-saving irrigation measures. Traditional field canal irrigation was the primary irrigation pattern used in the past, but, from the beginning of 2010, advanced water-saving irrigation models, such as micro, pipe, and greenhouse micro irrigation, were implemented in the entire oasis.

Table 5 shows that stability was in a stable level in 1987 and 1990 owing to low agricultural, domestic, and industrial water consumption. During this period, though each industry was gradually developing, stability was not extremely stable, which may have been due to limited water resources. Farmers' enthusiasm for production and cropland areas increased under reform and opening-up policies, but irrigation measures were difficult. At the same time, tourism in the Dunhuang Oasis began to flourish. When the national economy improved, the stability of the oasis fell to a metastable level from 1996 to 2000 and reached a dangerously unstable level from 2007 to 2010. Water resource exploitation and utilization rates nearly reached 100% in the oasis, in which agricultural water consumption accounted for nearly 90% of overall available resources [27]. Serious ecological problems, such as accelerated desertification and salinization, shrunken terminal lake and declining groundwater level, accompany rapid economic development [27]. Water has become the primary restricting and bottleneck factor in the socioeconomic development of the Dunhuang Oasis.

In this case, a series of water resource plans was implemented to address this issue, in which the most important program "Comprehensive Planning of the Rational Use of Water Resource and Protection of Ecosystem Services in the Dunhuang Basin" was proposed. This program aims to reduce the croplands of state farms, implement agricultural water-saving measures, and carry out a water diversion project from the Sugan Lank Basin to the Danghe River. Approximately 0.835×10^8 m^3 of water allocated from the water diversion project is intended for the improvement of the ecological environment, which plays a crucial role in alleviating the water crisis by increasing groundwater levels and recovering the vegetation in marginal areas of the oasis [20]. The system dynamic model simulated the agricultural water consumption under different scenarios in the Dunhuang Oasis and shows that the proportion of agricultural water consumption in overall water consumption can be reduced from 92.50% in 2010 to 86.30% in 2025 [20], but, if reduced by 168 km^2, to attain a stable level, the agricultural water consumption should be decreased to at least half of what it is now. In this study, the suitable oasis area is far less than the actual area, which is a common issue in the Endorheic watershed oasis in Northwest China [2,16,28]. Reducing cropland in the oasis is the most direct and effective means, which is difficult to achieve. Specifically, individual croplands in the Dunhuang Oasis should be reduced to preserve the ecological environment. However, several reasons highlight the difficulty of this solution. (1) The reduction of croplands will harm the economic interests of farmers and subsequently decrease their quality of life. Thus, the possibility of criminal problems due to poverty should be considered. (2) The reduction of croplands is not in line with the Chinese policy of farmland protection. Hence, only on the basis of maintaining water-saving irrigation, reducing domestic water consumption, improving industrial water consumption efficiency, forbidding sprawl inside and outside the oasis, and increasing the amount of water allocated to the oasis from the water-transfer project, can the stability of the oasis be improved and the sustainable development of the regional economy and ecology be maintained.

5. Conclusions

This study analyzed the stability of the Dunhuang Oasis against the background of planting structure changes during the 1987–2015 period. Our main findings and recommendation are as follows:

1. From 1987 to 2015, the oasis irrigation district area expanded internally and externally, and, at the same time, the planting structure underwent a marked transformation, from food crops to cash crops to orchards. In the Dunhuang Oasis, the structure of croplands might be quickly and flexibly changed according to economic perspective and visions and policy reforms
2. In the Dunhuang Oasis, agricultural water consumption is mainly for food crops, cash crops, and orchards. From 1987 to 2015, food crop water consumption decreased sharply by 1.334×10^8 m^3, cash crop water consumption (cotton) first increased by 2.374×10^8 m^3 and then decreased substantially, and grape water consumption was closely related to that of cotton, which increased slowly in 2010 before rising rapidly.
3. The Dunhuang Oasis was at a stable level in 1987 and 1990 but gradually declined until it reached a dangerously unstable level in 2010. Meanwhile, serious ecological problems emerged one after the other. Against the background of water-saving measures and the water-transfer project, the stable level of the oasis increased to a metastable level of 0.22 in 2015.
4. The oasis irrigation district should be reduced by at least 168 km^2 to reach a suitable scale. However, this goal does not facilitate the improvement of the living standards of farmers and is not in line with the Chinese policy of farmland protection. Hence, the most practical way at present is to increase allocated water resources from the water-transfer project to the oasis irrigation district.

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