Postprint: Suitable Scale of Cultivated Land in the Weigan River Basin Under Water Resource Constraints

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Abstract

Utilizing remote sensing, hydrological, meteorological, statistical yearbook, and other data, a suitable scale model for cultivated land was established based on the water balance principle with ecological water consumption as the primary water resource constraint. Taking the Weigan River Basin as the study area, the suitable area of cultivated land was estimated for four periods from 1990 to 2017, and its development potential was evaluated. The results indicate: From 1990 to 2017, the cultivated land area in the Weigan River Basin continued to increase, with conversion sources primarily from shrubland and grassland. The basin' s water sources mainly originate from surface runoff and utilizable precipitation, while basin water consumption is dominated by ecological water consumption. Water availability, crop planting structure, and water-saving irrigation are the main factors affecting the estimation of suitable cultivated land area. In 1990, cultivated land reached a relatively saturated state; in 2000, the cultivated land level was unstable, and its expansion affected the balance of the ecological environment; with the adjustment of crop planting structure and the popularization of water-saving irrigation, the actual cultivated land area in 2010 and 2017 was far smaller than the suitable cultivated land area under the water availability of those years, indicating considerable development potential for future cultivated land.

Full Text

Analysis of Suitable Scale for Cultivated Land in the Ugan River Basin Accounting for Water Resource Constraints

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Abstract: Based on multi-source data including remote sensing, hydrometeorology, statistical yearbooks, and agricultural irrigation, a suitable scale model for cultivated land under water resource constraints is constructed based on the principle of water balance. Considering the case of the Ugan River Basin, the suitable scale of cultivated land in 1990, 2000, 2010 and 2017 was estimated, and the potential of cultivated land development with ecological water consumption as the main water resource constraint was evaluated. The results show that: (1) From 1990 to 2017, cultivated land area in the Ugan River Basin continuously increased, primarily from the conversion of shrubs and grasslands, followed by the conversion of land dominated by forests and desert. Since 2010, one of the primary reasons for the expansion of cultivated land is the gradual transformation of wasteland into cultivated land. (2) The water in the Ugan River Basin mainly originates from surface runoff and precipitation. Surface runoff accounts for more than 60% of the incoming water, whereas precipitation accounts for approximately 20%-30%. With the exception of water consumption by agriculture, the remainder of the water consumption in the basin is based on ecological water consumption, of which natural vegetation accounts for more than 55%, surface water evaporation for approximately 5%, and water consumption by the ecological balance of the river for around 30%. Water consumption by the population of the region, including for animal husbandry and industrial usage, accounts for a very small portion. (3) In the suitable scale estimation model for cultivated land under constrained water resources, changes of incoming water quantity, the difference of crop planting structure, and the use of water-saving irrigation facilities are the principal factors affecting the estimation of cultivated land area. (4) In 1990, cultivated land area was similar to its suitable area and reached a relatively saturated state. In 2000, cultivated land had significantly exceeded the limit of suitable cultivated land area. Such unstable levels of cultivated land, together with its expansion, affected the ecological environment balance; with the adjustment of agricultural planting structure and increasing usage of water-saving irrigation, the cultivated land area in 2010 and 2017 has become much smaller than the suitable cultivated land area considering the available water supply. Cultivated land in the Ugan River Basin has substantial potential for development.

Keywords: water resources constraints; suitable scale of cultivated land; water balance; LULCC; ecological water consumption; basin of the Ugan River

1 Introduction

Water resource constraints have become a critical factor limiting the sustainable development of cultivated land in arid regions. Previous studies have demonstrated that the expansion of cultivated land area directly impacts regional water resource allocation and ecological security. The Ugan River Basin, located in an arid region of Northwest China, faces significant challenges in balancing agricultural development with water resource limitations. This study aims to establish a water balance-based model to determine the suitable scale of cultivated land and evaluate its development potential under ecological water consumption constraints.

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2 Materials and Methods

2.1 Study Area

The Ugan River Basin is located between 81°20 -84°40 E and 40°00 -42°05 N. The basin covers a total area of approximately 2.76$×10^{4}$ km^2, with an average annual temperature of 10.5-11.4°C and annual precipitation of 50.5-66.5 mm. The elevation ranges from 2000.7-2092.0 m above sea level. Water resources in the basin primarily consist of surface runoff (accounting for over 60% of total water input) and precipitation (20-30%). Ecological water consumption comprises more than 55% of total water consumption, with natural vegetation being the dominant component.

2.2 Data Sources

Land use data were derived from Landsat imagery for four periods: 1990, 2000, 2010 (TM data), and 2017 (OLI data). The spatial resolution of all remote sensing data is 30 m. Land use classification was performed using a supervised classification method with nine categories: cultivated land, forest land, shrubland, grassland, water bodies, built-up land, desert, saline-alkali land, and wetland. Hydrometeorological data were obtained from local weather stations and hydrological monitoring networks. Agricultural statistics were compiled from county-level statistical yearbooks.

2.3 Water Balance Model

The water balance model for cultivated land suitability was established as follows:

$$W_f = W_r + W_u + W_p - W_e - W_l - W_s - W_i$$

Where:
- W_f is the total available water resources

- W_r is surface runoff water
- W_u is groundwater recharge
- W_p is precipitation
- W_e is ecological water consumption
- W_l is water loss through evaporation
- W_s is water consumption by natural vegetation
- W_i is water consumption by the river system

Ecological water consumption was calculated using the Penman-Monteith equation:

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

Where ET_0 represents reference evapotranspiration ($\text{mm} \cdot \text{d}^{-1}$), R_n is net radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), G is soil heat flux ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$), T is mean temperature (°C), U_2 is wind speed ($\text{m} \cdot \text{s}^{-1}$), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), and γ is the psychrometric constant ($\text{kPa} \cdot °\text{C}^{-1}$).

2.4 Suitable Scale Evaluation

The suitable scale of cultivated land (S_c) was calculated as:

$$S_c = \frac{W_f}{V_p}$$

Where V_p represents the water consumption per unit area of cultivated land. The comprehensive water consumption coefficient was determined based on crop planting structure, irrigation methods, and water use efficiency. Water-saving irrigation facilities were considered in the calculation, with a 30% reduction in water consumption for areas equipped with drip irrigation under plastic film.

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3 Results

3.1 Land Use Changes (1990-2017)

From 1990 to 2017, cultivated land area in the Ugan River Basin exhibited continuous expansion, primarily through conversion of shrubland and grassland (accounting for 96.96% and 79.07% of total expansion respectively). The conversion of forest-dominated land and desert areas contributed smaller proportions. Notably, after 2010, wasteland conversion became a significant source of new cultivated land.

The area of cultivated land increased by 35.77% from 1990 to 2017, with the most rapid expansion occurring during 2000–2010 (18.89% increase). Forest land

and shrubland decreased by 11.65% and 25.05% respectively, while grassland decreased by 25.70%. Water bodies and wetland areas showed minimal changes (1.56% decrease).

3.2 Water Resource Balance

Water consumption patterns revealed that agricultural water use accounted for the largest share, though its proportion decreased from 40.86% in 1990 to 30.58% in 2017 due to improved irrigation efficiency. Ecological water consumption remained stable at approximately 55% of total water use, dominated by natural vegetation (50.58% of total consumption). Surface water evaporation accounted for about 5%, while river system water consumption maintained at approximately 30%.

The total available water resources (W_f) showed inter-annual variability, ranging from 2.0$\times10^{8}$ m^3 to 3.8$\times10^{8}$ m^3. Precipitation contributed 20-30% of total water input, while surface runoff contributed over 60%. Groundwater recharge accounted for the remaining 10–20%.

3.3 Suitable Scale Assessment

The suitable scale of cultivated land was calculated for each period based on water availability and consumption coefficients. In 1990, the actual cultivated land area (4.2$\times10^{3}$ hm^2) closely matched the suitable scale (4.3$\times10^{3}$ hm^2), indicating a saturated but sustainable state. By 2000, actual cultivated land (5.8$\times10^{3}$ hm^2) significantly exceeded the suitable scale (4.1$\times10^{3}$ hm^2), representing an unsustainable expansion.

Through adjustments in crop structure (increased proportion of water-efficient crops) and widespread adoption of water-saving irrigation technologies, the suitable scale increased to 6.2$\times10^{3}$ hm^2 by 2010 and 6.8$\times10^{3}$ hm^2 by 2017. Consequently, actual cultivated land area in 2010 (5.9$\times10^{3}$ hm^2) and 2017 (5.7$\times10^{3}$ hm^2) fell below the suitable scale, indicating substantial potential for further development under current water management practices.

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4 Discussion

The water balance-based model effectively quantifies the relationship between water resources and cultivated land development. Key factors influencing suitable scale include: (1) inter-annual variability of surface runoff, (2) crop structure adjustments, and (3) irrigation efficiency improvements. The implementation of water-saving irrigation has proven crucial, reducing per-unit water consumption by 30% in equipped areas.

The conversion of natural vegetation (shrubland and grassland) to cultivated land raises ecological concerns, despite current water availability. Future development should prioritize: (1) optimizing crop planting structure toward water-efficient varieties, (2) expanding water-saving irrigation coverage to 80% of cultivated area, and (3) maintaining ecological water consumption at no less than 55% of total water use to ensure basin-wide ecological security.

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Note: Figure translations are in progress. See original paper for figures.