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Optimizing the Cropland Fallow for Water Resource Security in the Groundwater Funnel Area of China

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Abstract: Excessive exploitation of groundwater for agricultural irrigation has resulted in groundwater funnel, causing land subsidence, water pollution, and vegetation degradation. The cropland fallow is an effective tool to maintain groundwater by reducing water consumption from agricultural irrigation. However, the cropland fallow program of fallow areas and fallow locations based on the protection of water resources at county level is unclear. The objective of this study is to improve the efficiency of cropland fallows under the premise of ensuring regional food security. In this study, we assessed the fallow urgency using IPLI (irrigation profit/loss index) and SGDCR (shallow groundwater depth change rate) and analyzed the cropland fallow areas and cropland fallow locations in Quzhou County, which is located in the world's largest groundwater funnel area. The results showed that winter wheat's irrigation water is in short supply (IPLI value is 0.1173), while that of summer maize and cotton's irrigation water are in excessive supply (−0.9849 and −0.0071, respectively), and the depth to groundwater is deeper in the south and east in Quzhou County. The GM (1,1) gray prediction model showed that the cropland area that can be fallowed is 4089.288 hm^2, 1189.288 hm^2 larger than the current cropland fallow area (2900 hm^2) according to official figures. In addition, two townships in southeast Quzhou county (Yizhuang and Houcun town) should be given high priority for cropland fallow; this is different from the current fallow cropland plots, distributed in eight townships (Yizhuang, Houcun, Nanliyue, Huaiqiao, Disituan, Henantuan, Baizhai, and Quzhou town). These results were useful to improve the cropland fallow program with the actual needs of the groundwater funnel area and develop the cropland fallow program from the aspects of "quality", "quantity", and "positioning" at county level.

Keywords: county level; water security; cropland fallow; fallow program; groundwater funnel area; Quzhou county

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1. Introduction

The global water demand has tripled since the 1950s, but the availability of fresh water has been declining [1]. Water scarcity can reduce crop yields and adversely affect food security [2]. Irrigated agriculture is the main consumer of water resources, accounting for about 80% of global water use [3,4]. Many of the world's major aquifers that support irrigated agriculture are being depleted at a rapid rate [5,6]. Long-term overexploitation of groundwater leads to a decline in the regional groundwater level, land subsidence, and seawater intrusion. The confined water is a non-renewable resource, which is difficult to recover in a short time [7,8]. Therefore, it is urgent to take actions to deal with the problem of groundwater overexploitation.

The cropland fallow is a favorable measure to solve the problems of overexploitation of groundwater. It performs well in effective environmental conservation with lower cost compared with other land protection measures [9]. Many research works have shown

that the fallow cropland can regulate grain yield, improve soil nutrient content, conserve water sources, and enhance cropland productivity [10–13]. Cropland fallow policy is a useful way to ensure the effect of cropland fallow [14]. For example, the United States implemented a land fallow protection plan (Conservation Reserve Program, CRP) in the 1930s and the European Union (EU) implemented a voluntary cropland fallow project in the 1980s [15,16]. These projects aim to address the problem of food overproduction and low farmer incomes. However, little attention has been paid to formulating policies for mitigating over-extraction of groundwater.

The North China Plain (NCP) is an important production area for winter wheat and summer maize, which plays an important role in food security of China. In the meanwhile, it became the world's largest groundwater funnel area in 2011 [17–19]. The water consumption of winter wheat and summer maize is approximately 400 mm and 500 mm, respectively, more than the annual precipitation of NCP (630 mm) [20,21]. Xu et al. (2005) showed that irrigation demand of agricultural water is the main reason for the decline in groundwater [22]. Thus, decreasing the consumption of groundwater while ensuring food security has become a great challenge. A series of policies and laws about the cropland fallow have been introduced successively in China to solve this problem. In 2014, the "No. 1 central document" proposed to carry out cropland fallow pilot projects and NCP was selected as one of the pilot areas. In November 2015, the government formulated the land fallow policy to support the socio-economic development in the upcoming Thirteenth Five-Year Plan [23]. With the implementation of the fallow policy, a growing number of studies were conducted to reveal farmers' responses to fallow policy, irrigation strategy optimization, and the impact of the fallow policy on groundwater or food security [23–25]. For example, Xie et al. (2018) discussed the farmers' responses and the influencing factors for the winter wheat fallow policy in the Hebei groundwater funnel area of China and showed that the proportion of farmers and per capita area of cropland had a significant impact on support for the fallow policy [24]. The results of Ti et al. (2021) showed that the winter fallow acreage should be expanded to maintain the groundwater table [19]. However, the research on the selection of the fallow location in areas where groundwater is overexploited is relatively lacking.

Quzhou County is a typical agricultural production area in the North China Plain, where the average annual groundwater overexploitation is 1.64×10^7 m^3 [26]. The fallow pilot area has increased from 666.67 hm^2 in 2014 to 2900 hm^2 in 2019 under the support of national policies in Quzhou County [27]. The implementation of the cropland fallow pilot program was expected to have a positive impact on reducing the consumption of groundwater resources by agricultural irrigation. However, the groundwater level monitoring data showed that the groundwater level did not rise significantly, but continued to fall downward, indicating the poor effectiveness of current fallow cropland [28]. Therefore, it is urgent to identify the reasonable fallow areas and establish a scientific fallow program based on the groundwater severity. Thus, this study aims to (1) analyze fallow urgency using IPLI and SDGCR indicators and quantify the fallow area at county level and (2) analyze the matching situation between the current fallow land and the predicted fallow land.

2. Materials and Methods

2.1. Study Area

Quzhou County is a typical plain county, located in the southern part of the Hebei Province (114°50′30″ E–115°13′30″ E, 36°34′45″ N–36°57′57″ N) with a total land area of 676.68 km^2, of which the agricultural land area is 560.47 km^2 (Figure 1). Within the agricultural land area, cropland accounted for 93.71%. The average annual precipitation in Quzhou is 525.4 mm. Rivers include the Fuyang River (natural river), the Zhizhang River (artificial river channel), and the Laosha River (artificial river channel). Quzhou county has 6 towns and 4 townships, including 342 administrative villages and 338 villages.

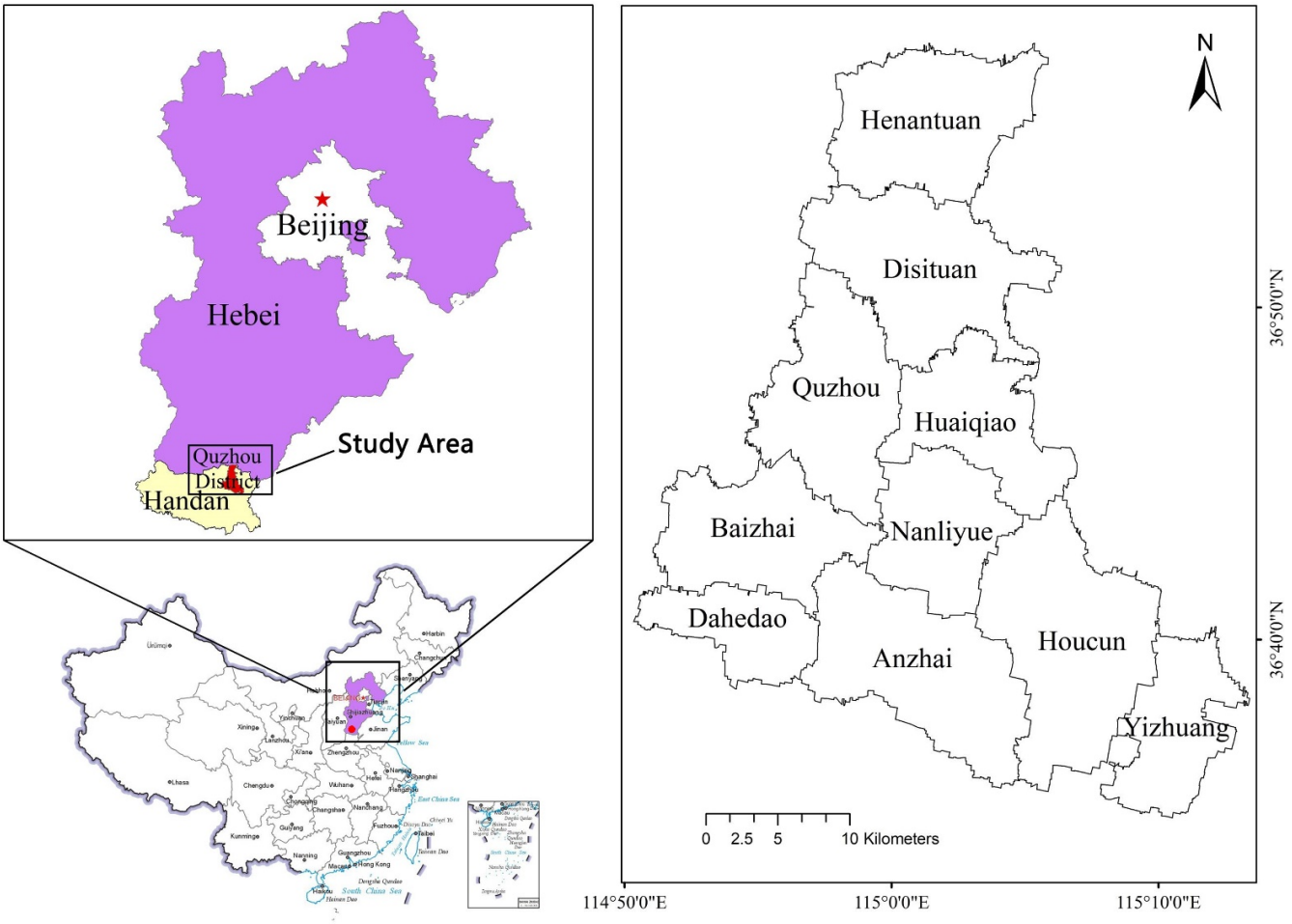

Figure 1. Location of Quzhou County in Hebei Province, China. Note: This map of China is from the standard map system of the Ministry of Natural Resources of China.

Winter wheat and summer maize are the main crops in Quzhou county. Cropland irrigation accounts for 80% of the total water consumption in Quzhou County and 80% of the irrigation water comes from groundwater. The average groundwater overexploitation in Quzhou County is 1.640×10^7 m^3 every year. Relevant studies show that the groundwater in the North China Plain had been declined from 1980 to 2020, during which the shallow groundwater level has decreased by 20–60 m and the deep groundwater level has decreased by 40–90 m [29]. The characteristics of groundwater dynamic variation show that the variation in groundwater potential is mainly affected by seasonal agricultural irrigation and exploitation. Since 2014, the measures, such as groundwater over-extraction control, south-to-north water diversion, ecological water replenishment of rivers and lakes, and agricultural water saving, have achieved initial results, which alleviated the declining trend of groundwater levels in urban areas. However, agricultural areas still have a downward trend because water is still needed for irrigation. Therefore, the groundwater level has dropped sharply and the dropping groundwater funnel has continued to expand.

2.2. Study Framework

This article defines the connotation of the cropland fallow program for water resources' security as follows. In a certain area, with the continuous development of the social economy and the continuous changes in the demand for resources of human production and life, the quantity, quality, and ecology of regional cropland resources and water resources are impacted. To ensure the sustainable development of the region, relevant measures are taken to improve and restore the problems faced by cropland resources and water resources.

Cropland and water resources are the material basis of socio-economic development and human life. Meanwhile, human activities consume and utilize cropland and water resources to promote socio-economic development, which forms an organic whole where "cropland–water–human–environment" interact with each other. However, it is also necessary to take corresponding measures to ensure the normal operation of the ecosystem when cropland and water resources cannot meet the requirements of socio-economic development and humans. Thus, we should correctly understand the impact of cropland resources and water resources owing to socio-economic development, human production, and living in the study of the fallow program. In addition, we must clarify the regulation mechanism of cropland fallow and water resource conservation and seek scientific and reasonable methods to regulate cropland and water resources, in order to realize the sustainable utilization of the resources.

This study aims to explore the cropland fallow program for water security, which mainly includes the fallow urgency of cropland, the cropland fallow area, and cropland fallow location. The theoretical framework for the study of the fallow program for water resource security is shown in Figure 2.

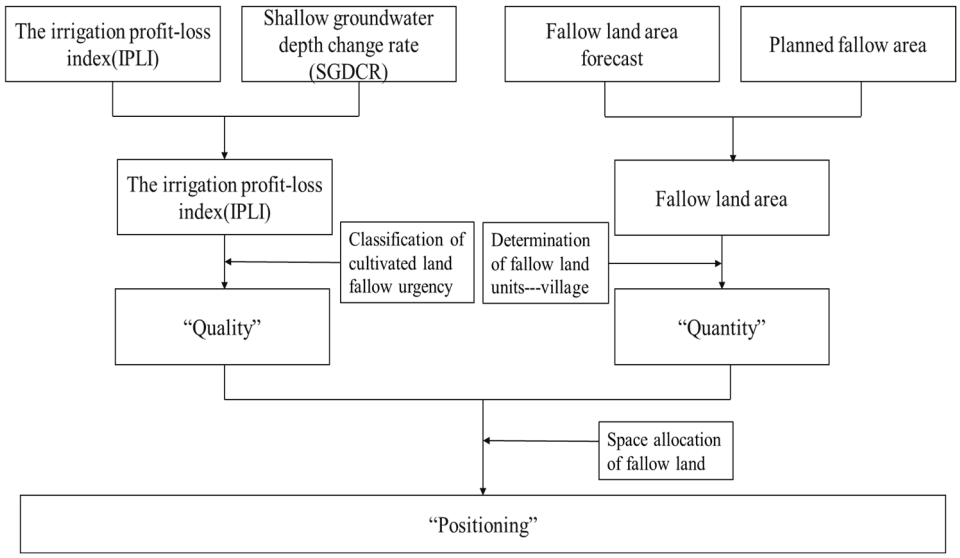

Figure 2. The overall framework of the study.

First, the irrigation profit/loss index (IPLI) and the shallow groundwater depth change rate (SGDCR) are used to obtain the urgency of fallow cropland, which is divided into five levels to achieve the "quality" of the cropland.

Second, based on the specific conditions and regional food security of the study area, the area of fallow cropland is determined, then this area is compared with the planned cropland fallow area to obtain the maximum potential scale of fallow land to determine the "quantity" of fallow cropland.

Third, by combining the results of the urgency of cropland fallow and the planned area of fallow cropland, the village unit is selected to realize the spatial "positioning" of the fallow cropland.

2.3. Data Sources and Processing

2.3.1. Data Sources

The groundwater monitoring data originate from the Quzhou County Water Conservancy Bureau and primarily include the groundwater test data (2013–2018) from typical stations in Quzhou County. The data of the cropland area, irrigated land area, population, total grain output, sown area of grain crops, and total sown area were derived from the "Quzhou County Statistical Yearbook (2013–2018)". Quzhou County's average precipitation per year and precipitation effective recharge coefficient are derived from Quzhou

County Water Resources Evaluation. The data of the main crop evapotranspiration come from the research results published in this research area. The map of the Quzhou County administrative district is from the Resource and Environmental Data Cloud Platform of Chinese Academy of Sciences "http://www.resdc.cn/ (accessed on 6 June 2022)".

2.3.2. Data Processing

(1) Monitoring point vectorization. According to the coordinates of the known monitoring sites, the points are converted into decimal coordinates and then imported into ArcGIS 10.4 for conversion of the point files into shape format; the geographic coordinate system and projected coordinate system are defined; then, the data are saved as vector point data.

(2) Data space interpolation. Thirty-three shallow groundwater monitoring sites are introduced in ArcGIS 10.4, and the shallow groundwater depth is spatially interpolated using the Kriging spatial interpolation method to obtain the shallow groundwater depth distribution in different areas of Quzhou County.

(3) Database construction. ArcGIS 10.4 is used to establish a spatial database and the spatial coordinate system format of each layer is unified (Geographic Gauss_Kruger, Xian_1980_3_Degree_GK_Zone_38), which is convenient for spatial superposition analysis, and the data of cropland area, cropland quality, groundwater depth, and so on are integrated to form a comprehensive attribute database.

(4) The value of main crop evapotranspiration. To reduce the error, we choose the average of empirical values as the evapotranspiration value of the main crops in this article.

2.4. Methods

2.4.1. Fallow Urgency

The resource constraints in this paper refer to shallow groundwater resources. Considering the regional characteristics and data availability, we introduce the IPLI and SGDCR as evaluation indexes to evaluate the potential ecological resilience of cropland under groundwater resource constraints. More importantly, these indexes can reflect the urgency of fallow cropland.

Evaluation of Potential Ecological Resilience of Cropland

① The irrigation profit/loss index (IPLI)

The IPLI is an indicator reflecting the relationship between irrigation water use and irrigation water demand during a crop's growth period. The IPLI can be calculated using the following formula:

$$R = \frac{W_s - W_r}{W_r} \quad (1)$$

where R represents IPLI and W_s and W_r represent the irrigation water requirement (m^3) and the actual irrigation water consumption (m^3) in the study area, respectively. If $R > 0$, this indicates that the regional irrigation water cannot meet the crop water demand, and the total water supply is insufficient; if $R < 0$, this indicates that the regional irrigation water exceeds the actual irrigation water demand, and the supply of crop irrigation water exceeds the demand, resulting in wasting of water resources; and, if $R = 0$, this shows that the regional irrigation water just meets the actual irrigation demand, and the water supply is balanced. In fact, the amount of irrigation water needed and the actual irrigation water in a certain area are not typically equal. Therefore, when the value range of $[W_s - W_r]$ is set to $[-1, 1]$, $R = 0$ is considered.

The regional irrigation water demand and the actual irrigation water consumption are determined by the planting area of the main crop and the irrigation water consumption of the crop. The formulations of W_s and W_r are as follows:

I. The irrigation water requirement of crops (W_s)

The irrigation water requirement of crops refers to the difference between the water demand and effective precipitation during a crop's growth period. This value can be used

as an evaluation index of the balance between the water supply and demand during the growth period of crops, which can reflect whether the crop needs irrigation during the growing period. The irrigation water requirement is calculated as follows:

$$W_s = ETc - P_e \quad (2)$$

where W_s, ETc, and P_e represent the irrigation water requirement (mm) during the whole growth period of the crop, the water requirement (mm) during the whole growth period, and the effective precipitation (mm), respectively.

In this study, the crop water requirement is calculated by multiplying the water demand of the reference crop with the crop coefficient; the effective precipitation refers to the amount of precipitation out of the total precipitation that can be stored in the main crop's water absorption layer. The calculation formulas are as follows:

$$ET_c = K_c \times ET_0 \quad (3)$$

$$P_e = \sum_{i=1}^{n} P_{ei} \times \sigma_i \quad (4)$$

where ET_c represents the crop water requirement (mm); K_c represents the crop coefficient (Liu et al., 2000); P_e represents the total effective precipitation (mm) during the entire crop growth period; P_{ei} represents the total precipitation (mm) of the i-th precipitation; and σ_i represents the effective utilization coefficient. When $P_{ei} > 50$ mm, $\sigma_i = 0.75$; when 5 mm $\leq P_{ei} \leq 50$ mm, $\sigma_i = 0.9$; and when $P_{ei} \leq 5$ mm, $\sigma_i = 0$; ET_0 means crop evapotranspiration (mm/d) and we use the Penman formula, which has more extensive and higher precision, in the calculation.

According to the survey and official documents, the main food crops in Quzhou County are wheat, maize, and cotton, and the sown area accounts for 81.8% of the total cropland "http://www.qzx.gov.cn/xxgk-show-102.html (accessed on 9 June 2022)". The irrigation water requirements of the main crops are calculated and shown in Table 1.

Table 1. Irrigation water consumption of the main crops in Quzhou County.

Main Crop	Growing Season	Water Requirement during the Full Growth Period (mm)	Effective Precipitation during the Whole Growth Period (mm)	Water Demand for Irrigation (m^3/hm^2)
Winter wheat	October–June	499.9	122.79	3771
Summer maize	June–September	357.6	355.86	17
Cotton	April–October	502.2	390.54	1117

Note: The author's calculation is based on survey data.

II. Irrigation water consumption of crops (W_r)

Based on surveys of Quzhou County, we find that the main crops are winter wheat, summer maize, and cotton. The irrigation times of winter wheat are 4~5, while the times of summer maize and cotton range from 1 to 2, respectively, and the single irrigation amounts of winter wheat, summer maize, and cotton are 600~900 m^3/hm^2 [30]. To facilitate calculation and reduce errors, the number of irrigations and the irrigation amounts are intermediate values. The irrigation water consumption of the main crops in Quzhou County is shown in Table 2.

Table 2. Irrigation water consumption of the main crops in Quzhou County.

Main Crop	Number of Irrigation Times	Volume of Water Irrigation (m^3/hm^2)
Winter wheat	4.5	3375
Summer maize	1.5	1125
Cotton	1.5	1125

Note: The author's calculation is based on survey data.

② Shallow groundwater depth change rate (SGDCR)

The change rate of shallow groundwater depth reflects the variation in shallow groundwater per unit time, and the numerical value has an important impact on the ecological resilience of the regional cropland. To a certain extent, SGDCR can reflect the local farmers' utilization of groundwater resources. When groundwater resources are overutilized or even depleted, the primary dynamics of the sustainable development of cropland are destroyed and sustainable development cannot be achieved, which indicates that SGDCR affects the potential ecological resilience of cropland. The calculation formula is as follows:

$$V_{ij} = \frac{\Delta h_{ij}}{\Delta t_{ij}} \tag{5}$$

where V_{ij} represents SGDCR from the i-th year to the j-th year (m/a); Δh_{ij} represents the change in shallow groundwater depth from the i-th year to the j-th year (m); and Δt_{ij} indicates the time interval from the i-th year to the j-th year. When $\Delta h_{ij} > 0$, this means that the shallow groundwater depth increases from the i-th year to the j-th year. At this time, the larger the V_{ij}, the more quickly the shallow groundwater depth will become shallower; when $\Delta h_{ij} = 0$, this means that the shallow groundwater depth did not change from the i-th year to the j-th year; when $\Delta h_{ij} < 0$, this indicates that the shallow groundwater depth decreased from the i-th year to the j-th year and, the larger the $|V_{ij}|$, the faster the shallow groundwater depth drops.

Cropland Fallow Urgency

The urgency of fallow cropland is related to the potential ecological resilience of cropland. The potential ecological resilience of cropland is mainly related to the IPLI and SGDCR. The urgency formula for fallow cropland is as follows:

$$\mathrm{U} = \left[R, V_{ij}\right] \tag{6}$$

where U represents the degree of urgency of fallow cropland and $\left[R, V_{ij}\right]$ represents the spatial superposition relationship.

Method for Dividing the Degree of Fallow Land Urgency

We divide the grading degree of fallow land into three major steps. First, according to the area ratio of winter wheat, summer maize, and cotton in each township, the IPLI of the main crops is converted for each township. Then, the overlay analysis tool in the spatial analyst module of ArcGIS 10.4 is used to spatially superimpose the IPLI and SGDCR and obtain the urgency degree of the cropland fallow. Finally, the urgency of fallow land is reclassified using the reclassification tool, and the natural breakpoint method is used to divide the fallow land into five levels, with the level 1 fallow area representing the strongest urgency of fallow.

2.4.2. Fallow Area

Cropland is the foundation of social-economic-ecological health and sustainable development, which ensures regional food security and sustainable economic and social development. The scale of cropland in Quzhou County is predicted in this paper, and this scale is compared with the scale of fallows issued by leaders to explore the rationality of

the scale of cropland fallow under current policy guidance. We use 2014 as the base year and 2018 as the target year to predict the target year's cropland fallow scale and compare it with the fallow quota issued by leaders in 2018. The fallow scale prediction model is as follows:

$$Q = Q_m - Q_n \tag{7}$$

where Q represents the theoretical cropland fallow scale, Q_m represents the scale of cropland in the base year, and Q_n represents the amount of cropland in the target year.

Based on the relevant literature [31], we consider the feasibility of data acquisition and the actual production status of Quzhou County, and the final prediction model of cropland holding quantity in this paper is calculated as follows:

$$Q_n = \frac{S \times R \times \gamma}{e \times f \times k \times \lambda} \tag{8}$$

where Q_n represents the target annual cropland demand, indicating the amount of cropland in the target year; and S, R, and γ represent the target annual per capita food demand, the number of resident populations, and the food self-sufficiency rate, respectively. e, f, k, and λ indicate the output per unit area of grain in the base year, the area planted with grain as a percentage of the total crop planting area, the multiple cropping index, and the growth rate of food production, respectively.

In addition, to ensure the scientific prediction of the cropland quantity, the GM (1,1) gray system model is used to predict the relevant indicators of cropland in Quzhou County (2013–2018); then, the predictive model is calibrated by comparing the difference between the predicted and actual values. The formulas for the GM (1,1) gray system are as follows:

$$x^{(0)}(k) + ay^{(1)}(k) = b \tag{9}$$

$$x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i) \tag{10}$$

where $x^{(0)} \geq 0; k = 1, 2, 3 \ldots n; y^{(1)} = 0.5x^{(1)}(k' - 1), k' = 2, 3, \ldots n$.

According to the correlation between the actual value and the predicted value (Table 3), the relative average error results are 0.533%, 0.640%, 0.448%, 1.059%, 0.533%, and 0.250%, and the error is within a reasonable range. The posterior difference ratio C is between 0.195% and 0.421%, indicating that the posterior difference ratio is qualified. The error probability p is between 0.877 and 1.000, indicating that the prediction accuracy of the gray model is above the second-level standard and the prediction accuracy is above the qualified level. In summary, the forecasting model has good credibility, and the model can be used to predict the relevant indicators of cropland quantity.

2.4.3. Fallow Location

The spatial location of the fallow land in this paper is mainly based on the urgency level of cropland fallow and the scale of cropland. Simultaneously, to strengthen the supervision and management of fallow land, we use the village as the unit to carry out the plotting of fallow land. The space layout model of fallow land is as follows:

$$\mathrm{P} = [U, Q] \tag{11}$$

where P represents the spatial layout of the fallow land and $[U, Q]$ represents the spatial superposition relationship.

Table 3. Results of model calibration.

Year	Total Population		Sown Area of Food Crops (hm^2)		Total Grain Output (t)		Grain Yield Per Unit Area (t/hm^2)	
	Actual Value	Predictive Value	Actual Value	Predictive Value	Actual Value	Predictive Value	Actual Value	Predictive Value
2013	482,710	482,710.000	54,784	54,784.000	428,447	428,447.000	7.821	7.821
2014	499,227	501,932.823	54,818	54,607.471	413,989	415,306.331	7.552	7.598
2015	513,610	511,142.897	56,108	56,033.586	418,883	418,778.204	7.466	7.472
2016	523,585	520,521.969	56,771	57,496.945	425,972	422,279.100	7.503	7.347
2017	527,304	530,073.139	59,453.69	58,998.521	423,338.24	425,809.263	7.120	7.224
2018	538,263	539,799.566	60,899	60,539.311	428,754	429,368.938	7.120	7.104
Relative average error (%)	0.533		0.640		0.448		1.059	
Precision (%)	95.407		93.512		91.250		93.514	
Posterior difference ratio (C)	0.239		0.421		0.221		0.195	
Small error probability (P)	1.000		1.000		1.000		1.000	

3. Results

3.1. Classification of Cropland Fallow Urgency

3.1.1. Irrigation Profit/Loss Index (IPLI)

Based on the analysis of the irrigation water requirements of the main crops in Quzhou County in 2018, the IPLI was calculated. The results showed that the IPLI value of winter wheat is 0.1173 (Table 4), which means the irrigation water is in short supply during the growing season. In contrast, the IPLI values of summer maize and cotton are −0.9849 and −0.0071, respectively. These results show that corn and cotton's irrigation is in excessive supply, resulting in a waste of water resources.

Table 4. Irrigation profit/loss index (IPLI) of the main crops in Quzhou County in 2018.

Main Crop	Irrigation Profit/Loss Index (IPLI)
Winter wheat	0.1173
Summer maize	−0.9849
Cotton	−0.0071

Note: Author's calculation.

3.1.2. Shallow Groundwater Depth Change Rate (SGDCR)

By analyzing the SGDCR results from the trend analysis chart from a spatial perspective (Figure 3), we found that the groundwater depth decreases rapidly from north to south (the blue curves) and from west to east (the green curves). Based on the current situation of shallow groundwater resources in Quzhou County, the depth to shallow groundwater in the south and east is deeper than that in the north and west.

3.1.3. Classification of the Urgency of Fallow Cropland

The spatial overlap of IPLI and SGDCR lines can better perform the determination of the urgency of fallow cropland, and is shown in Figure 4a. The results showed that the urgency level of cropland fallow in Quzhou County gradually decreased from south to north.

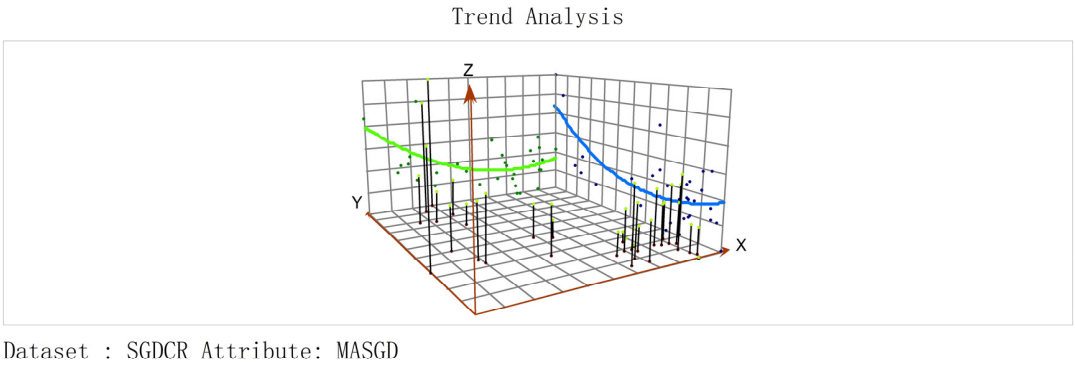

Figure 3. Shallow groundwater depth change rate (SGDCR) in Quzhou County in 2018 (multi-year average of shallow groundwater depth (MASGD)).

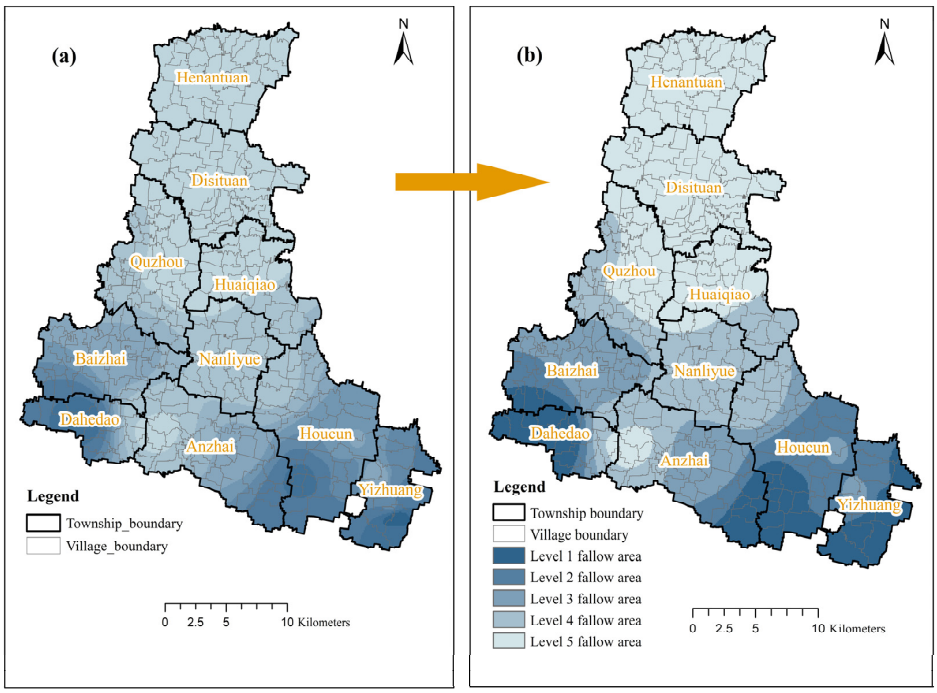

Figure 4. Classification of the urgency situation (**a**) and urgency level (**b**) of cropland fallow in Quzhou County in 2018.

In order to express the urgency of fallow cropland in Quzhou County, we divided the urgency of fallow cropland into five levels from the level 1 fallow area (the strongest urgency of fallow) to the level 5 fallow area (the weakest degree of cropland fallow). Overall, the urgency level of fallow is high in the south and low in the north (Figure 4b). The strongest urgency of fallow area (level 1) is mainly distributed in the towns of Yizhuang, Houcun, Baizhai, and Dahedao; the weakest degree of cropland fallow (level 5) area is mainly distributed in the towns of Disituan and Henantuan.

3.2. Current Situation and Assessment of Fallow Cropland

3.2.1. Cropland Fallow Area

The GM (1,1) gray prediction model was used after verification to predict the results of related indicators of cropland holdings in Quzhou County in 2018; the basic information is shown in Table S1. The cropland holding amount of Quzhou County is 63,610.712 hm^2. According to official figures, the predicted fallow cropland area is 4089.288 hm^2 under the premise of ensuring food security, which is 1189.288 hm^2 more than the current cropland fallow area, by 2900 hm^2, according to government data (Figure 5).

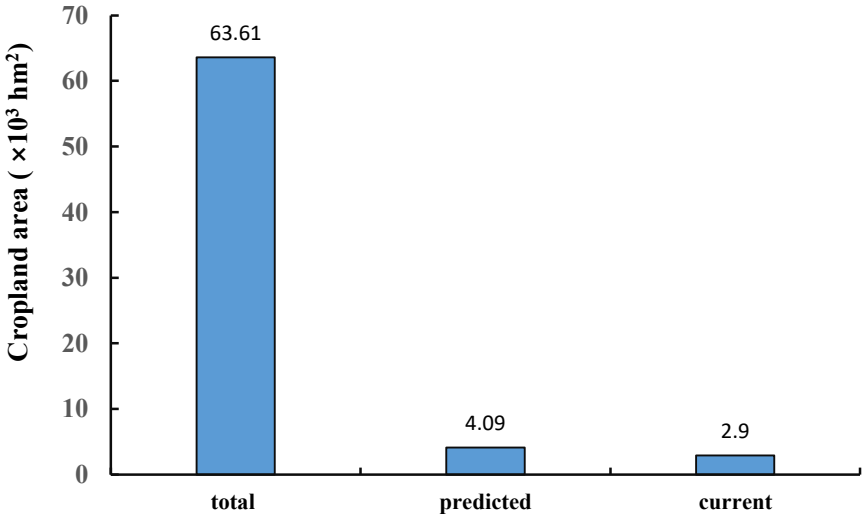

Figure 5. The total cropland, predicted fallow cropland, and current cropland in Quzhou County in 2018.

3.2.2. Space Allocation of Fallow Land

In 2018, the fallow cropland plots in Quzhou County are mainly distributed in Yizhuang, Houcun, Nanliyue, Huaiqiao, Disituan, Henantuan, Baizhai, and Quzhou towns, which is a total of 8 townships involving 17 administrative villages (Figure 6a). According to the degree of urgency of the cropland fallow, the areas of different levels of urgency were counted (Table S2) and, combined with the cropland fallow area (2900 hm^2), the selected cropland for fallow is concentrated in the towns of Yizhuang and Houcun, involving nine administrative villages (Figure 6b). By comparing Figure 6a,b, the original fallow plots in Quzhou County are scattered and the theoretical fallow land distribution is more concentrated and located in the places where water resources are scarce.

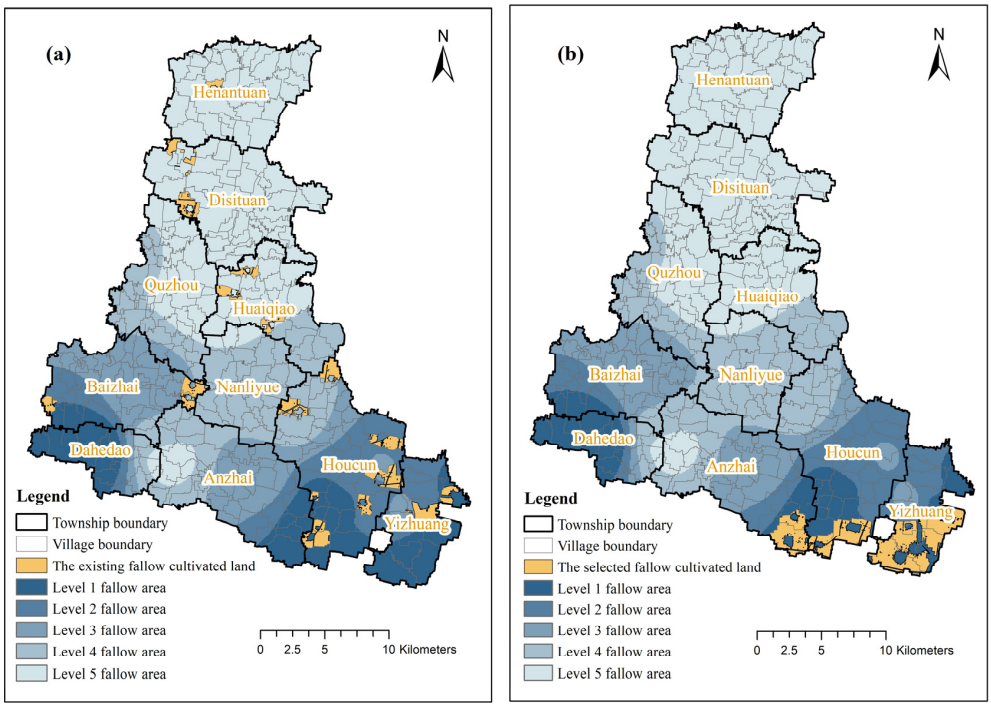

Figure 6. Spatial distribution of the existing fallow cropland (**a**) and the selected fallow cropland (**b**) in Quzhou County in 2018.

4. Discussion and Policy Implications

4.1. Discussion

Cropland fallow should not bring food security risks to the region. A reasonable area of cropland fallow will not affect regional food security based on alleviating regional resource pressure. Scientific calculation of the area of fallow cropland can not only ensure food security, but also predict a reasonable area of fallow cropland. At the national scale, determination of the fallow scale needs to consider the huge differences between regions in actual conditions, causing the results to vary greatly. Li and Liu (2014) have predicted that the area of fallow in China would be 97×10^4 hm^2 [32], accounting for 0.81% of the total cropland. Meanwhile, research by Luo et al. (2015) has showed that the fallow rate can reach 20% in China [33]. In this study, we investigated at the county level, which avoids the great regional difference at a large scale. A relevant model was used to calculate the cropland holding amount and the fallow area of cropland under the condition, with which we can ensure that the fallow cropland does not affect regional food security. Based on the quantitative calculations and statistics from the government, our results showed that the predicted fallow cropland area is 1189.288 hm^2 greater than the current fallow cropland area issued by the government in 2018. The fallow area calculated is more reasonable at the county level, which provides methods and ideas for the government to formulate the fallow area of cropland. Moreover, this can not only guarantee regional food security, but also regulate the balance between food supply and demand.

The fallow urgency determination for cropland can enable more accurate positioning of fallow cropland. The United States adopted the environmental benefit index (environmental benefits index) as the standard for evaluating fallow land, which considers the water and soil loss, air quality, possible pollution of surface water and groundwater, diversity of wild animals and plants, possible implementation cost, and long-term benefits [34]. At present, the distribution of fallow land in China is mostly determined by the "top-down" and "level by level" indicator distribution and ignores the quantitative analysis of the regional arable land resource endowment and the practical conditions of fallow, which has caused the amount of fallow land to be inefficient, scattered, and unfavorable for management. In our research, we reasonably determine the position of fallow cropland based on fallow urgency. By selecting the relevant factors restricting the development of regional cropland based on the current status of the region, and then evaluating the fallow urgency of regional cropland, it is possible to formulate methods to evaluate the fallow urgency of regional cropland according to local conditions, and then more accurately locate the position of fallow cropland. In addition, farmer households are the behavioral subject and stakeholders of implementing the fallow and the cropland is an important way to guarantee farmers' life, meaning that that farmers' willingness analysis and ecological compensation are necessary to ensure the implementation of fallow policy [16,35,36].

Reasonable spatial allocation of fallow land can implement fallow land where it is most needed, which can achieve the government's main purpose of implementing fallow cropland and maximizing fallow cropland benefits. Research by Song et al. (2022) showed that fallow is closely related to topographic factors such as altitude [37]. Mountainous areas are prone to farmland abandonment after the land fallow in south China [38,39]. In contrast, in the relatively flat plain, farmers take the initiative to apply for fallow to obtain compensation for fallow. The occurrence of fallow is largely related to the spontaneous behavior of farmers [40]. In fact, the spatially optimal allocation of fallow land should combine the fallow urgency level and fallow area. Based on the allocation of fallow urgency and fallow area, the fallow land is mainly distributed in the southern part of Quzhou County, located in the groundwater funnel area, where groundwater resources are in short supply. In addition, on the one hand, the reasonable spatial allocation of fallow land can make the spatial distribution of fallow land more centralized and easier for unified management by relevant departments. On the other hand, the allocation of limited fallow area to the most needed fallow land can improve the land fallow efficiency.

4.2. Policy Suggestion and Future Work

Improving the cropland fallow program can improve the benefits of fallow. At present, the fallow pilot location, fallow area, and fallow time determined by the fallow program for cropland in China are qualitative descriptions, and no in-depth quantitative research has been conducted, which limits the benefits that fallow cropland can bring. In addition, the cropland fallow program should focus on solving the main problems. As far as the groundwater funnel area is concerned, the main purpose of cropland fallow is to save groundwater resources and gradually restore the groundwater depth. However, most of the related research focuses on the farmers' willingness and the amount of fallow compensation instead of the changes in groundwater resources. Moreover, the area and location of fallow land are important factors and key nodes of the fallow program. Therefore, it is urgent to formulate a fallow program for cropland. Finally, in formulating a regionally differentiated cropland fallow program, this article mainly detailed the specific content of the cropland fallow program in the groundwater funnel area, which has obvious regional characteristics and provides a perspective for the detailed fallow scheme. Cropland fallow programs should be studied according to the restrictive factors in different regions (such as desertification areas, heavy metal pollution areas, and so on).

In addition, the following aspects of this research require further study: (1) The effect of fallow land on groundwater resources should be evaluated by combining with corresponding models [41]. (2) The calculation method of the amount of fallow cropland should be further optimized. The methods to properly and accurately determine the area of cropland fallow need to be explored. For example, the regional hydrogeological characteristics of key aquifers should be considered [42]. (3) The research scope should be expanded to increase the urgency determination of fallow cropland. To make the cropland fallow programs more universal, different cropland fallow programs should be formulated according to the characteristics of different regions. For example, heavy metal pollution of farmland should focus on pollutant types, pollution degree, and crops with high biomass and cumulative absorbing effects [43]. (4) The allocation of fallow space should be combined with the wishes of farmers to ensure that there is no conflict between the government and farmers.

5. Conclusions

Water resources are vital to regional sustainable development, especially in agricultural production areas. Facing the increasingly severe shortage of groundwater resources, the fallow of cropland is a favorable measure. At present, the cropland fallow program is relatively rough and related studies have not specifically refined the cropland fallow urgency, area, and position. To fill this gap, this study selects Quzhou County, a county with severe water shortage and a fallow pilot county, to analyze the urgency of the fallow of cropland, which area should be fallowed, and how much area should be fallowed. Our results showed that the urgency of fallow can be determined using the IPLI and SGDCR. The area of cropland fallow obtained through quantitative calculations is 1189.288 hm^2 greater than the actual area of cropland fallow (2900 hm^2) in 2018. Considering the allocation of fallow urgency and fallow area, the fallow land would be mainly distributed in the southern part (2 towns, 9 villages) of Quzhou County, rather than the current scatter spatial distribution (8 towns, 17 villages). This research can provide methods and ideas for accurately formulating the cropland fallow program; more research perspectives (society, economy, and ecology) are suggested to be considered and integrated into the development of the fallow program of multi-objective synergy in future research work.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land12020462/s1, Table S1: Results of related indicators of cultivated land holdings in Quzhou County in 2018; Table S2: Statistical results of the area of different fallow urgency levels in Quzhou County in 2018.

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