An integrative modeling approach for compromising between water saving and environment protection based on the water footprint theory

S Zhang¹, Q Tan¹,², S Liu¹, T Zhang¹ and W Q Zhao³

¹College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China
²Institute of Environmental & Ecological Engineering, Guangdong University of Technology, Guangdong 510006, China
³Center for Industrial Diagnostics and Fluid Dynamics (CDIF), Polytechnic University of Catalonia (UPC), Barcelona, Spain

E-mail: qian_tan@cau.edu.cn

Abstract. In this study, an interval optimization programming based on water footprint (IOMWF) method was developed for supporting the optimal use of land and water resources in agricultural. The developed IOMWF model not only provided optimal planting scheme considering the whole process of agriculture water consumption to save water, increase benefits and control pollution, but also effectively dealt with the uncertainties in the process of allocation. This method was applied to address a case in Hetao Irrigation Districts. The obtained solution demonstrated that corn would be the best crop with lower water consumption and nitrogen pollution, being followed by sunflowers and wheat. In addition, the utilization rate of green water would be lower than 0.5 and have a larger potential room to improve.

1. Introduction
Water is one of the most important material resources, which is indispensable to human survival and development [1]. Agriculture is by far the largest consumer of water resources which accounts for more than 70% of water withdrawals from rivers, lakes and aquifers [2,3]. In addition, water consumption in global crop production is causing significant environmental impacts on natural resources [4]. Many research reports in different countries and regions had proved that poor natural water endowment and mismanagement of water resources, especially in the agricultural sector, is the primary cause leading to water deficit and environmental deterioration. Thus, it is very urgent and important to seek optimal management schemes for alleviating the water resources scarcity and water pollution.

Water footprint, which can be separated into green water, blue water and grey water footprint, refers to the quantities of water consumption to produce products and services. As a comprehensive index for water resources, water footprint can be used to evaluate the types, quantities, efficiency and environmental impacts of water resources that is consumed in multi-links of agricultural production such as irrigation and drainage. At present, many scholars have studied the consumption of blue and green water of crops from the global [5], national [6-8], and regional [9,10] scales. These research results estimated the demand and consumption of irrigation water and rainfall for various crop types in different regions, predicted the changes of population, economy, production and structure in the future,
and provided suggestions to government on water resources management [5-11].

Optimization models were widely used to help water managers obtain optimal allocation schemes for saving water and protecting the environment [12,13]. The combination of simulation model and optimization model is a research hotspot for solving water problem at present. There have been some studies on water resources management with a focus on water footprint theory, including but not limited to linear programming, nonlinear programming and multi-objective programming. For instance, Su et al [14] proposed a multi-objective fractional programming model to minimum fairness difference in the utilization of water and maximum the economic benefits and utilization rate of green water; Sedghamiz et al [15] developed a bi-level programming model to maximize the share of green water in water footprint and benefits.

However, major challenges still remained for alleviating the water resources scarcity and water pollution. Firstly, most of the previous work only focus on irrigation or drainage of agriculture, but lack the comprehensive studies in the whole process of agriculture water consumption. Secondly, due to the limitations of data and research methods, few studies have coupled the water footprint with the optimization model, letting along considering the uncertainties of decision-making processes and multiple water utilization links. Therefore, to overcome the prescribed shortcomings, the objective of this research aimed to establishing an interval optimization programming based on water footprint (IOMWF). The developed model taking the maximum economic benefits as the objective and taking blue, green and grey water footprint as the boundary conditions, will provide an optimal allocation scheme of land and water resources for decision makers.

2. Methodology

2.1. Determination of the water footprint (WF)

In this research, water footprint is separated into green water, blue water and grey water. The green and blue water footprint (WF) of crops is defined as the crop water consumption (CWC) (m$^3$ ha$^{-1}$) during a cropping period divided by the crop yield (CY) (kg ha$^{-1}$). Since plant transpiration and soil evaporation are the main ways of CWC over the crop-growing period, the VWC of crops can be calculated as follow [16]:

$$WF_{\text{green}} = \frac{CWC_{\text{green}}}{CY} = 10 \times \frac{ET_{\text{green}}}{CY} \quad (1)$$

$$WF_{\text{blue}} = \frac{CWC_{\text{blue}}}{CY} = 10 \times \frac{ET_{\text{blue}}}{CY} \quad (2)$$

where $WF_{\text{green}}$ and $WF_{\text{blue}}$ are the green and blue water footprint of crops, respectively (m$^3$ kg$^{-1}$); $CWC_{\text{green}}$ and $CWC_{\text{blue}}$ are the green and blue water consumption over the crop growing period (m$^3$/ha$^2$) and $ET_{\text{green}}$ and $ET_{\text{blue}}$ are the green and blue water evapotranspiration value (mm), which can be estimated using the Food and Agriculture Organization’s CROPWAT model:

$$ET_{\text{green}} = \min(ET, P_r) \quad (3)$$

$$ET_{\text{blue}} = \max(0, ET - P_r) \quad (4)$$

where $ET$ is evapotranspiration and is calculated on the basis of the crop coefficient approach and the FAO Penman-Monteith equation (mm/day); and $P_r$ is the effective rainfall over the crop-growing period (mm).

The best available grey water footprint ($WF_{\text{grey}}$) approach is on that estimates grey water as the volume of water need to dilute the degree of pollution of the water used [17]. Here, per crop and per year, $WF_{\text{grey}}$ related to anthropogenic pollution loads to freshwater bodies were calculated based on the procedure introduced by Hoekstra et al [18].
\[ \text{WF}_{\text{grey}} = \frac{\text{LA}}{\text{C}_{\text{max}} - \text{C}_{\text{nat}}} \]  

(5)

where LA is the pollution load to freshwater bodies (kg ha\(^{-1}\) year\(^{-1}\)), and \(C_{\text{max}}\) and \(C_{\text{nat}}\) are respectively, the ambient water quality standard (i.e., maximum allowable concentration in kg m\(^{-3}\)) and its natural background concentration in receiving body (kg m\(^{-3}\)).

2.2. Formulation of an interval optimization programming based on water footprint (IOMWF)

Blue, green and grey water footprint can be used to evaluate the irrigation district from two aspects: water quantity and water quality. However, providing decision makers with more intuitive and scientific cultivation advice can give full play to the value of water footprint. Therefore, the objective of the IOMWF model is to maximize the agricultural economic benefits considering the coordination of multiple factors and uncertainties by allocating limited plan areas and water resources to different crops. The objective function was expressed as the net income from selling the cultivated crops with the miscellaneous expenditures such as seed purchase, labor and pollution control being deducted.

The constraints of the developed model could be roughly classified into two groups: constraints related to land use and those regarding water resource. The developed model is described as follows:

\[
\begin{align*}
\text{max } f^z &= \sum_{i=1}^{I} \sum_{j=1}^{J} (P_i^z Y_{ij} - CT_i^z) x_{ij}^z - \sum_{i=1}^{I} \sum_{j=1}^{J} C_{r_{ij}}^z \cdot x_{ij}^z \\
\text{subject to:}
\end{align*}
\]

(6)

Farmland availability constraints

\[
X_{ij_{\min}}^z \leq X_{ij}^z \leq X_{ij_{\max}}^z, \quad \forall i, j
\]

(7)

Green-water utilization-rate constraints

\[
\sum_{j=1}^{J} x_{ij}^z Y_{ij} \cdot \text{WF}_{\text{green}}^z \geq \theta_{\text{green}}, \quad \forall i
\]

(9)

\[
\sum_{j=1}^{J} x_{ij}^z Y_{ij} \cdot \text{WF}_{\text{blue}}^z \leq \sum_{j=1}^{J} \sum_{i=1}^{I} m_{ij}^z x_{ij}^z
\]

(10)

\[
\frac{A R_{ij}^z \cdot x_{ij}^z}{C_{\text{max}} - C_{\text{nat}}^z} \leq F I_i^z \gamma^z, \quad \forall i
\]

(11)

Water availability constraints

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} m_{ij}^z x_{ij}^z \leq Q I^z \rho^z
\]

(12)
Food security constraints

\[
\sum_{i=1}^{I} \sum_{j=1}^{J} x_{ij}^+ \theta_{ij}^+ \geq D_j^+, \ \forall j
\]  

(13)

Non-negativity constraints

\[
x_{ij}^+ \geq 0, \ \forall i, j
\]  

(14)

where \( f^z \) is the economic benefits from crop cultivation (yuan); \( J \) represents the index of crops, \( j \) takes values from 1 to 3 that represents wheat, corn and sunflower; \( I \) represents the index of counties, \( i \) takes values from 1 to 5 that represents Linhe, Wuyaun, Dengkou, Qiangqi and Hanghou, respectively; \( P_j^z \) is the selling price for on kilogram of crop \( j \) (yuan/kg); \( Y_j^z \) is the yield of crop \( j \) from one hectare of land in county \( i \) (kg/hm\(^2\)); \( CT_j^z \) is the cost for per unit area of crop \( j \) (yuan/hm\(^2\)); \( CT_j^z \) is the cost of disposal of the leaching loss of N for each crop (yuan/hm\(^2\)); \( x_{ij}^+ \) is the planting area of crop \( j \) in county \( i \) (hm\(^2\)); \( x_{ij}^- \) is the minimum and maximum arable area of crop \( j \) in county \( i \) (hm\(^2\)); \( S_{\text{min}}^z \) and \( S_{\text{max}}^z \) are the minimum and maximum available total area in county \( i \) (hm\(^2\)); \( \theta_{\text{greeni}}^z \) is the utilization rate of green water in county \( i \); \( m_j^z \) is the irrigation quota of crop \( j \) (m\(^3\)/hm\(^2\)); \( FL_i^z \) is the autumn irrigation quota in county \( i \) (m\(^3\)); \( \gamma^z \) is the utilization rate of water in autumn irrigation (%); \( QI^z \) is the available volumes of surface water and groundwater in growing period (m\(^3\)); \( \rho^z \) is the utilization rate of irrigation water (%); and \( D_j^z \) is minimum demand for crop \( j \) (kg).

According to Huang [19] and Fan [20], the developed IOMWF can be converted into two deterministic sub-models, which correspond to the lower and upper bounds of the desired objective. The sub-model corresponding to the lower bound of the objective-function value (i.e., \( f^- \)) should be first formulated as follows:

\[
\max f^- = \sum_{i=1}^{I} \sum_{j=1}^{J} (P_j Y_j^z - CT_j^z) x_{ij}^+ - \sum_{i=1}^{I} \sum_{j=1}^{J} C^+_{ij} x_{ij}^-
\]  

(15)

\[
X_{ij,\text{min}}^+ \leq x_{ij}^- \leq X_{ij,\text{max}}^+, \ \forall i, j
\]  

(16)

\[
S_{\text{min}}^+ \leq \sum_{j=1}^{J} x_{ij}^- \leq S_{\text{max}}^-, \ \forall i
\]  

(17)

\[
\sum_{j=1}^{J} x_{ij}^+ Y_{ij,\text{WF}}^+ \geq \theta_{\text{greeni}}^-, \ \forall i
\]  

(18)

\[
\sum_{j=1}^{J} x_{ij}^- Y_{ij,\text{WF}}^- \leq \sum_{j=1}^{J} m_j^+ x_{ij}^-
\]  

(19)
\[ \sum_{j=1}^{I} \frac{L_{ij}^+ \cdot x_{ij}^-}{C_{mi}^- - C_{ni}^+} \leq FL_i^+ y^+, \quad \forall i \quad (20) \]

\[ \sum_{i=1}^{I} \sum_{j=1}^{J} m_j^+ x_{ij}^- \leq QI^- \rho^- \quad (21) \]

\[ \sum_{i=1}^{I} x_{ij}^- g_i^+ \geq D_j^+ PE^+, \quad \forall j \quad (22) \]

\[ x_{ij}^- \geq 0, \forall i, j \quad (23) \]

Let \( x_{ijopt}^- \) is the solutions of model (15) to (23). The second sub-model corresponding to the upper bound of the objection function value (i.e., \( f^+ \)) is:

\[ \max f^+ = \sum_{j=1}^{J} \sum_{i=1}^{I} (P_j^+ Y_{ij}^- - CT_j^-) x_{ij}^- - \sum_{i=1}^{I} \sum_{j=1}^{J} C_{ij}^- \cdot x_{ij}^- \quad (24) \]

\[ X_{ijmin}^- \leq x_{ij}^- \leq X_{ijmax}^+, \quad \forall i, j \quad (25) \]

\[ S_{jmin}^- \leq \sum_{j=1}^{J} x_{ij}^- \leq S_{jmax}^+, \quad \forall i \quad (26) \]

\[ \sum_{j=1}^{J} x_{ij}^- Y_{ij}^W F_{greeni}^- \geq \theta_{greeni}^+, \quad \forall i \quad (27) \]

\[ \sum_{i=1}^{I} \sum_{j=1}^{J} x_{ij}^- Y_{ij}^W F_{blueij}^- \leq \sum_{i=1}^{I} \sum_{j=1}^{J} m_j^+ x_{ij}^- \quad (28) \]

\[ \sum_{j=1}^{J} \frac{L_{ij}^- \cdot x_{ij}^+}{C_{mi}^+ - C_{ni}^-} \leq FL_i^- y^-, \quad \forall i \quad (29) \]

\[ \sum_{i=1}^{I} \sum_{j=1}^{J} m_j^- x_{ij}^+ \leq QI^- \rho^- \quad (30) \]

\[ \sum_{j=1}^{J} x_{ij}^- g_i^- \geq D_j^- PE^-, \quad \forall j \quad (31) \]

\[ x_{ij}^+ \geq 0, \forall i, j \quad (32) \]
$$x_{ij}^+ \geq x_{ij}^-$$, $\forall i, j$ \hfill (33)

Let $x_{ij}^+$ is solution of model (24) to (33). The solutions of the developed IOMWF model are obtained by integration of the resulting solutions from its sub-models. The obtained solutions provide stable intervals for the optimized economic benefits and planting areas, which can be expressed as:

$$f_{\text{opt}}^\pm = [f_{\text{opt}}^-, f_{\text{opt}}^+]$$ \hfill (34)

$$x_{ij}^\pm = [x_{ij}^-, x_{ij}^+]$$, $\forall i, j$ \hfill (35)

3. Case study

The Hetao Irrigation District is situated the west of the Inner Mongolia Autonomous Region, China (106°20'-109°19'E, 40°19'-41°18'N) and includes five counties: Dengkou (DK), Hangjinhouqi (HH), Linhe (LH), Wuyuan (WY) and Wulateqianqi (QQ) (figure 1). The region is one of the main grain production regions in China, with an irrigated area of $5.74 \times 10^3$ km$^2$. Spring wheat, spring corn and sunflowers are the major crops. The mean annual precipitation is from 130 mm to 250 mm, and mainly occurring from June to August, and the mean annual evaporation is from 2100 mm to 2300 mm. Therefore, irrigation is very important for crop growth in Hetao Irrigation District, which will get $[4.35, 5.19]$ billion m$^3$ from Yellow River. The current water use efficiency coefficient in this irrigation district is $[35, 45]$. In order to reduce soil salinity, autumn irrigation was fixed to October each year and consumed $[1.53, 2.34]$ billion m$^3$ of the irrigation water. Simultaneously, the negative effects of drainage, which was caused by extensive autumn irrigation, on environment cannot be ignored. Specific data related to agricultural production, water resources and pollution were obtained from the experimental station and Statistical Yearbook of Bayannur (2009-2016) (tables 1 and 2). To alleviate water shortage and environmental pollution in Hetao Irrigation District, land use and water resources management are considered as the most important and effective ways to mitigate these problems.

![Figure 1. Study area.](image)

**Table 1.** Region-related parameters.

| Parameters | LH  | WY  | DK  | QQ  | HH  |
|------------|-----|-----|-----|-----|-----|
| Yield $(10^3 \text{kg/hm}^2)$ | [5.29, 6.23] | [5.08, 5.36] | [5.20, 5.44] | [4.78, 5.48] | [5.80, 6.09] |
| Wheat      |     |     | [5.08, 5.36] |     |     |
| Corn       | [10.10,] | [10.24,] | [9.56, 10.85] | [10.37,] | [10.68,] |
Table 2. Crop-related parameters.

| Parameters                        | Wheat       | Corn         | Sunflowers  |
|-----------------------------------|-------------|--------------|-------------|
| Irrigation quota (m³/hm²)         | [5,194, 5,046] | [4,312, 4,488] | [3,038, 3,162] |
| Price (yuan/kg)                   | [3.1, 3.5]  | [2.2, 2.6]   | [6.3, 6.7]  |
| Cost (yuan/hm²)                   | [10,030, 11,086] | [8,763, 9,685] | [3,757, 4,153] |
| The cost of nitrogen treatment (yuan/hm²) | [5,135, 6,486] | [802, 1,419] | [573, 912] |
| Demand (10³kg)                    | [2.89, 3]   | [2.47, 2.58] | [2.21, 2.3] |

4. Results analysis and discussion

4.1. Spatial and temporal distribution of water footprint

Based on the method introduced in section 2.1, the water footprint of three main crops including wheat, corn and sunflowers were determined in Hetao-Irrigated Area from 2012 to 2016. Figures 2 to 4 are the spatial and temporal distribution of blue, green and grey water footprint, respectively.

Figure 2 shows the blue water footprint of wheat, corn and sunflowers in five counties from 2012 to 2016. Comparing with table 1, it can be found that the order of these regions in blue water footprint would be completely opposite in total production. The order from the lowest to the highest would be Dengkou, Qianqi, Linhe, Wuyuan and Hanghou. However, such a sequence does not agree with their ET. This result indicates that the yield would be the main cause for the spatial variation of blue water footprint in Hetao Irrigation Area. On the other hand, the order of the blue water footprint of crops that
was corn < sunflowers < wheat was not consistent with the order of yield that was corn > wheat > sunflowers. This implies that yield and ET may be the main factors to affect the blue water footprint of different crop types. Figure 2 also reveals that blue water footprint firstly increases before and then decreases with the time going on, reaching its peak in 2014 or 2015. Since there is no significant change in yield during different years, ET, which is associated with climate change, might be primarily responsible for this trend. The temporal variation of green water footprint in figure 3 is similar to that of blue water footprint, which is the best verification for this conclusion. In addition, green water footprint of Dengkou County is generally smaller than that of the other four counties, which is the biggest difference between blue and green water footprint.

Figure 2. Blue water footprint of crops (m$^3$/kg).

Figure 3. Green water footprint of crops (m$^3$/kg).

Figure 4. Grey water footprint of crops (m$^3$/hm$^2$).
Being different from the principle of blue and green water footprint, grey water footprint is in direct proportion with the emissions of pollutants and in negative proportion with the concentration difference before and after dilution of the pollutant. Therefore, the variation law of grey water footprint is quite different from that of blue and green water. Taking nitrogen as an example, figure 4 illustrate the time-space variation of the grey water footprint of crops. It can be seen that the grey water footprint of sunflowers was higher than that of wheat and corn; with the exception of the Qianqi County, which had the largest grey water footprint, the remaining four counties have a similar grey water footprint; and the grey water footprint of all crops decreased from 2012 to 2016 in five counties. However, the research data showed that the maximum allowable concentration ($C_{\text{max}}$) and natural background concentration ($C_{\text{nat}}$) were unchanged with time and space, so that the emission load (AR) would be the main parameter to affect the grey water footprint. Therefore, it can be inferred that the leaching loss of N of sunflowers is greater than that of wheat and corn, the utilization rate of N fertilizer in Wulate County is the lowest and the Zero-fertilizer policy have generated positive results in Hetao Irrigation Area.

4.2. Optimal plans for irrigated cropping
Based on the quantitative analysis of the water footprint, decision makers could obtain the utilization of water resources for many years. But this cannot provide an accurate management scheme for future development. Therefore, this study improved the optimal allocation model of land and water resources by adding the blue, green and grey water footprints as boundary conditions of the optimization model, such as constraints (9) to (11). After calculated from Model (3), the optimal planting plan and the corresponding index including the economic benefits, water footprint and utilization rate of green water.

4.2.1. Optimal allocation of planting areas

Figure 5 presents the optimal allocation scheme of planting areas among the three crops. The optimal results showed that corn and sunflower would be the most popular crops in the whole irrigation area. For instance, the maximum planting area of wheat would be [20,434, 20,545] hm$^2$ from Hanghou County, which would lower than the minimum planting area of corn and sunflowers, [23,656, 28,913] hm$^2$ and [20,531, 26,269] hm$^2$ respectively. As shown in figures 2 to 4, the blue, green and grey water of corn would be the smallest of the three crops. Large-scale cultivation of corn would be helpful to water saving and pollution control in Hetao Irrigation District. On the contrary, sunflower would consume a number of water resources for growing and diluting pollutants. However, it would still occupy a larger proportion of planting area. In particular, the optimal planting area of sunflower would be [95,269, 110,984] hm$^2$, which would be three times as much as that of corn and...
six times as much as that of wheat. This may be because sunflower is the local characteristic economic crops and can bring higher income for farmers. This results also reflect the trade-off effect of the optimization system in terms of economic benefits, water saving and pollution control.

![Figure 6](image.png)

**Figure 6.** The contribution of different crop types and regions to the total cultivation area, economic benefits and water footprint. (a) Different crop types; (b) Different regions.

Taking the upper bound for example, figure 6 illustrates the contribution of different crop types and regions to the total cultivation area, economic benefits and water footprint. As shown in figure 6(a), wheat would account for 9% of the total planting area, consume 7% of the green water and 9% of the blue water while contribute less than 2% of the economic benefits and need 37% of the irrigation water to dilute the leached nitrogen to its initial concentration. The planting area of corn and sunflowers would be similar, which would be 295 and 298 thousand hectares respectively. Both of them could contribute about 6 billion of the economic benefits, which would reach 30 times form wheat. At the same time, less water would be wanted to dilute nitrogen emissions during the growth period of corn and sunflowers than that of wheat. Corn would be a high water-consuming crop since it might consume 48% and 62% of green and blue water respectively.

Figure 6(b) compares the economic benefits, water consumption and N pollution in five counties. It can be found that Linhe County, Wuyuan County and Qianqi County would have higher contribution
rates in terms of planting areas, economic benefits and the total consumption of blue and green water footprint. Nevertheless, this conclusion would not apply to grey water footprint. For instance, the grey water footprint of Qianqi County is only higher than Dengkou County whose grey water footprint would rank in the top three. This may be due to a lower consumption of chemical fertilizer or higher utilization rate in Qianqi County. In addition, the utilization rate of green water of five counties were lower than 0.5 and would be a larger potential room to improve.

4.3. Discussion

Based on the above results, we can summarize the characteristics of the three crops. Per kilogram of corn would consume the least irrigation water and rainfall in the whole growth period. What’s more, per hectare corn would discharge the least nitrogen pollutions. Therefore, corn would be the crop with the highest utilization coefficient of water resources and lower nitrogen leaching. Wheat would be the one consuming the most irrigation water per kilogram. But it would consume less green water than sunflowers. This may be due to the earlier growth period of wheat in Hetao Irrigation Area--March to July, which would miss the rainy season and have to rely on irrigation water to maintain its growth. There is no doubt that wheat would be the crop with lower efficiency of water resources. However, it is also necessary to ensure the total yield of wheat to maintain the basic local demand. Sunflowers, as the local characteristic crop, would consume more water for growth and environmental restoration, but its contribution to the economic benefits cannot be replaced by wheat and corn.

To sum up, corn would be suitable for regions with developed industries, wheat would be available for regions with abundant water resources, and sunflowers would be preferred for underdeveloped regions. In detail, Linhe County, Wuyuan County and Qianqi County belong to heavier pollution area. Therefore, decision makers can appropriately expand the planting area of corn to reduce environmental pressures and save water resources in these counties. Dengkou and Hanghou Counties are near the water intake and have enough water resources. If the center of wheat planting were moved to these two regions, the management could only open channels near the water intake when the wheat would be irrigated in March. This would reduce the loss of water in channels.

5. Conclusions

In this research, an interval optimization programming based on water footprint (IOMWF) was developed for supporting the regional water and land allocation under uncertainty. Based on the quantitative analysis of crop water footprint, the developed model determines the range of water requirement for different irrigation regions and crops in the whole process of agriculture water consumption. The developed IOMWF model not only provided optimal planting scheme considering the irrigation and drainage for saving water, increasing benefits and controlling pollution, but also effectively dealt with the uncertainties in the process of allocation.

The IOMWF model has been successfully applied to the planning of regional land and water resources allocation in Hetao Irrigation Area which was considered to be one of the most water-scare and ecological vulnerable area worldwide. According to the calculation of the water footprint, corn would be the best crop with lower water consumption and nitrogen pollution, being followed by sunflowers and wheat. Optimal plans regarding crop cultivation reconfiguration were generated from the IOMWF model. According to the model results, corn and sunflowers would be the most popular crops. Except that the sunflowers planting area in Wuyuan County would be larger than that of corn, the remained areas would be more suitable for planting corn. In addition, the utilization rate of green water would be lower than 0.5 and have a larger potential room to improve.

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