Cropping pattern optimization considering uncertainty of water availability and water saving potential

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Abstract: In arid and semi-arid areas, the profitability of irrigated agriculture mainly depends on the availability of water resources and optimal cropping patterns of irrigation districts. In this study, an integrated agricultural cropping pattern optimization model was developed with considering the uncertainty of water availability and water saving potential in the future, aiming to maximize agricultural net benefit per unit of irrigation water. The available water which was based on the uncertainty of runoff was divided into five scenarios. The irrigation water-saving potential in the future was quantified by assuming an increase in the rate irrigation water-saving of 10% and 20%. The model was applied to the middle reaches of Heihe River basin, in Gansu Province, China. Results showed that if the irrigation water-saving rate was assumed to increase by 10%, then the net water-saving quantity would increase by 21.5-22.5 million m^3 and the gross water-saving quantity would increase by 275.7-303.0 million m^3. Similarly, if the irrigation water-saving rate increased by 20%, then the net water-saving quantity would increase by 43.0-45.1 million m^3 and the gross water-saving quantity would increase by 331.7-383.2 million m^3. If the agricultural cropping pattern was optimized, the optimal water and cultivated area allocation for maize would be greater than those for other crops. Under the premise that similar volume of irrigation water quantity was available in different scenarios, results showed differences in system benefit and net benefit per unit of irrigation water, for the distribution of available irrigation water was diverse in different irrigation districts.

Keywords: cropping pattern optimization, irrigation water-saving potential, different scenarios, water availability, water use efficiency, particle swarm optimization (PSO)

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1 Introduction

Optimization of cropping patterns plays an important role in high-benefit and water-saving agricultural management[1], which determines the water requirement at the head and ultimately helps estimate the required capacity of the reservoir and the canal system[2]. In arid and semi-arid areas, the profitability of irrigated agriculture mainly depends on the availability of irrigation water and the cropping pattern of irrigation districts. Irrigation water is a key determinant of a crop area optimization model[3]. However, waste of irrigation water, owing to the lower use efficiency, has made aggravated the crisis of irrigation water[4,5]. At present time in northwest of China, irrigation efficiency is low, meaning there is higher agriculture water-saving potential[6]. In order to alleviate water shortage for irrigation, it is therefore essential to develop water-saving irrigation. Estimation of irrigation water-saving potential, which can calculate how much water could be saved by adopting water-saving measures, is desired and would benefit agricultural water management[7,8]. Many studies have investigated water-saving potential[6,9,10]. Jägermeyr et al.[11] incorporated a process-based irrigation system representation n into a bio-agrosphere model to calculate the water saving potential. Yan et al.[12] investigated on-farm techniques to assess water consumption of some crops. Gao et al.[13] applied user's preference for saving water and adopting end use analysis to analyze water conservation. Damerau et al.[14] estimated water saving potential from the viewpoint of development of future food and energy supply. However, previous literature focused on applying experimental and statistical methods to quantify agricultural water saving potential but relatively little attention was given to the irrigation water-saving potential caused by agricultural water-saving engineering development.

An optimal cropping pattern depends upon the water availability, with the objective of meeting the maximum irrigation potential as well as the maximum economic return[2]. Mathematical models, such as linear programming[15-17] and non-linear programming[7,18-20], have been widely used for achieving different objectives. For cropping pattern optimization, different optimization objectives, such as single objective[21] or multi objectives[22,23] need to be considered for the decision maker. For a multi objective model, mathematical techniques that can handle all the objectives simultaneously are needed. Examples of such mathematical techniques include goal programming[24,25], fuzzy optimization[26-28], and stochastic optimization[29-31].

Numerous factors can influence the results of cropping pattern optimization. Some researchers have studied cropping pattern

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optimization considering the influence of these factors. For example, Zhang and Guo[8] obtained optimal solutions of planting structure by adjusting planting scale and multiple cropping indexes to determine the rule of water saving quantity-benefit. Cid-Garcia et al.[32] determined an optimal crop pattern for maximizing the farmer's expected profit by assessing the chemical and physical management zones. Dong et al.[4] combined the vulnerability and contribution rate assessment to propose an effective solution for crop structure adjustment.

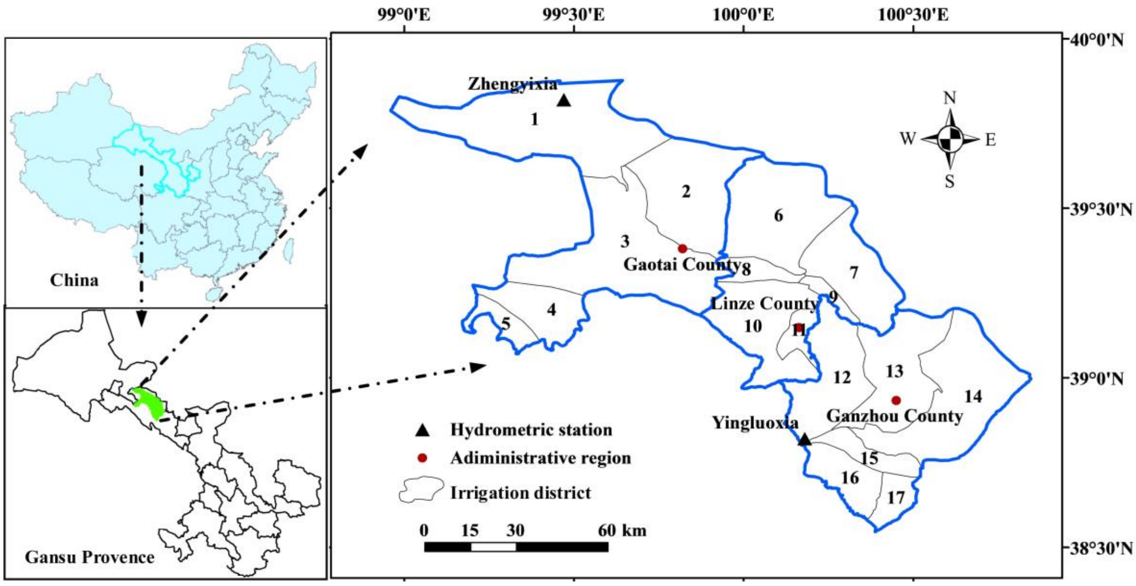
However, incorporating the irrigation water-saving potential in cropping pattern optimization does not seem to have been investigated. Therefore, it would be desirable to develop a model that can handle uncertainties and complexities in cropping pattern optimization, with the aim to maximize profitability of irrigation water. This paper focuses on the irrigation water-saving potential, estimating how much water could be saved and reused in an irrigation system through the development of water-saving agriculture in future. Therefore this paper proposed a development pattern of agricultural crops in the future, based on agricultural cropping pattern optimization model considering different hydrological frequencies, and in conjunction with agricultural irrigation water-saving potential in future.

2 Materials and methods

2.1 Study area

The study area is located in the middle reaches of Heihe River basin (97°37′-102°06′E, 37°44′ -42°40′N), northwest of China. In the arid and semi-arid areas, crop growth mainly depends on agricultural irrigation. Thus, agricultural available water should be taken into consideration, when making decision for suitable and sustainable cultivated land scale[34]. However, it is estimated that the water use efficiency of agricultural irrigation in the middle reaches merely approaches to 0.52[3,5]. This suggests that there is high agricultural water-saving potential. Improving the efficiency of irrigation water use thus becomes the effective way to improve agricultural benefit[36]. Hence there is enormous potential to improve agricultural water resources. Therefore, estimating irrigation water-saving potential, which can calculate how much water could be saved by adopting water-saving measures, is desired and would benefit water-saving agricultural development.

The study area includes 17 irrigation districts in Ganzhou District, Linze County and Gaotai County (as shown in Figure 1).



1. Luocheng irrigation district (LC) 2. Liuba irrigation district (LB) 3. Youlian irrigation district (YL) 4. Xinba irrigation district (XB) 5. Hongyazi irrigation district (HYZ) 6. Pingchuan irrigation district (PC) 7. Banqiao irrigation district (BQ) 8. Liaoquan irrigation district (LQ) 9. Yanuan irrigation district (YN) 10. Liyuanhe irrigation district (LYH) 11. Shahe irrigation district (SH) 12. Xijun irrigation district (XJ) 13. Yingke irrigation district (YK) 14. Daman irrigation district (DM) 15. Shangshan irrigation district (SS) 16. Huazhai irrigation district (HZ) 17. Anyang irrigation district (AY)

Figure 1 Study system of the middle reaches of Heihe River basin

2.2 Methods and data

2.2.1 Data acquisition

Data related to water-saving condition (water-saving area, irrigation quota in water-saving condition) were collected through Zhangye Irrigation Management Report (http://swj.zhangye.gov.cn/). Parameters related to irrigation quota, crop yield, the net irrigation quota of crop, cost and price of 7 crops were collected through the Statistical Yearbook of Zhangye City (http://www.zytj.gov.cn/). Agricultural price data were obtained from the Gansu prices net (http://www.gswj.gov.cn/). Annual minimum grain and vegetable demand were according to China Food and Nutrition Development Outline (http://www.moa.gov.cn/). Available irrigation water under different probabilities of water level in irrigation districts (as shown in Table 1) was obtained from Zhao et al.[38]

The category of five flow year was based on the frequency analysis method[38]. Let p denotes the hydrological frequencies, the flow years divided into five conditions of very-high, high, middle-level, low and very low with $p\leq 12.5\%$, $12.5\%<p\leq 37.5\%$, $37.5\%<p\leq 62.5\%$, $62.5\%<p\leq 87.5\%$ and $87.5\%<p$, respectively.

2.2.2 Irrigation water-saving potential

In order to explore agricultural water-saving potential by adopting efficient agricultural water management inside an agriculture irrigation system, this study quantified agricultural water-saving potential by distinguishing "net water saving" and "gross water saving" based on irrigation water-saving potential estimation theory[6] at the irrigation district scale under different proportions of an agricultural water-saving irrigation area. According to this theory, the concepts "gross water saving" and "net water saving" were introduced to avoid the argument between engineering-type water-saving and real water-saving. Gross water saving is the quantity of irrigation water saving on account of improving the efficiency of irrigation water use and reducing seepage loss and soil evaporation. The net water saving is the quantity of saving of invalid water consumption and invalid loss water[6].

Table 1 Available irrigation water under different hydrological frequencies in irrigation districts million m^3

Administrative region	Irrigation districts		Very-low years	Low years	Middle-level years	High years	Very-high years
Gaotai County	1	LC	36.14	36.05	35.82	35.72	35.64
	2	LB	23.75	23.62	23.85	24.00	23.99
	3	YL	253.31	241.87	236.00	231.94	230.81
	4	XB	44.88	44.88	44.88	44.88	44.88
	5	HYZ	22.03	22.03	22.03	22.03	22.03
	6	PC	73.99	71.81	68.89	66.76	66.81
Linze County	7	BQ	89.96	76.15	71.62	66.87	66.98
	8	LQ	33.82	33.81	33.12	32.87	32.89
	9	YN	21.93	22.02	21.92	21.95	21.95
	10	LYH	49.99	166.85	166.85	166.85	166.85
	11	SH	39.34	34.56	32.90	31.66	33.44
Ganzhou District	12	XJ	234.21	224.93	216.94	211.95	221.52
	13	YK	201.31	194.40	187.64	183.43	191.54
	14	DM	169.35	168.92	164.12	161.18	167.03
	15	SS	86.43	75.94	72.05	68.71	73.40
	16	HZ	7.30	7.30	7.30	7.30	7.30
	17	AY	26.68	26.68	26.68	26.68	26.68
Sum			1414.43	1471.82	1432.61	1404.77	1433.73

Figure 2 illustrates a detailed decomposition of gross water saving and net water saving. Gross water saving mainly includes two parts, one is invalid water loss reduced and the other is invalid water consumption reduced.

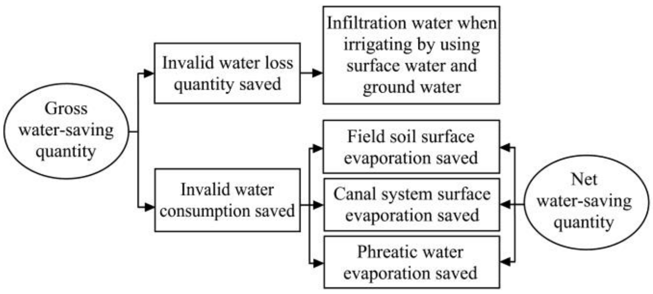


Figure 2 Components of gross water-saving quantity and net water-saving quantity[6]

Gross water saving gives an account of engineering-type water-saving potential, which is the water saved in irrigation canal systems, field irrigation systems and management of water saving irrigation project. In other words, gross water saving is the amount of irrigation water saving on account of improving the efficiency of irrigation water use, which gives an account of the difference in value between irrigation water availability at the present time and water saving scenarios in future. According to the irrigation water-saving potential estimation theory established by Lei et al.[6], net water-saving quantity and gross water-saving quantity can be expressed as below.

(1) Net water-saving quantity

The net water-saving quantity is defined as the saving quantity of invalid water consumption, expressed as Equation (1):

$$\Delta W_{net} = \sum_{1}^{n} \Delta A_i \cdot \Delta I_i \tag{1}$$

where, ΔW_{net} is the net water-saving quantity; ΔA_i is the increasing area of water-saving measure i; and ΔI_i is the reduction of net irrigation quota of water-saving measure i.

(2) Gross water-saving quantity

Gross water-saving is the amount of water-saving on account of improving the efficiency of irrigation water use and reducing seepage loss and soil evaporation, expressed as Equation (2):

$$\Delta W_{\text{gross}} = W_0 - W_t = A_0 \left(\frac{I_{\text{net}0}}{\eta_0} - \frac{I_{\text{net}t}}{\eta_t}\right) \tag{2}$$

where, ΔW_{gross} is the gross water-saving quantity; W_0 is the irrigation water in the status quo condition; W_t is the irrigation water in the water-saving condition; A_0 is the irrigation area; I_{net0} is the net irrigation quota in the status quo condition; I_{nett} is the net irrigation quota in the water-saving condition; η_0 is the efficiency of water use in irrigation systems in the status quo condition; η_t is the efficiency of water use in irrigation systems in the water-saving condition. Here I_{net0} can be formulated as Equation (3), I_{nett} can be formulated as Equation (4), η_t can be formulated as Equation (5), η_i denotes the efficiency of water use of water-saving measure i.

$$I_{net0} = \frac{W_0 \cdot \eta_0}{A_0} \tag{3}$$

$$I_{nett} = \frac{A_0 \cdot I_{net0} - \sum_{i}^{n} \left(\Delta A_i \cdot \Delta I_i\right)}{A_0} = I_{net0} - \frac{\Delta W_{net}}{A_0} \tag{4}$$

$$\eta_t = \frac{\sum_{i=1}^{n} \left(A_i \cdot \eta_i\right)}{A_0} \tag{5}$$

2.2.3 Crop structure optimization model based on irrigation water-saving potential

In this study, an integrated agricultural cropping pattern optimization model is built, based on the present agricultural crop development pattern, in conjunction with agricultural water saving potential in the future to gain high-efficiency water management solutions. The question under consideration is quantifying agricultural water saving potential and how to determine the optimal structure which could obtain maximum agricultural net benefit per unit of irrigation water by allocating the limited water to seven main crops (maize, wheat, potato, maize seed, cotton, oil crops, and vegetables), which is in the pursuit of the maximum water use efficiency. The objective function of integrated agricultural cropping pattern optimization model can be expressed as follow equations:

$$\max f = \sum_{i=1}^{n}\sum_{j=1}^{7}((y_{ij}v_{ij} - c_{ij}) \cdot x_{ij} / ET_{ij}) / \sum_{i=1}^{n}\sum_{j=1}^{7} x_{ij} \quad (6)$$

where, f is the expected net benefit per unit of irrigation water (RMB/m^3); i (i=1,2,$\cdots$,17) is subarea, the meaning has been illustrated in Table 1; j (j=1,2,$\cdots$, 7) is the crop type, with j=1 means maize, j=2 wheat, j=3 means potato, j=4 means maize seed, j=5 means cotton, j=6 means oil crops, j=7 means vegetables; x_{ij} is decision variable, which expresses the planting area of crop j on irrigation district i (ha); y_{ij} is the yield per unit area of crop j in the irrigation district i (kg/ha); c_{ij} is the cost of crop j in the irrigation district i (RMB/ha); and ET_{ij} is the net irrigation quota of crop j in the irrigation district i (m^3/hm^2).

Subject to the following constraints:

Water supply to irrigation district would be less than the available water:

$$\sum_{i=1}^{n}\sum_{j=1}^{7} m_{ij}x_{ij} \le Q_i + \Delta W_{\text{gross}i} \quad (7)$$

The crop area would be less then the irrigation district area:

$$\sum_{i=1}^{n}\sum_{j=1}^{7} x_{ij} \le X_n \quad (8)$$

Agricultural product (crop and vegetable) would be to meet the local demand:

$$\sum_{i=1}^{n}\sum_{j=1}^{4} x_{ij} \cdot y_{ij} \ge K \cdot P \cdot FN \quad (9)$$

$$\sum_{i=1}^{n}\sum_{j=9} x_{ij} \cdot y_{ij} \ge K \cdot P \cdot VN \quad (10)$$

$$x_{ij} \ge 0 \quad (11)$$

where, m_{ij} is the gross irrigation quota of crop j in the irrigation district i (m^3/hm^2); Q_i is the available water supply in the irrigation district i (m^3); $\Delta W_{\text{gross}i}$ is the gross water-saving quantity in the irrigation district i (m^3); X_n is the effective irrigated area of the irrigation district i (hm^2); P is the population in the study area; FN is the per person grain demand, 135 kg/person; and VN is the per person vegetable demand, 140 kg/person.

2.2.4 Particle swarm optimization

There are a large number of variables in the agricultural cropping pattern optimization model. Particle swarm optimization (PSO) is an effective alternative for dealing with multiple variables which is stochastic population-based algorithm motivated by intelligent collective behavior of birds.

In PSO, an individual is compared to a particle and the population is called as a swarm[33]. The particle moves in a search space by updating velocity and position which represent the possible way to the problem and the direction to obtain the global optimal value. The position and velocity can be upgraded by formulas (12) and (13):

$$v_i(t+1) = \omega(t) \cdot v_i(t) + c_1 \cdot r_1 \cdot (P_i(t) - x_i(t)) + c_2 \cdot r_2 \cdot (P_g(t) - x_i(t)) \quad (12)$$

$$x_i(t+1) = x_i(t) + r \cdot v_i(t+1) \quad (13)$$

where, $v_i(t)$ and $x_i(t)$ are the velocity and position of particle i at iteration t; $P_i(t)$ is the position with the best fitness value; $P_g(t)$ is the global best position; c_1 and c_2 are positive constant parameters which are called acceleration coefficients, and are usually assigned a value 1; r_1, r_2 are random numbers between 0 and 1; and ω represents the inertia weight.

$\omega(t)$ can be upgraded according to the following formula[37]:

$$\omega(t) = \omega_{\max} - (\omega_{\max} - \omega_{\min}) \cdot t / t_{\max} \quad (14)$$

where, $\omega_{\max}$ and $\omega_{\min}$ are the maximum and minimum values of inertia weight, and are usually assigned values of 1 and 0; and $t_{\max}$ is the number of iterations.

$P_i(t)$ and $P_g(t)$ can be upgraded according to the following formulas:

$$p_i(t) = \begin{cases} x_i(t+1), & \text{if } fitness(x_i(t+1)) < fitness(x_i(t)) \\ P_i(t), & other\ wise \end{cases} \quad (15)$$

The optimal position of the whole swarm at time t is calculated from Equation (11):

$$P_g(t) = \min\{fitness(P_1(t)), fitness(P_2(t)), \cdots, fitness(P_N(t))\} \quad (16)$$

3 Results and discussion

The aim of model was to generate desired alternatives for crop area based on maximizing the net benefit per unit of irrigation water and given constraints. The model equations were solved using the method described in 2.2.4.

3.1 Irrigation water-saving potential

Irrigation water quantity is a key determinant of crop area optimization model. However, besides irrigation water, the irrigation water-saving potential in irrigation district can be used as irrigation water if engineering-type water-saving is considered.

The water-saving rate was represented as the relative proportion of water-saving irrigation area and effective irrigated area in this study. For the current situation, the effective irrigated area is 140 349 hm^2, and the water-saving irrigation area is 58 217 hm^2, therefore the water-saving rate was 41.48%. The water use efficiency is 0.52 in this region. The current condition was defined as scenario S_0. According to the water resources planning of Zhangye City (http://www.zhangye.gov.cn/), the water use efficiency should exceed 0.60 by 2020. After the calculation in this paper, when the water-saving rate increased by 10% and 20%, it would increase to 0.6 and 0.62, which fulfills requirements of water resources planning. Therefore, the situations when water-saving rates increase 10% and 20% were defined as scenario S_1 and scenario S_2 respectively.

Assuming the effective irrigated area 140 349 hm^2 is invariable, when the water-saving rate was assumed to increase 10%, the increment of water-saving irrigation area would be 14 035 hm^2. However, when relative proportions of the canal water-saving irrigation area and field water-saving irrigation area exhibit randomness which will lead to highly uncertain water-saving quantity, because the reduction of net irrigation quota of field water-saving irrigation was 1605 m^3/hm^2, while the reduction of net irrigation quota of canal water-saving irrigation was 1530 m^3/hm^2. For example, in case the increment area was all allocated to canal water-saving irrigation area, assuming the relative proportions between cannel leakage prevention and low pressure pipe transport is invariable, then the cannel leakage prevention area should be 42 760 hm^2 and the low pressure pipe transport area should be 23 273 hm^2. If the increment area was all allocated to field water-saving irrigation area, then the area of cannel leakage prevention and low pressure pipe transport should be the same as the area in S_0 scenario. The water-saving area of canal and field under different scenarios can be calculated (as shown in Table 2).

Based on the area analysis above, the water-saving potential was calculated according to the Equations (1)-(5), under the current circumstance, gross irrigation quota is 13 096 m^3/hm^2, when water-saving rate increases 10%, it would drop to 10 937-11 132 m^3/hm^2, meanwhile net irrigation quota would drop from 6810 m^3/hm^2 to 6650-6657 m^3/hm^2. Accordingly, water use efficiency would change from 0.520 to 0.598-0.608. Similarly, when water-saving rate increases 20%, it would drop to 10 366-10 733 m^3/hm^2, meanwhile net irrigation quota would drop to 6489- 6504 m^3/hm^2, accordingly, water use efficiency would rise to 0.606-0.626 (as shown in Table 3).

In order to solve the irrigation water-saving area in future, the maximum and minimum values of net water-saving quantity were calculated in order to mitigate the impact of uncertainty.

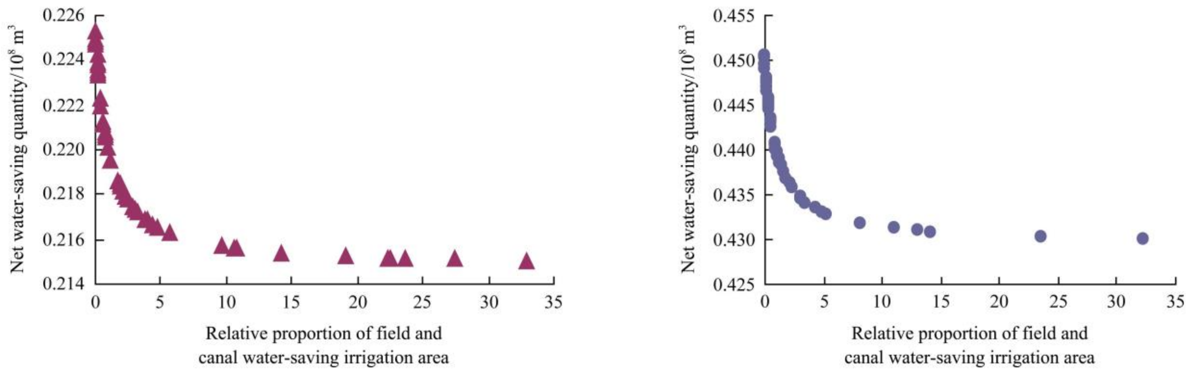
Table 2 Water-saving area under different water-saving scenarios

Scenario	Water-saving rate/%	Effective irrigated area/hm^2	Canal water-saving irrigation area/hm^2		Field water-saving irrigation area/hm^2			Total /hm^2
			Cannel leakage prevention	Low pressure pipe transport	Drip irrigation	Spray irrigation	Other measures	
S_0	41.48	140349	33667	18328	6067	129	27	58217
S_1	51.48	140349	33667-42760	18328-23273	6067-19747	129-420	27-87	72252
S_2	61.48	140349	33667-51840	18328-28220	6067-33433	129-713	27-147	86287

Table 3 Water-saving potential under different water-saving scenarios

Scenario	Gross irrigation quota /m^3 hm^{-2}	Net irrigation quota /m^3 hm^{-2}	Water use efficiency	Net water-saving quantity /million m^{-3}	Gross water-saving quantity /million m^{-3}
S_0	13096	6810	0.520		
S_1	10 937-11 132	6650-6657	0.598-0.608	21.5-22.5	275.7-303.0
S_2	10 366-10 733	6489-6504	0.606-0.626	43.0- 45.1	331.7-383.2

Figure 3 shows the relationship between net water-saving quantity and relative proportions of canal water-saving irrigation area and field water-saving irrigation area. In case the increment area was all allocated to canal water-saving irrigation area, the net water-saving quantity would be 21.5 million m^3. Otherwise, in a situation in which the increment area was all allocated to field water-saving irrigation area, the net water-saving quantity would be 22.5 million m^3. Namely, if water-saving rate increases by 10%, the net water-saving quantity would increase by 21.5-22.5 million m^3, the gross water-saving quantity would increase by 275.7-303.0 million m^3. Similarly, if the water-saving rate increased by 20%, the net water-saving quantity would increase by 43.0-45.1 million m^3, the gross water-saving quantity would increase by 331.7-383.2 million m^3.



a. Water-saving rate 51.48% b. Water-saving rate 61.48%

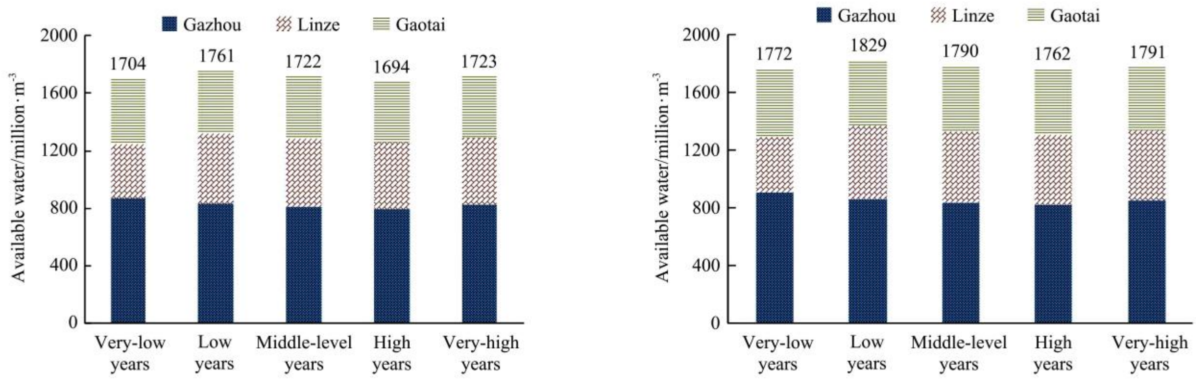
Figure 3 Net water-saving quantity under different water-saving rate

3.2 Available irrigation water

A development pattern of agricultural crop structure in the future was proposed by considering an agricultural cropping pattern optimization model under different probabilities of water level, and in conjunction with agricultural water saving potential in future. Figure 4 shows the available irrigation water when water-saving rate increases 10% and 20%. In Heihe River basin, State Council of the People's Republic of China introduced a series of regulations about water reallocation of the Heihe River to recover ecological environment in the downstream area and relieve water contradiction in Heihe River basin. The plan of water reallocation of the Heihe River stipulates the water discharge of Zhengyixia station under different probabilities of water level, for example, when the probability of water level is 90%, stream flow in Yingluoxia station is 1900 million m^3, there must be 1320 million m^3 discharge at Zhengyixia station. However, when the probability of water level is 10%, stream flow in Yingluoxia Station is 1290 million m^3, there must be 630 million m^3 discharges at Zhengyixia station. Therefore, the available water for agriculture will become less in high flow year compared with the low flow year.

3.3 Cropping pattern optimization

According to various flow levels and agricultural water saving potential, 7 different crops and 10 scenarios of water availability were designed to analyze agricultural cropping patterns in future. Scenarios 1 and 2 are in very-low years, the water-saving rates are 51.48% and 61.48%, respectively, and the available water volumes for agriculture are 1704 million m^3 and 1772 million m^3; scenarios 3 and 4 are in low flow years, the water-saving rates are 51.48% and 61.48%, respectively, and the available water volumes for agriculture are 1761 million m^3 and 1829 million m^3; scenarios 5 and 6 are in normal flow years, the water-saving rates are 51.48% and 61.48% respectively, and the available water volumes for agriculture are 1722 million m^3 and 1790 million m^3; scenario 7 and 8 are in high flow years, the water-saving rates are 51.48% and 61.48%, respectively, and the available water volumes for agriculture are 1694 million m^3 and 1762 million m^3; and scenarios 9 and 10 are in very-high flow years, the water-saving rates are 51.48% and 61.48%, respectively, and the available water for agriculture are 1723 million m^3 and1791 million m^3.



a. Water-saving rate 51.48% b. Water-saving rate 61.48%

Figure 4 Available irrigation water under different water-saving rate

Figure 5 presents the optimized crop area patterns in different scenarios of Ganzhou, Linze and Gaotai County. In conjunction with available irrigation obtained from Figure 4, the total cultivated areas were different, because of the different available water under different scenarios.

The process of determining the optimal cropping pattern was operating at the level of irrigation district. In fact, optimal solutions of planting structure were related to various variables, such as irrigation quota and yield per hectare, which were different in different irrigation districts. Figure 5a gives the optimal cropping pattern under very low flow level. In Figure 5a, as water-saving rate increases under the same water level, the cultivable area of maize seed increases in Ganzhou, Linze and Gaotai county, while the vegetable and potato area is transferred to other 5 crops in Ganzhou county, the wheat and potato area is transferred to other 5 crops in Linze county, and the wheat area is transferred to other 6 crops in Gaotai county.

It can be found in Figure 5 and Table 4 that the cultivable area of maize seed and the optimal system benefit increases in Ganzhou, Linze and Gaotai county, while the total quantity of irrigation water increases. That means the optimal water and cultivated area allocation to maize seed is greater than water and cultivated area allocation to other crops. For the reason that compares with other crops, the irrigation quota of maize seed is smaller than maize, potato and vegetable in most irrigation districts and the unit price is higher than maize, wheat, potato and vegetable in most irrigation districts, so that the benefit per unit of water is higher than other crops.

Another relevant result is the fact that the major crops in Ganzhou, Linze and Gaotai county are similar, while the proportions of the main crops are different in these three counties. For example, the proportion of maize seed in Ganzhou, Linze and Gaotai County is about 77%, 59%, 40% respectively. Except for maize seed, the cultivable area of maize area is the second largest in Ganzhou county, accounting for about 10% in different scenarios, and then is vegetable and wheat, accounting for about 7% and 5%, respectively.

While the cultivable area of wheat is the second largest in Linze County, approaching 26% in different scenarios, and then is vegetable and maize, the proportions of them are nearly 9% and 6%, respectively. However, the cultivable area of maize is the second largest in Gaotai County, accounting for approximately 23% in different scenarios, and then is vegetable and cotton; the proportions of them are nearly 14% and 12%, respectively.

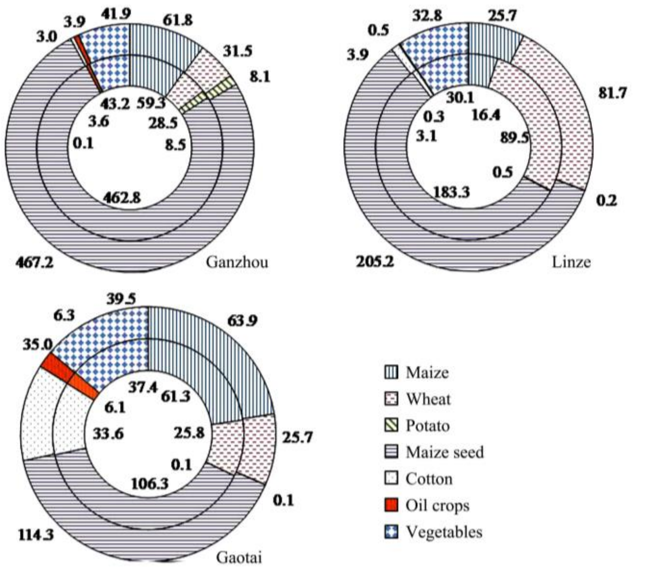
Comparing Figure 5c with Figure 5e, it can be found that the total quantities of irrigation water are approximate under normal flow level and very-high flow level, however, the optimized crop area patterns showed some differences, for the available irrigation water allocation is different in irrigation districts.

The solutions obtained can not only provide an effective evaluation under present scenarios, but also reveal the associated economic implications. Different scenarios would result in varied system benefits. Table 4 gives the system benefits of the middle reaches of Heihe River basin under different scenarios. Results reveal that stream flow level is an important variable which can directly affect optimal system benefit.

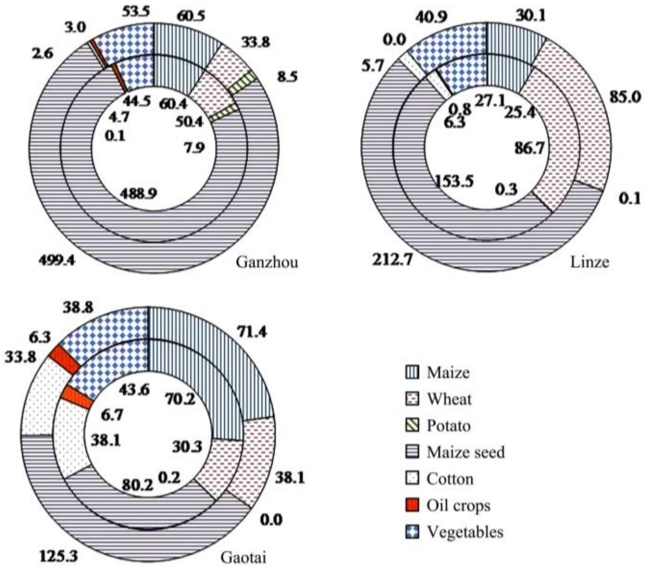
Under the premise of maximum economic benefit per unit of irrigation water, optimal total benefit achieves 2.68 billion RMB, and the benefit of per unit of irrigation water is 2.703 RMB/m^3 under low flow level, with the available irrigation water quantity being 1761 million m^3 and the water-saving rate being 51.48%, when the water-saving rate increases to 61.48%, optimal total benefit would achieve 2.87 billion RMB, and benefit of per unit of irrigation water would be 2.731 RMB/m^3.

It reveals under the same distribution of available irrigation water that as the quantity decreases, the system benefit and net benefit per unit of irrigation water would decrease for the reason of less water availability. For example, optimal total benefit achieves 2.54 billion RMB, and benefit of per unit of irrigation water is 2.699 RMB/m^3 under high flow level, with available irrigation water quantity being 1694 million m^3 and water-saving rate being 51.48%, when the water-saving rate increases to 61.48%, optimal total benefit would achieve 2.65 billion RMB, and benefit of per unit of irrigation water would be 2.716 RMB/m^3.

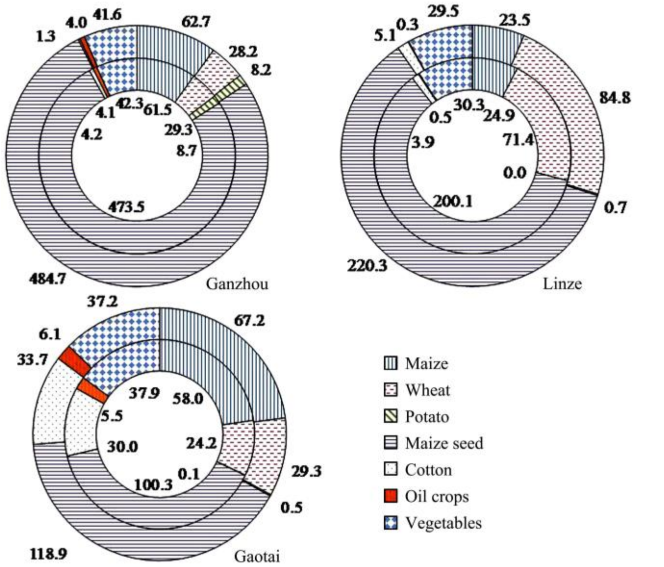
The result shows the difference between system benefit and net benefit per unit of irrigation water, under the approximate available irrigation water quantity (Scenarios 5, 6, 9, 10). Because under very-high flow level, the allocation of available irrigation water is different from the allocation under normal flow level, there is more available irrigation water in some well-equipped irrigation districts, which lead to more benefit per unit of water compared with other irrigation districts.



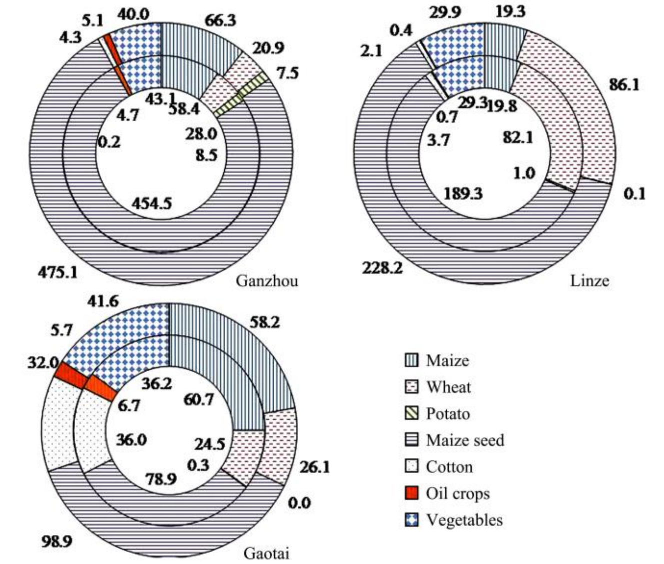
a. Very-low years



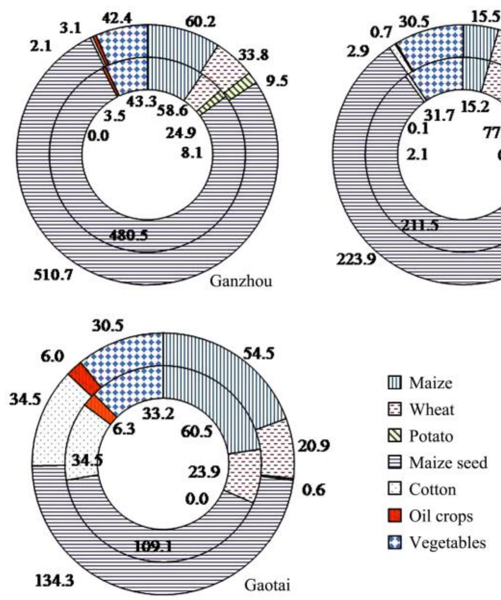
b. Low years



c. Middle-level years



d. High years



e. Very-high years

Note: The inner circle presents water-saving rate is 51.48%; the outer circle presents water-saving rate is 61.48%.

Figure 5 Crop structure under in different scenarios (hundred hm^2)

Table 4 Optimal system benefit under different water-saving scenarios

Scenario	Flow level	Water-saving rate	Water use efficiency	Available irrigation water quantity/million m^3	net benefit per unit of irrigation water/RMB·m^{-3}	Optimal system benefit /billion RMB
1	Very-low	51.48%	0.59	1704	2.682	2.61
2		61.48%	0.61	1772	2.715	2.68
3	Low flow	51.48%	0.59	1761	2.703	2.68
4		61.48%	0.61	1829	2.731	2.87
5	Normal flow	51.48%	0.59	1722	2.678	2.64
6		61.48%	0.61	1790	2.730	2.71
7	High flow	51.48%	0.59	1694	2.699	2.54
8		61.48%	0.61	1762	2.716	2.65
9	Very-high	51.48%	0.59	1723	2.727	2.63
10		61.48%	0.61	1791	2.742	2.81

4 Conclusions

The development pattern of agricultural crops structure in the future was proposed by considering an agriculture cropping pattern optimization model under different probabilities of water levels, and in conjunction with agricultural water-saving potential in future and was applied to Heihe River basin in Gansu Province, China.

This model is based on quantifying agricultural water-saving potential and determining the optimal structure which could obtain maximum agricultural net benefit per unit of irrigation water by allocating the limited water to 7 main crops. The main advantage of this model is that it can quantify the water-saving potential of irrigation area in future by calculating the maximum and minimum values of net water-saving quantity.

Under the premise of water-saving agricultural irrigation development, there is enormous water-saving potential in the middle reaches of Heihe River basin. Under the current circumstance the gross irrigation quota is 13 096 m^3/hm^2, when the water-saving rate increases by 10%, it would drop to 10 937-11 132 m^3/hm^2, accordingly, the water use efficiency would change from 0.520 to 0.598-0.608. As a result, there would be 275.7-303.0 million m^3 irrigation water to be saved. Similarly, when water-saving rate increases by 20%, there would be 331.7-383.2 million m^3 irrigation water to be saved.

Seven different crops and 10 scenarios of water availability have been designed to analyze the different agriculture cropping patterns in future according to various flow levels and agriculture water saving potential, aiming at maximizing the profitability of irrigation agriculture by incorporating a more efficient use of irrigation water through effective crop structure adjustment. It suggests that the optimal water and cultivated area allocation to maize seed is greater than to other crops. The irrigation quota of maize seed is smaller than maize, potato and vegetable in most irrigation districts and its unit price is higher than maize, wheat, potato and vegetable in most irrigation districts, so that the benefit per unit water is higher than other crops.

Under the premise of similar volume of irrigation water quantity available in different scenarios, results show the difference in system benefit and net benefit per unit of irrigation water, for the distribution of available irrigation water is diverse in different irrigation districts.

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