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Agricultural planting structure optimization and agricultural water resources optimal allocation of Yellow River Irrigation Area in Shandong Province

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ABSTRACT

A model for agricultural water resources optimal allocation is established by taking the maximization of the net irrigation benefit as a target in this paper. The first level is partition subsystem, and at this level an optimal allocation model of water supply for different crops is established. The second level is the irrigation area overall system, and at this level an optimal allocation model of water supply for different partitions is established. This model is applied in Tao Cheng-Pu Yellow River Irrigation Area in Shandong Province to optimize the agricultural planting structure and the annual distribution of surface water and ground water in different periods. The results show that compared with present, the optimized net irrigation benefit increased about 23.7% and the optimization scheme is feasible, which provides a scientific basis for the adjustment of agricultural planting structure and the management of water in this area.

Keywords: Yellow River Irrigation Area; Agricultural planting structure; Agricultural water resources; Optimal allocation

1. Introduction

In the condition of a given agricultural water use, the water resources optimization goal is that with a goal of ensuring agricultural output to realize optimal allocation and joint control of irrigation area water resources on the base of keeping groundwater in balance. Existing problems of Yellow River Irrigation Area in Shandong Province is that because of a larger water use in the upper reaches, excess water from irrigation soaks into underground and raises the water level. Meanwhile without rational exploitation of groundwater, secondary salinization would happen. However, the groundwater has been excessively exploited in the lower reaches because of difficult water diversion. So, it is especially important to determine a reasonable exploitation quantity of underground water as well as allocate surface water and ground water resources rationally in Yellow River

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Irrigation Area [1,2]. In view of above mentioned problems, a model for agricultural water resources optimal allocation is established in this paper.

2. Model building

According to the distribution of groundwater, the whole irrigation area is divided into three partitions, which is the upper (Partition Ⅰ), middle (Partition Ⅱ), and lower (Partition III) reaches. Water distribution is optimized both between different partitions and different crops as well as different development stages of the crops to ascertain the water allocation in whole irrigation area and optimal agricultural planting structure [3]. Take the partition subsystem as the first level to establish the optimal model of water distribution between different crops, and take the irrigation area overall system as the second level to establish the optimal model of water distribution between different partitions [4–6].

2.1. The first-level partition subsystem optimal allocation model building

2.1.1. Objective function

Take the maximum net irrigation benefit (the benefit of increasing yield by irrigation minus the irrigation cost of both surface water and ground water) of each partition as target, which is:

$$F_{i\max} = \sum_{j=1}^{J} [\delta_{ij} c_{ij} A_{ij} (\alpha_{ij} \cdot Y_{ij\max})] - \sum_{j=1}^{J} (C_1 \cdot Q_{1ij} + C_2 \cdot Q_{2ij})$$

In above formula, F_i = net irrigation benefit of partition i; δ_{ij} = irrigation benefit sharing coefficient; c_{ij} = the unit price of crop j in partition i; A_{ij} = planting area of crop j in partition i, hm^2; $\alpha_{ij=}$relative yield of crop j in partition i; Y_{ij} = the yield per hectare, kg/hm^2; C_1, C_2 = the irrigation cost of surface water, groundwater; Q_{1ij}, Q_{2ij} = surface, ground water use of crop j in partition i, $Q_{1ij} + Q_{2ij} = M_{ij} A_{ij}$, and M_{ij} = net irrigation quota of crop j in partition i.

2.1.2. Decision variables

Decision variables including crop irrigation quota, surface water use, ground water use, planting area, and yield. Decision variables of optimal allocation model are showed in Table 1.

2.1.3. Constraint conditions

(1) Planting area constrain.

$$A_{ij} \leqslant \varepsilon_{ij} A_{ij} \quad \forall i, j$$

$$\sum_{j=1}^{J} A_{ij} \leqslant A_i$$

In above formula, A_i = planting area of partition i, hm^2; A_{ij} = planting area of crop j in partition i, hm^2; and ε_{ij} = the proportion of planting area of crop j in partition i to total planting area.

(2) Crop water consumption constraint

$$\sum_{j=1}^{J} M_{ij} A_{ij} / \eta = \eta_1 \sum_{j=1}^{J} Q_{1ijt} + \eta_2 \sum_{j=1}^{J} Q_{2ijt} \quad \forall i, t$$

In above formula, η_1, η_2 = the utilization coefficient of surface water, ground water.

(3) Crop irrigation quota and relative yield constraint

$$\alpha_{ij} = \frac{Y_{ij}}{Y_{ij\max}} = \begin{cases} 1 & M_{ij\max} \leqslant M_{ij} \\ m_{0ij} + m_{1ij} M_{ij} + m_{2ij} M_{ij}^2 & M_{ij} \leqslant M_{ij\max} \end{cases}$$

In above formula, $M_{ij\max}$ = the optimal net irrigation quota corresponds to $Y_{ij\max}$; m_{0ij}, m_{1ij}, m_{2ij} = fitting coefficient of function relation between the optimal irrigation quota of crop j in partition i and relative yield.

(4) Surface water use constraint

$$\sum_{j=1}^{J} Q_{1ij} / \eta_1 \leqslant W_{1it} \quad \forall i, t$$

In above formula, t = a period of time, it is divided by month in different development stages of the crops, $t = 1, 2, \ldots, 12$; W_{1it} = available surface water supply for irrigation in partition i in the period of time t, m^3.

(5) Ground water use constraint

$$\sum_{j=1}^{J} Q_{2ij} / \eta_2 \leqslant W_{2it} \quad \forall i, t$$

$$H_i' < H_{it} \leqslant H_i''$$

Table 1
Decision variables of optimal allocation model

Partitions	Partition I					Partition II					Partition III				
Crops	Wheat	Corn	Vegetable	Fruit tree	Others	Wheat	Corn	Vegetable	Fruit tree	Others	Wheat	Corn	Vegetable	Fruit tree	Others
Planting area	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{21}	A_{22}	A_{23}	A_{24}	A_{25}	A_{31}	A_{32}	A_{33}	A_{34}	A_{35}
Irrigation quota	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{21}	M_{22}	M_{23}	M_{24}	M_{25}	M_{31}	M_{32}	M_{33}	M_{34}	M_{35}
Surface water consumption	X_{111}	X_{112}	X_{113}	X_{114}	X_{115}	X_{121}	X_{122}	X_{123}	X_{124}	X_{125}	X_{131}	X_{132}	X_{133}	X_{134}	X_{135}
Ground water consumption	X_{211}	X_{212}	X_{213}	X_{214}	X_{215}	X_{221}	X_{222}	X_{223}	X_{224}	X_{225}	X_{231}	X_{232}	X_{233}	X_{234}	X_{235}
Yield	Y_{11}	Y_{12}	Y_{13}	Y_{14}	Y_{15}	Y_{21}	Y_{22}	Y_{23}	Y_{24}	Y_{25}	Y_{31}	Y_{32}	Y_{33}	Y_{34}	Y_{35}

$$H_{it} = H_{it-1} + (\mu_i A_i 10^6)^{-1}\left(\beta_1 \sum_{j=1}^{J} Q_{1ijt-1} + \beta_2 \sum_{j=1}^{J} Q_{2ijt-1} + W'_{it-1} - ET_{it-1} + IN_{it-1} - OUT_{it-1} + 10^3\sigma_{it-1}P_{it-1}A_i\right)$$

In above formula, W_{2it} = available ground water supply for irrigation in partition i in the period of time t, m^3; H_{it}, H'_i, H''_i = bury of groundwater in the period of time t, the minimum allowed bury of groundwater and the maximum allowed bury of groundwater in partition i; μ_i = ground water specific yield in partition i; β_1, β_2 = surface water, ground water irrigation return flow rate; W'_{it-1} = groundwater exploitation, not including irrigation use, in the period of time $t-1$, m^3; ET_{it-1} = ground transpiration in partition i in the period of time $t-1$, m^3; IN_{it-1} = ground water inflow in partition i in the period of time $t-1$, m^3; OUT_{it-1} = ground water outflow in partition i in the period of time $t-1$, m^3; P_{it-1} = rainfall in partition i in the period of time $t-1$, mm; σ_{it-1} = the rainfall infiltration coefficient in partition i in the period of time $t-1$.

(6) Nonnegative constraints

All decision variables cannot be negative.

2.2. The second level-irrigation area overall system optimal allocation model building

The irrigation area overall system optimal allocation model, based on the feedback index F_i from the first level is used to determine surface and ground water allocation. It has the same decision variables and period division with the first level.

2.2.1. Objective function

In above formula, F = the net irrigation benefit of irrigation area; F_i = the net irrigation benefit of partition i.

$$F_{\max} = \sum_{i=1}^{I} F_{i\max}$$

2.2.2. Constraint conditions

(1) Planting area constraint

$$\sum_{i=1}^{I} A_i \leqslant A$$

In above formula, A = the total planting area, hm^2 ; A_i = planting area of partition i, hm^2.

(2) Crop water consumption constraint

$$\sum_{i=1}^{I}\sum_{j=1}^{J} M_{ij}A_{ij}/\eta = \sum_{i=1}^{I}(\eta_1 Q_{1it} + \eta_2 Q_{2it}) \quad \forall t$$

(3) Surface water use constraint

$$\sum_{i=1}^{I}\sum_{j=1}^{J} Q_{1ij}/\eta_1 \leqslant W_{1t} \quad \forall t$$

In above formula, W_{1t} = available surface water supply for irrigation in irrigation area in the period of time t, m^3.

(4) Ground water use constraint

$$\sum_{i=1}^{I}\sum_{j=1}^{J} Q_{2ij}/\eta_2 \leqslant W_{2t} \quad \forall t$$

$$H' \leqslant H_t \leqslant H''$$

$$H_t = H_{t-1} + (\mu A 10^6)^{-1}\left(\beta_1 \sum_{j=1}^{J} Q_{1jt-1} + \beta_2 \sum_{j=1}^{J} Q_{2jt-1} W'_{t-1} - ET_{t-1} + IN_{t-1} - OUT_{t-1} + 10^3 \sigma_{t-1} P_{t-1} A\right)$$

In above formula, W_{2t} = available ground water supply for irrigation in irrigation area in the period of time t, m^3; H_{it}, H'_i, H''_i = bury of groundwater in the periodoftime t, the minimum allowed bury of groundwater and the maximum allowed bury of groundwater in irrigation area; μ = ground water specific yield in irrigation area; W'_{t-1} = groundwater exploitation, not including irrigation use, in the period of time $t-1$, m^3; ET_{t-1} = ground transpiration in irrigation area in the period of time $t-1$, m^3; IN_{t-1} = ground water inflow in irrigation area in the period of time $t-1$, m^3; OUT_{t-1} = ground water outflow in irrigation area in the period of time $t-1$, m^3; P_{t-1} = rainfall in irrigation area in the period of time $t-1$, mm; σ_{t-1} = the rainfall infiltration coefficient in irrigation area in the period of time $t-1$.

(5) Nonnegative constraints

All decision variables cannot be negative.

3. Model solution

Take the function relation between the optimal irrigation quota and relative yield in the first level as a constraint condition to satisfy the second level directly. Then, the optimization results will be achieved by using LINGO 8.0 computer program.

4. Model application

Take the agricultural water resources optimal allocation of Tao Cheng Pu Yellow River Irrigation Area for example.

4.1. Basic information

Tao Cheng Pu Yellow River Irrigation Area located in southern Liaocheng City in Shandong Province, and the designed irrigation area is 53333hm^2. The most major crops are wheat and corn, and planting area is 43593hm^2 in the current year [7] (Table 2).

Table 2
Planting area and proportion of irrigation area in the current year

Crop / Planting area and proportion	Wheat	Corn	Vegetable	Fruit tree	Others	Total
Planting area (hm^2)	43,593	43,593	4,443	1,707	3,591	53,333
Planting proportion (%)	81.74	81.74	8.33	3.20	6.73	100

Table 3
Annual average optimized planting area and proportion of irrigation area

Crop / Planting area and proportion	Wheat	Corn	Vegetable	Fruit tree	Others	Total
Planting area (hm^2)	30,667	30,667	6,133	6,200	10,333	53,333
Planting proportion (%)	57.50	57.50	11.50	11.63	19.38	100

Table 4
Optimal allocation of surface and ground water

Month			1	2	3	4	5	6	7	8	9	10	11	12	Total
Item															
Water resources quantity (10^4 m^3)		Surface water	0	0	44	613	687	1953	1,033	1,033	1,156	1,033	867	1,357	9,776
		Ground water	621	743	822	807	927	32	42	32	32	22	124	124	4,328
		Total	621	743	866	1,420	1,614	1985	1,075	1,065	1,188	1,055	991	1,481	14,104
Water resources distribution between crops (10^4 m^3)	Wheat	Surface water	0	0	0	613	613	0	0	0	0	0	0	613	1,839
		Ground water	0	0	0	0	0	0	0	0	0	0	0	0	0
		Total	0	0	0	613	613	0	0	0	0	0	0	613	1,839
	Corn	Surface water	0	0	0	0	0	920	0	0	0	0	0	0	920
		Ground water	0	0	0	0	0	0	0	0	0	0	0	0	0
		Total	0	0	0	0	0	920	0	0	0	0	0	0	920
	Vegetable	Surface water	0	0	0	0	0	930	930	930	930	930	744	744	6,138
		Ground water	497	619	619	683	744	0	0	0	0	0	0	0	3,162
		Total	497	619	619	683	744	930	930	930	930	930	744	744	9,300
	Fruit tree	Surface water	0	0	44	0	74	0	0	0	123	0	123	0	364
		Ground water	0	0	79	0	49	0	0	0	0	0	0	0	128
		Total	0	0	123	0	123	0	0	0	123	0	123	0	492
	Others	Surface water	0	0	0	0	0	103	103	103	103	103	0	0	515
		Ground water	124	124	124	124	134	32	42	32	32	22	124	124	1,038
		Total	124	124	124	124	134	135	145	135	135	125	124	124	1,553

4.2. Model parameters determination

(1) Planting proportion: According to the emphasis of agricultural planting structure optimization [8] and agricultural overall planning, food crops should have a certain proportion in the upper reaches and high-value crops, such as fruit tree and vegetable are mainly planted; food crops are mainly planted in the middle and lower reaches with a certain proportion of fruit trees and vegetables. So, it is determined that optimized planting area of food crops is not less than 55% of total agricultural acreage, fruit tree is not more than 25%, and vegetable etc. is not more than 20%.

(2) Yield: According to the investigation of local crop irrigation and yield, the average yield is determined as wheat 7,725 kg/hm^2, corn 9,070 kg/hm^2, fruit tree 27,900 kg/hm^2, and vegetable 55,800 kg/hm^2.

(3) Irrigation quota: Irrigation quotas of wheat and corn are calculated based on optimized water allocation, and fruit tree and vegetable's are determined according to the standard [9]. The results show that fruit tree net irrigation quota is 3,225 m^3/hm^2 and gross irrigation quota is 5,760 m^3/hm^2, and the corresponding values of vegetable are 4,650 m^3/hm^2, 8,310 m^3/hm^2 under 50% irrigation guarantee rate. Fruit tree net irrigation quota is 4,050 m^3/hm^2 and gross irrigation quota is 7,230 m^3/hm^2, and the corresponding values of vegetable are 5,250 m^3/hm^2, 9,375 m^3/hm^2 under 75% irrigation guarantee rate.

(4) Crop price and irrigation benefit sharing coefficient: the price of wheat is 2.1 Yuan/kg, corn 1.9 Yuan/kg, fruit 3.0 Yuan/kg, vegetable 2.5 Yuan/kg; irrigation benefit sharing coefficient is 0.69 [10].

(5) The utilization coefficient of irrigation water: It is about 0.56 in current year and would be raised to 0.70 after the water-saving reform.

(6) Available surface and ground water supply for irrigation: annual average water diversion from the Yellow River of main canal head is $13{,}966 \times 10^4\,m^3$, and allowable groundwater exploitation is $5{,}410 \times 10^4\,m^3$.

(7) Irrigation cost: original Yellow River water supply price is 0.143 m^3/Yuan and terminal surface water price is 0.21 m^3/Yuan; the terminal ground water price is 0.21 m^3/Yuan with taking energy cost and maintenance cost into account [11].

4.3. Optimization results

4.3.1. Optimization scheme of agricultural planting structure

It is showed in Table 3: The proportion of food crop and cash crop is adjusted from 8:2 to 6:4, comparing with the original planting structure. Planting area of food crops is reduced by 24.24%, meanwhile planting area of fruit tree, vegetable, and others are

Table 5
Comparative analysis of irrigation benefit before and after optimization

Item		Current parameter	Optimized parameter	Parameter change
The proportion of food crop and cash crop		8:2	6:4	−24.24% (Planting proportion of food crop)
Total irrigation benefit (Ten thousand Yuan)		204,249	253,310	+49,061
Irrigation water use (104 m^3)	Surface water	7,821	9,776	+1955
	Ground water	3,462	4,328	+866
	Total	11,283	14,104	+2,821
Irrigation cost (Ten thousand Yuan)	Surface water	1,323	2052	+729
	Ground water	837	1,298	+461
	Total	2,160	3,350	+1,190
Net irrigation benefit (Ten thousand Yuan)		138,772	171,434	+32,662

raised, respectively by 3.17, 8.43, and 12.64%. The adjustment is in line with the development tendency that inhibiting food crops planting area properly and expand vegetable planting area so that to achieve the goal of peasantry increasing income [12,13].

4.3.2. Optimization distribution scheme of surface water and ground water

As it is shown in Table 4, surface water is mainly used by food crops, such as wheat and corn in the period before flood season and in June. Because the period is the main growth period of wheat as well as the "spring drought" in irrigation area [14], and the average ground transpiration nearly five times as rainfall in the same period which leads to the rainfall not nearly enough to meet crop water requirements. Ground water exploitation is concentrated before flood season, the quantity during January to May is $3{,}920 \times 104\,m^3$, about 91% of the total. Therefore, the ground water should be mainly used before flood season in order to empty the underground storage capacity for rainfall in flood season.

4.4. Results analysis

As it is shown in Table 5, although the utilization coefficient of irrigation water is raised about 25% after the agricultural planting structure optimization and agricultural water resources optimal allocation, but the irrigation water use and irrigation cost still increased due to the planting area expansion of high water-consuming crops. However, compared to the higher economic benefit of fruit tree and vegetable, it does not stop promoting the irrigation benefit which still raised about 23.7%.

5. Conclusions

(1) It is suggested that the proportion of food crop and cash crop is adjusted to 6:4.
(2) Water resources distribution between crops is that wheat: corn: fruit tree: vegetable: others = 13:7:3:66:11.
(3) To promote the development of high-efficiency water saving irrigation technology and make the utilization coefficient of irrigation water raise to 0.70.

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