Optimization of Water Allocation in Canal Systems of Chengai Irrigation Area

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Abstract: Chengai Yellow River Irrigation Area is situated in Liangshan County, Shandong Province, China. In history, no formalized irrigation regulations exist because of limitations on the project facilities and management capability. The utilization of water resources was unreasonable with serious waste of water and prolonged rotations and low irrigation benefits. Potential benefits have not been realized. With the development of agriculture production, it was considered urgently necessary to carry out research on the optimum water allocation in Chengai Yellow River Irrigation Area using system engineering methodology. Therefore, Based on the principle of system engineering and in accordance with the secondary main canal of the Chengai Yellow Irrigation Area, and taking the maximum irrigation benefits and minimum irrigation rotation as the objectives, the optimal crop pattern and irrigation water allocation models have been developed. Through calculations, the desirable optimal crop pattern and water allocation results were achieved. It proved in practice that the present research play very important role in water saving, irrigation and production improvement, and facilitation of irrigation area scientific management level.[Nature and Science, 2004;2(1):89-94].

Key words: irrigation canal systems; crop pattern; optimal water allocation model

1 Introduction

Chengai Yellow River Irrigation Area covers a total area of 542 km^2, of which 38000 ha are farmland, 20000 ha are gravity irrigated and 18000 ha lift irrigated. Main crops are wheat, maize, beans as well as other crops such as millet, sweet potatoes and sorghum, etc.

The irrigation area is situated in the warm temperature zone, with a continental monsoon climate. The average annual precipitation is only 647 mm, but evaporation reaches 1365 mm, which corresponds to semi-arid conditions. The distribution of rainfall is extremely uneven in time and space, resulting in serious water shortages. The principal source of water is the Yellow River supplementing groundwater. The annual diversion from the Yellow River is 150 million m^3 and the annual exploitation of groundwater amounts to 105 million m^3.

No formalized irrigation regulations exist because of limitations in the project facilities and in management capability. The utilization of water resources was unreasonable with serious waste of water and prolonged rotations. Potential benefits have not been realized. Therefore, it was considered urgently necessary to carry out research on optimum water allocation in Chengai Yellow River Irrigation Area using system engineering methodology.

The present research is based on the North Main Canal System in the gravity irrigation area, which includes 18 branch canals (Table 1). A mathematical model was established to determine the optimum crop patterns and water allocations with the minimum rotation times. Satisfactory results were obtained from the analysis and may be extended into the whole irrigation area.

2 Optimization Model for the Optimal Crop Pattern

In order to utilize the water resources reasonably, to match water supply and requirement and reach the maximum economic benefit, the optimum crop pattern for each branch canal was first determined. Linear programming was adopted in the present study to apply an optimization model to each branch canal separately.

Table 1 Parameters of the north main canal system in Chengai irrigation area

CANAL	Length (m)	Irrigated Area (ha)	Flow Capacity (m^3/s)	Distance to the head of Main Canal (m)
North Main Canal	10100	1018.86	2.50	0
Branch 1	1300	52.00	0.42	870
Branch 2	1279	61.40	0.37	1150
Branch 3	1262	49.40	0.37	1740
Branch 4	1260	67.13	0.37	2410
Branch 5	1307	45.73	0.37	3100
Branch 6	1308	61.67	0.20	3470 (Lined)
Branch 7	1340	66.00	0.42	3990 (Lined)
Branch 8	1389	69.33	0.42	4670
Branch 9	1420	53.33	0.37	5200
Branch 10	600	27.00	0.37	5900
Branch 11	450	20.27	0.37	6250
Branch 12	1420	46.87	0.42	6730
Branch 13	1390	91.73	0.42	7220
Branch 14	1320	82.20	0.67	8050
Branch 15	620	14.27	0.37	8440
Branch 16	620	44.00	0.37	8700
Branch 17	1350	94.67	0.42	9420
Branch 18	790	71.87	0.37	10100

2.1 Selection of decision variables

There are five kinds of crops in Chengai Yellow River Irrigation Area: wheat, maize, beans, cotton and other food grains. In order to determine the optimum crop area irrigated by every branch canal, the areas of different crops irrigated by each branch canal were selected as decision variables (parameters). Therefore, the selected decision variables are as follows:

$A_{i,j}$ = optimum planting area of crop j in the ith branch canal (ha).

i = 1,2 .... 18.

j=1,2 .... 5, where 1 stands for wheat, 2 for maize, 3 for beans, 4 for cotton, 5 represents other food grains.

2.2 Design of the objective function

For the purposes of this paper, the objective function is the maximum net benefit, for which the formula is as follows:

$$MaxZ_i = \varepsilon\sum_{j=1}^{N} A_{ij}P_j\Delta d_j - E\sum_{j=1}^{N} A_{ij} \tag{1}$$

where: ε = irrigation benefit allocation coefficient (0.4 in the study).

P_j = price of the crop j (＄/kg) (Table 2).

Δd_j = increased output of crop j through irrigation (kg/ha).

E = annual operational fee in the gravity irrigated area (13.6 ＄/ha).

N = number of the crops (5 in the study).

i = canal reference number 1, 2, ... 18.

j = crop characteristics reference number, 1, 2….5

Table 2 Characteristics of crops in the north main canal system

CROPS	Wheat	Maize	Beans	Cotton	others
Max. crop pattern*	0.90	0.60	0.20	0.25	
Min. crop pattern*	0.80	0.50	0.12	0.11	
Gross duty (m^3/ha)	1275	1125	1050	1125	
Growth period (days)	255	110	120	165	
price ($/kg)	0.171	0.12	0.236	1.091	
Output,1965(kg/ha)	765	1237.5	682.5	165	
Output,2000(kg/ha)	4590	4875	2040	750	
Increment (kg/ha)	3825	3637.5	1357.5	585	
Increment through irrigation ($/ha,)	261.4g	174.6	128.35	255.27	195.57
Irrigation periods	(1)26/11-5/12 (2)10/3-18/3 (3)3/4-17/4 (4)11/5-20/5	(6)21/5-28/5 (3)25/6-30/6	(6)21/5-28/5	(5)3/4-7/4 (7)21/6-24/6	(6)21/5-28/5 (8)25/6-30/6

2.3 Constraints

In the calculation of the optimum crop area, besides the maximum objective function, the relevant constraints must be included. These consist of limitations of total area, maximum and minimum crop areas and water supply. They are as follows:

2.3.1 Constraints of total area

The combined crop area irrigated per branch canal should be equal to or smaller than the total area irrigated by the canal. Considering the inter-plantation of wheat, maize, beans and the other food grains, the sum of the areas planted in wheat and cotton should not be larger than the total area controlled by the canal system. The total planting area of maize, beans and the other food grains should not be larger than the total area either, that is:

$$A_{i,1} + A_{i,4} \leqslant A_i \quad \text{(ha)...} \qquad (2)$$

where: A_i = area irrigated by the ith branch canal

$$\text{and} \quad \sum_{j=2}^{5} A_{i,j} \le A_i \quad \text{(ha)...} \qquad (3)$$

2.3.2 Constraints of maximum and minimum planting areas

According to local practice and the requirements of contracted farmland, on every branch canal there are maximum and minimum limitations on the planting area of different crops. The maximum and minimum constraint conditions are as follows:

$$0.9A_i \geqslant A_{i,1} \geqslant 0.8\,A_i \quad \text{(ha) (wheat)} \qquad (4)$$
$$0.6A_i \geqslant A_{i,2} \geqslant 0.5\,A_i \quad \text{(ha) (maize)} \qquad (5)$$
$$0.2A_i \geqslant A_{i,3} \geqslant 0.12\,A_i \quad \text{(ha) (beans)} \qquad (6)$$
$$0.25A_i \geqslant A_{i,4} \geqslant 0.11\,A_i \quad \text{(ha) (cotton)} \qquad (7)$$
$$0.15A_i \geqslant A_{i,5} \geqslant 0.11\,A_i \quad \text{(ha) (others)} \qquad (8)$$

2.3.3 Constraints of water supply

The irrigation area requires water supply 8 times annually; specific irrigation periods can be seen in Table 2. Every irrigation rotation should be finished within the required time, otherwise the crop yields will be influenced. The volume of water use can be obtained through calculation of crop area and the related irrigation duty (Table 2). The volume of water supply has been obtained from the maximum possible capacity of the North Main Canal. The constraints of water supply are as follow;

$$A_{ij}M_{k1} \leqslant \eta_m \eta_{bi} \frac{Q_m \times A_i}{F} \times d_k \times 24 \times 3600 \qquad (9)$$

where: M_{k1} = irrigation duty for crop 1 in kth irrigation rotation (m^3/ha),

K = 1,2,3, ...

η_m = water use coefficient in the main canal (0.92.),

η_{bi}= water use coefficient in each branch canal, η_{b6} = 0.99, η_{b7}= 0.9,

η_{bi} =0.71 for other branch canals,

d_k = total days of the kth irrigation rotation,

Q_m= maximum diversion flow in the North Main Canal (2.5 m^3/s),

F =irrigated area controlled by the North Main Canal (1019 ha),

The influence of soil moisture content has not been considered in the above formula for it is very difficult to forecast long-term soil moisture content. Therefore, the present paper selected the average irrigation duty to analyse crop patterns.

Because the first four irrigation rotations are for wheat, the conditions for wheat irrigation determine the water requirements; they can be merged into the one equation (Eq. 4).

The fifth rotation

$$A_{i,4}\ M_{5,4} \leqslant \eta_m \eta_{b,i} \frac{Q_m \times A_i}{F} \times d_5 \times 24 \times 3600 \quad (10)$$

The sixth rotation

$$A_{i,2}\ M_{6,24} + A_{i,3} M_{6,3} + A_{i,5}\ M_{6,5} \leqslant \eta_m \eta_{b,i} \frac{Q_m \times A_i}{F} \times d_6 \times 24 \times 3600 \quad (11)$$

The seventh rotation

$$A_{i,4}\ M_{7,4} \leqslant \eta_m \eta_{b,i} \frac{Q_m \times A_i}{F} \times d_7 \times 24 \times 3600 \quad (12)$$

The eighth rotation

$$A_{i,2}\ M_{8,2} + A_{i,5} M_{8,5} \leqslant \eta_m \eta_{b,i} \frac{Q_m \times A_i}{F} \times d_8 \times 24 \times 3600 \quad (13)$$

The result is shown in Table 3. All the calculations were undertaken on the computer. The optimum crop areas served by the branch canals and the objective function values have been printed out (OBJ.FUNC). Interactive dialogue was used. The following parameters should be input: k (number of branch canal), FK (area controlled by branch canals),G_2 (water use coefficient in branch canals), Q_m(the maximum flow capacity in the main canal).

3 Optimum Water Allocation Based on the Minimum Irrigation Rotation Time

A trial algorithm was used to calculate the minimum irrigation rotation required in the north main canal irrigation systems for the optimum crop areas. The optimum water allocation was calculated for different branch canals under the condition of maximum flow in the north main canal. The irrigation rotation order and water diversion volume of each branch canal were regulated to realize the shortest irrigation rotation and the optimum water allocation scheme.

Table 3 Results of crop optimization (ha)

Canals	CROPS					OBJ.FUNC ($)
	1	2	3	4	5	
1	46.280	31.20	7.280	5.720	7.80	13756.77
2	54.646	36.84	8.596	6.754	9.21	16243.57
3	43.966	29.64	6.916	5.434	7.41	13068.93
4	59.749	40.28	9.399	7.385	10.07	17760.34
5	40.703	27.44	6.403	5.031	6.86	12098.90
6	54.883	37.00	8.633	6.783	9.25	16314.11
7	58.74	39.60	9.24	7.26	9.90	17460.51
8	61.707	41.60	9.707	7.627	10.40	18342.35
9	47.467	32.00	7.467	5.867	8.00	14109.51
10	24.030	16.20	3.780	2.970	4.05	7142.94
11	18.037	12.16	2.837	2.229	3.04	5361.61
12	41.711	28.12	6.561	5.155	7.03	12398.72
13	81.643	55.04	12.843	10.091	13.76	24268.35
14	73.158	49.32	11.508	9.042	12.33	21746.28
15	12.697	8.56	1.997	1.569	2.14	3774.29
16	39.160	26.40	6.160	4.840	6.60	11640.34
17	84.253	56.80	13.253	10.413	14.20	25044.37
18	63.961	43.12	10.061	7.905	10.78	19012.55

3.1 Decision variables

The discharge Q_m in the north main canal for the rotations was selected as the decision variable.

3.2 Objective function

The minimum irrigation duration (TK) related to different irrigation rotations was selected as the objective function, that is:

$$MinTK = \frac{\sum_{i=j}^{M}\sum_{j=1}^{N} A_{ij}(M_j - W_k)}{Q_m \times \eta_m \times \eta_b \times 24 \times 3600} \quad (14)$$

In which, W_k = soil moisture content (m^3/ha).

Q_m = maximum discharge in the North Main Canal (m^3/s).

3.3 Constraints

3.3.1 Constraint of maximum discharge

The flow in the North Main Canal and the branch canals cannot be greater than the maximum canal capacities:

$$Q_{mi} \leqslant Q_m \quad (15)$$

in which: Q_{mi}=the ith discharge diversion in the North Main Canal, i = 1,2 .... (m^3/s).

3.3.2 Constraints of minimum discharge

In order to prevent the main and branch canal systems from silting up, the flow in the main and branch canals should not be less than half of the maximum flow capacity.

$$Q_R \geqslant Q_m/2 \quad (16)$$

$$q_{Ri} \geqslant q_{mi}/2 \quad (17)$$

in which: Q_R = practical flow diversion in the North Main Canal (m^3/s).

q_{Ri} = practical discharge diversion in the branch canal i (m^3/s).

q_{mi} = maximum flow capacity in the branch canal i (m^3/s).

3.3.3 Constraint of irrigation rotation practice

While regulating irrigation order, it is necessary to irrigate from downstream to upstream in order to minimize water loss caused by evaporation and infiltration, that is: i = 18,17,... 1.

In order to minimize the objective function and guarantee irrigation from downstream to upstream, irrigation was ordered by branch canals.

Table 4 Optimum scheme of the minimum irrigation rotation

CANALS	DAYS										
	1	2	3	4	5	6	7	8	9	10	11
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.42	0.42	0.
2	0.00	0.00	0.00	0.00	0.00	0.19	0.37	0.37	0.37	0.00	0.
3	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.37	0.37	0.00	0.
4	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.37	0.37	0.37	0.
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.37	0.37	0.
6	0.00	0.00	0.00	0.00	0.00	0.09	0.19	0.19	0.19	0.19	0.
7	0.00	0.00	0.00	0.00	0.00	0.42	0.42	0.42	0.00	0.00	0.
8	0.00	0.00	0.00	0.42	0.42	0.42	0.42	0.00	0.00	0.00	0.
9	0.00	0.00	0.00	0.00	0.37	0.37	0.37	0.00	0.00	0.00	0.
10	0.00	0.00	0.00	0.24	0.37	0.00	0.00	0.00	0.00	0.00	0.
11	0.00	0.00	0.00	0.00	0.30	0.37	0.00	0.00	0.00	0.00	0.
12	0.00	0.25	0.25	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.
13	0.42	0.21	0.21	0.42	0.42	0.42	0.00	0.00	0.00	0.00	0.
14	0.35	0.66	0.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.
15	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.
16	0.37	0.37	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.
17	0.42	0.42	0.42	0.42	0.42	0.00	0.00	0.00	0.00	0.00	0.
18	0.37	0.37	0.37	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.
Qm	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.28	1.48	0.

4 Analysis of Research Results

The results can be seen in Table 4. It shows that the flow in the North Main Canal reaches maximum capacity in the first 8 days, and that flow is greater than half of its capacity in the following 2 days, which can prevent silting up in branch canals as well as control the discharge diversion at the head of branch canals conveniently. One irrigation rotation under the optimum water allocation requires 10 days, which saves about 4 days, compared with 14 days in the traditional irrigation system. Therefore, the purpose of time and water saving has been achieved.

The time unit of the present research is based on days for convenient management. The time unit can be shortened for further water saving purposes; as long as the parameter Ti in the programme is changed, the relevant results will be obtained. When irrigation starts, the measured W and Q_m must be input into the computer and the results will be achieved through calculation. The data input is interactive, which is very convenient for application.

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