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Simulation of Water–Energy Nexus of the Spatial Patterns of Crops and Irrigation Technologies in the Cascade Pump Station Irrigation District

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Abstract: Cascade pump station irrigation districts (CPSIDs) consume vast amounts of irrigation water and energy. The aim of this study was to adjust the spatial patterns of crops and irrigation technologies in the CPSID to reduce the consumption of water and energy under the condition of conserving crop irrigation water. The irrigation district (ID) is divided into several sub-districts according to the topography elevation difference and the distribution of cascade pump stations (CPSs). The mathematical models of the irrigation water and energy consumption in each sub-district were established based on the relationship between the spatial patterns of crops and irrigation technologies in each sub-district. According to the present situation of the Jingdian Phase I Irrigation District in the arid region of northwest China, three modes of adjusting the crop planting structure and drip irrigation area were proposed. Based on the combination of these modes, three schemes of the spatial patterns of crops and irrigation technologies were generated. The annual energy consumption and irrigation water consumption of each sub-district in the ID of these three schemes were obtained through simulation. Compared with the present spatial patterns of crops and irrigation technologies in the Jingdian Phase I Irrigation District, Scheme 3 has the best water-saving and energy-saving effects, with an annual water saving and energy saving of 1753 $\times$ 10^4 m^3 and 2898 $\times$ 10^4 kWh, and the water-saving rate and energy-saving rate were 12.34% and 15.74%, respectively. This paper also shows that the synchronous adjustment of crops and irrigation technologies among the sub-districts of ID can achieve significant water-saving and energy-saving effects.

Keywords: cascade pump station; irrigation district; crop; irrigation technology; water saving; energy saving

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1. Introduction

With the development of the social economy, the demand for energy and water is increasing, and the demand for environmental protection is also increasing [1,2]. There are many cascade pump station irrigation districts (CPSIDs) in China, Myanmar, India, and Central Asian countries [3,4]. In these irrigation districts (IDs), to irrigate crops, water is sent to the drylands with higher elevations through the cascade pump stations (CPSs) to provide reliable water resources for the development of local agricultural planting and greatly improve the production and living conditions of local farmers. The cumulative head can be up to hundreds of meters in some CPS, and irrigating crops in these IDs consumes a large amount of water and energy.

In recent years, much research has been carried out on the water–energy nexus in irrigation systems [4–8]. The nexus between water and energy in the CPSIDs is getting closer. It is a problem worthy of attention to reduce the irrigation water and energy consumption in the CPSIDs to ensure the irrigation water needed for crop growth.

The research results show that the advantage of the traditional surface irrigation technology is low cost; however, its disadvantage is low water use efficiency [9], which is caused by two reasons: one is a large amount of soil evaporation during surface irrigation, and the other is the large percolation [10]. Adopting water-saving irrigation technology can greatly reduce evaporation and percolation [11], thereby improving water use efficiency. Drip irrigation has become a widely used water-saving irrigation technology, in which the pressurized water is delivered to the soil near crops through pipeline systems and emitters. Although the initial cost is a relatively high initial cost, drip irrigation technology can improve the water use efficiency to reduce the consumption of water resources and improve the uniformity of irrigation [12,13]. Drip irrigation saves water up to 50~66% with an increment in the yield of 30~40% compared to surface irrigation [14]. It has been confirmed by many studies that the effect of water saving is significant when replacing surface irrigation with drip irrigation [15,16].

Adjustment of the crop planting structure is helpful to solve the problem of insufficient water resources [17–20]. It can also increase crop water productivity, which results in more potential for water saving and less environmental damage as well as more socio-economic gain. This is extremely meaningful in arid and semi-arid regions such as Iran, Morocco, and China [21–23]. A recent study has shown that adjusting the crop planting structure globally can reduce water consumption by 12.1–13.6% [24]. How to combine the adjustment of irrigation technology and crop planting structure in the CPSID, to effectively reduce the consumption of energy and irrigation water of the CPSID is a problem to be studied, but research on the issue has rarely been reported.

The CPSID is divided into several sub-districts according to the topography elevation difference and the distribution of CPSs. The CPSID is a complex system consisting of CPSs, channels, pipes, and sub-districts, in which each part has a close water–energy nexus. The spatial patterns of water and energy are determined by the spatial patterns of irrigation technologies and crops in each sub-district. Changing the spatial patterns of irrigation technologies and crops in each sub-district will change the spatial patterns of water and energy in each sub-district, resulting in a change in the water–energy nexus in the whole CPSID. This study aimed to adjust the spatial patterns of crops and irrigation technologies according to the characteristics of the CPSID, to more effectively achieve the goal of water and energy savings.

2. Methodology

2.1. Study Area and Analysis

Data for the Jingdian Phase I Irrigation District were obtained from the administrative department of the district, namely the Jingtaichuan Electric Lifting Irrigation Water Resources Utilization Center of Gansu Province.

The Jingdian Phase I Irrigation District is located in the central part of Gansu Province in northwest China, at 103°20′–104°04′ E and 37°26′–38°41′ N. The location of the ID is shown in Figure 1. The terrain of the ID is high in the southwest and low in the northeast. The ID belongs to an extremely arid region. The average annual precipitation and the average annual evaporation are 184 mm and 2289.9 mm, respectively. The soil of the ID is sandy loam.

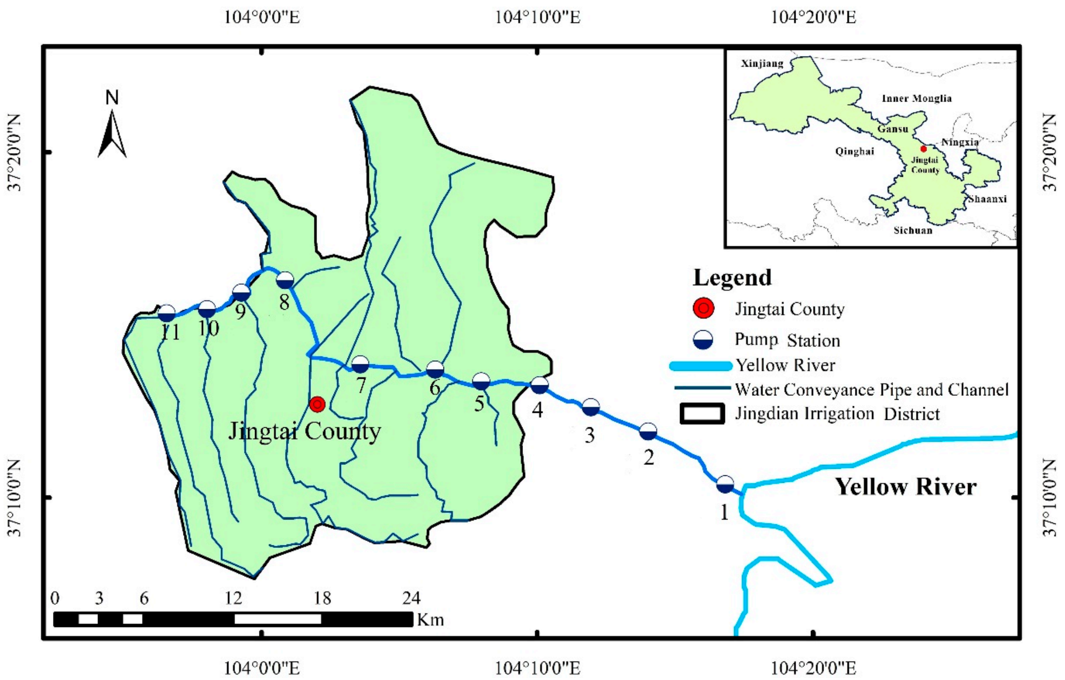

Figure 1. Location of the Jingdian Phase I Irrigation District.

There are 13 pump stations in the Jingdian Phase I Irrigation District. The irrigation area controlled by the last two pump stations is only 212 ha (0.01% of the total area of the ID), so the last two pump stations are incorporated into the 11th pump station; that is, there are 11 pump stations in the ID. The parameters of the pump stations are shown in Table 1. According to the elevation difference and the distribution of the CPSs, the ID is divided into eight sub-districts; the parameters of each sub-district are shown in Table 2. Water from the Yellow River is transported to the farmland through the CPS, water conveyance pipe and channel (WCP&C), as well as the water distribution pipe and channel system (WDP&CS) of each sub-district. The irrigation techniques for the farmland in the ID are surface and drip irrigation. The Jingdian Phase I Irrigation District comprises a complex water source system (Figure 2) (the Yellow River), 11 CPSs, 11 WCP&C segments, and eight sub-districts. Each sub-district contains WDP&CS, a surface irrigation unit (SIU), and a drip irrigation unit (DIU), as shown in Figure 3. The WDP&CS consists of open channel systems and pipe networks. Water from the WCP&C is diverted to the SIU by the open channel system for surface irrigation. The water from the WCP&C is sent to the DIU through pipe networks. There are eight crops in the SIU and five crops in the DIU, as shown in Figure 3 and Table 3.

Table 1. The parameters of the pump stations.

Pump Station	Pump Station Head (m)	Design Discharge of Pump Station (m^3/s)	Efficiency of Pump Station (%)
1	80.92	13.17	86
2	80.28	13.14	85
3	80.03	13.13	87
4	29.57	13.12	86
5	26.70	12.96	87
6	36.72	11.57	85
7	29.23	7.70	75
8	32.20	6.27	75
9	27.47	5.79	75
10	28.87	3.36	75
11	27.11	1.45	70

Table 2. The parameters of the sub-districts.

Sub-District	Cumulative Head (m)	Elevation Range (m)	Efficiency of Surface Irrigation Unit (%)	Efficiency of Drip Irrigation Unit (%)	Area (ha)
1	270.80	1561–1580	0.72	0.94	357
2	297.50	1580–1596	0.69	0.93	2306
3	334.22	1596–1620	0.67	0.93	6533
4	363.45	1620–1638	0.70	0.95	2375
5	395.65	1638–1658	0.69	0.94	806
6	423.12	1658–1676	0.68	0.92	4054
7	451.99	1676–1694	0.71	0.93	3454
8	479.10	1694–1711	0.72	0.94	2066

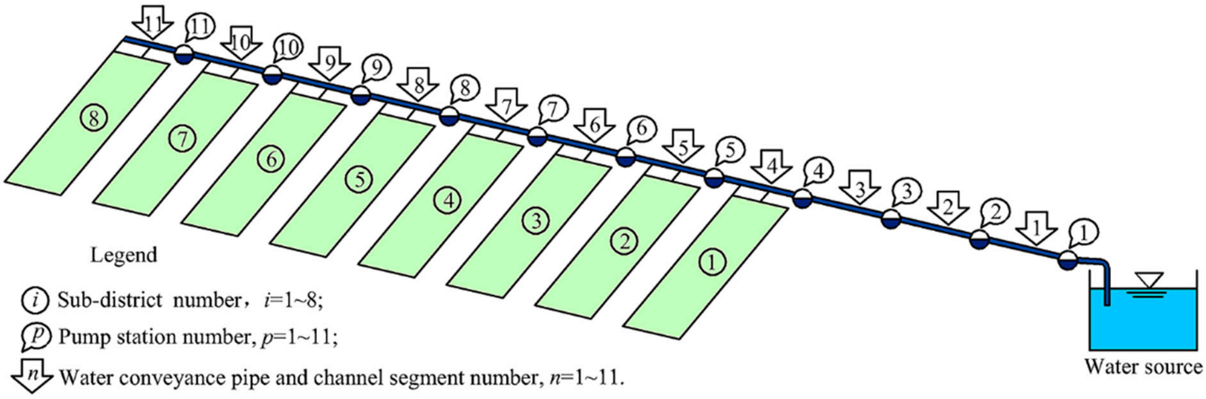

Figure 2. Jingdian Phase I Irrigation District system.

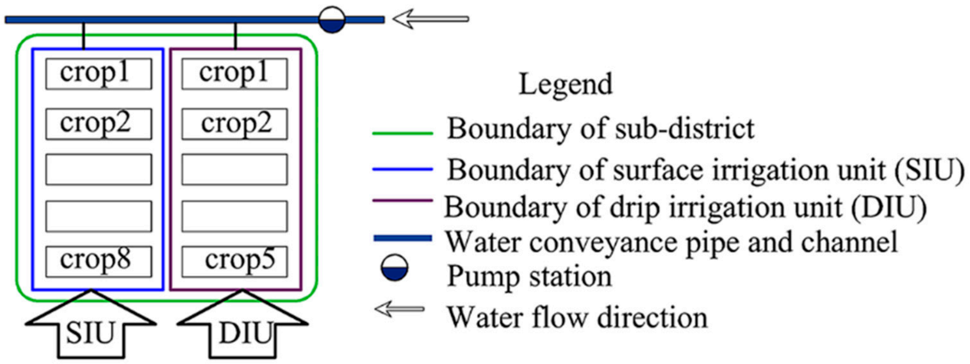

Figure 3. Various crops of surface irrigation unit and drip irrigation unit in each sub-district.

Table 3. The net irrigation quota of various crops under different irrigation types.

	Surface Irrigation Unit								Drip Irrigation Unit				
Crop	**W**	**M**	**F**	**A**	**P1**	**V**	**P2**	**O**	**A**	**P1**	**V**	**P2**	**O**
Net irrigation quota (m^3/ha)	4080	4135	3416	3226	3084	4540	3426	3750	1784	1696	2497	1884	2070
Sequence number	11	12	8	7	6	13	9	10	2	1	5	3	4

Note: The net irrigation quotas of different crops under the two irrigation methods are sorted by the principle of small to large, represented by sequence number. Crop abbreviation: W—Wheat; M—Maize; F—Flax; A—Apple; P1—Pear; V—Vegetable; P2—Potato; O—Oil sunflower. There are 8 crops (on the left) for Surface Irrigation Unit and 5 crops (on the right) for Drip Irrigation Unit.

The first pump station pumps water from the Yellow River, and the design discharge of each pump station decreases successively (Table 1) due to two reasons. One reason is the loss of water that occurs in each WCP&C segment connecting the two pump stations.

Another reason is that the WCP&C supplies water to various sub-districts for crop irrigation. The efficiency of the WCP&C segment represents the water loss degree of the segment between 2 pump stations, which can be represented as the ratio of its outflow and inflow (Table 4). From the 4th pump station, water from the WCP&C is fed into the WDP&CS of the sub-districts to irrigate the crops in the farmland. The water supply of each sub-district should cover two parts. The first part is the irrigation water for crop growth in the sub-district, which is related to the net irrigation quota (Table 3) based on the type of irrigation technologies and crops. The other part is the water loss through the WDP&CS in the sub-district and the water loss in the farmland, which is related to the irrigation technology. Table 2 shows the irrigation efficiency of different irrigation units (SIU and DIU) in each sub-district. The irrigation area of the Jingdian Phase I Irrigation District was 21,951 ha in 2020, the annual irrigation water is 14,210 $\times$ 10^4 m^3, the annual energy consumption of the CPS and DIU is 18,412 $\times$ 10^4 kWh. The present situation of the spatial patterns of crops and irrigation technologies in 2020 (Scheme 0) is shown in Table 5.

Table 4. Efficiency of the water conveyance pipe and channel segment.

Water Conveyance Pipe and Channel Segment	1	2	3	4	5	6	7	8	9	10	11
Efficiency (%)	0.97	0.98	0.97	0.97	0.98	0.99	0.95	0.96	0.96	0.97	0.98

Table 5. Present situation of the spatial patterns of crops and irrigation technologies (ha, Scheme 0).

Sub-District	Surface Irrigation Unit								Drip Irrigation Unit				
	W	M	F	A	P1	V	P2	O	A	P1	V	P2	O
1	64	112	20	24	30	27	36	18	26	0	0	0	0
2	415	726	127	155	194	174	233	116	0	166	0	0	0
3	1176	2058	359	439	549	494	659	329	0	0	200	270	0
4	428	748	131	160	199	179	239	120	0	0	0	0	171
5	145	254	44	54	68	61	81	41	0	58	0	0	0
6	730	1277	223	272	341	306	409	204	182	0	110	0	0
7	622	1088	190	232	290	261	348	174	0	100	0	149	0
8	372	651	114	139	174	156	208	104	0	0	148	0	0

Note: Crop abbreviation as shown in Table 3.

The focus of this study is to reasonably determine the spatial patterns of crops and irrigation technologies in each sub-district. A good arrangement will reduce the total consumption of energy and irrigation water in the whole ID. This involves the present situation of the ID, the cumulative head of each sub-district, the irrigation water consumption of various crops, and the water efficiency of various irrigation technologies.

2.2. Mathematical Model of Irrigation Water and Energy Consumption

For crop k in irrigation unit j of sub-district i, the calculation of the gross irrigation quota is as follows:

$$q_{ijk} = \frac{q_{1k}}{\lambda_{i1} \prod_{n=1}^{i+3} \eta_n} + \frac{q_{2k}}{\lambda_{i2} \prod_{n=1}^{i+3} \eta_n} \tag{1}$$

where i is the number of sub-districts, I = 1,2, ... ,8; j is the number of irrigation units, j = 1 is surface irrigation, j = 2 is drip irrigation; k is the number of crops, as shown in Tables 3 and 5, in the order from left to right, k = 1,2, ... ,8 for SIU (j = 1), k = 1,2, ... ,5 for DIU (j = 2); q_{jk} is the net irrigation quota (m^3/ha, Table 3); λ_{ij} is the efficiency of the irrigation unit (%, Table 2); n is the number of WCP&C segments; η_n is the efficiency of the WCP&C segment n (%, Table 4). q_{ijk} is the gross irrigation quota of various crops for SIU and DIU in each sub-district (m^3/ha, Table 6).

Table 6. The gross irrigation quota of various crops (m^3/ha).

Sub-District	Surface Irrigation Unit								Drip Irrigation Unit				
	W	M	F	A	P1	V	P2	O	A	P1	V	P2	O
1	6611	6700	5535	5227	4997	7356	5551	6076	2168	2061	3035	2290	2516
2	6746	6837	5648	5334	5099	7507	5665	6200	2212	2103	3096	2336	2567
3	6814	6906	5705	5388	5151	7582	5722	6263	2235	2124	3128	2360	2593
4	7173	7269	6005	5671	5422	7981	6023	6593	2352	2236	3292	2484	2729
5	7472	7572	6256	5908	5648	8314	6274	6867	2450	2329	3430	2588	2843
6	7783	7888	6516	6154	5883	8660	6535	7153	2526	2401	3536	2668	2931
7	6611	6700	5535	5227	4997	7356	5551	7599	2604	2476	3645	2750	3022
8	8187	8298	6855	6474	6189	9110	6875	7525	2657	2526	3719	2806	3083

Note: Crop abbreviation as shown in Table 3.

The annual irrigation amount of sub-district i is calculated by:

$$w_i = \sum_{k=1}^{8} q_{i1k} s_{i1k} + \sum_{k=1}^{5} q_{i2k} s_{i2k} \tag{2}$$

where w_i is the annual irrigation water consumption of sub-district i (m^3); s_{ijk} is the area of crop k in unit j of sub-district i (ha), as shown in Table 5.

The annual irrigation amount of the ID is calculated by:

$$W = \sum_{i=1}^{8} w_i \tag{3}$$

where W is the annual irrigation amount of the ID (m^3).

As shown in Figure 2, in the process of irrigation, water from the Yellow River should be pumped to sub-district i through pump station $p = 1, 2, \ldots, i + 3$. The annual energy consumption per unit area of crop k of an SIU ($j = 1$) in sub-district i is calculated according to Equation (4) [6,25]:

$$e_{i1k} = \frac{q_{1k}}{367.34\lambda_{i1}} \sum_{p=1}^{i+3} \frac{H_p}{\alpha_p \prod_{n=p}^{i+3} \eta_n} \tag{4}$$

where e_{i1k} is the annual energy consumption per unit area of an SIU (kWh/ha); p is the number of pump stations, H_p is the head of pump stations (m), α_p is the efficiency of pump stations (%). The above data can be obtained from Table 1.

The annual energy consumption per unit area of crop k of a DIU ($j = 2$) in sub-district i is calculated according to Equation (5):

$$e_{i2k} = \frac{q_{2k}}{367.34\lambda_{i2}} \sum_{p=1}^{i+3} \left(\frac{H_p}{\alpha_p \prod_{n=p}^{i+3} \eta_n} + \frac{H_2}{\alpha_2} \right) \tag{5}$$

where e_{i2k} is the annual energy consumption per unit area of a DIU (kWh/ha); H_2 is the head of the pump station of the drip irrigation system (m), H_2 = 50 m. The 50 m head should meet the requirements of two aspects: firstly, the working head of the drip emitter is 10 m; secondly, the head loss of the pipe network system of drip irrigation is 40 m. α_2 is the efficiency of the pump station of the drip irrigation system (%, α_2 = 82%).

Table 7 shows the annual energy consumption per unit area of crops under different irrigation technologies.

Table 7. The annual energy consumption per unit area of various crops (kWh/ha).

Sub-District	Surface Irrigation Unit								Drip Irrigation Unit				
	W	**M**	**F**	**A**	**P1**	**V**	**P2**	**O**	**A**	**P1**	**V**	**P2**	**O**
1	5668	5744	4745	4481	4284	6037	4759	5209	2188	2080	3062	2310	2538
2	6347	6432	5314	5018	4797	7062	5329	5833	2410	2292	3374	2546	2797
3	7212	7309	6039	5703	5452	8025	6056	6629	2694	2561	3771	2845	3126
4	8353	8465	6993	6604	6314	9295	7014	7677	3068	2917	4295	3240	3560
5	9574	9703	8016	7570	7237	10,654	8039	8800	3469	3298	4855	3663	4025
6	10,749	10,894	9000	8499	8125	11,961	9026	9880	3854	3664	5394	4070	4472
7	11,922	12,083	9982	9427	9012	13,266	10,011	10,958	4239	4030	5933	4476	4918
8	13,029	13,204	10,908	10,302	9848	14,498	10,940	11,975	4602	4375	6441	4860	5339

Note: Crop abbreviation as shown in Table 3.

The annual energy consumption of sub-district i is calculated according to Equation (6):

$$E_i = \sum_{k=1}^{8} e_{i1k} s_{i1k} + \sum_{k=1}^{5} e_{i2k} s_{i2k} \quad (6)$$

where E_i is the annual energy consumption of the sub-district i (kWh).

The annual energy consumption of the ID is calculated according to Equation (7):

$$F = \sum_{i=1}^{8} E_i \quad (7)$$

where F is the annual energy consumption of the ID (kWh).

2.3. Calculation Method of Irrigation Water Consumption and Energy Consumption

According to the above models, the irrigation water and energy consumption of each sub-district are calculated. Combined with the present situation (Table 5, Scheme 0), the calculation steps are as follows:

(1) The data in Tables 2–4 were substituted into Equation (1) to obtain the gross irrigation quota q_{ijk} (Table 6).

(2) The data in Tables 5 and 6 were substituted into Equation (2) to obtain the annual irrigation water consumption of sub-district w_i (Table 8). According to Equation (3), the annual irrigation amount of the ID is 14,210 × 10^4 m^3 (Scheme 0).

(3) The data in Tables 1–4 were substituted into Equations (4) and (5) to obtain the annual energy consumption per unit area e_{ijk} (Table 7).

(4) The data in Tables 5 and 7 were substituted into Equation (6) to obtain the annual energy consumption E_i of each sub-district (Table 9). According to Equation (7), the annual energy consumption of the irrigation district is 18,412 × 10^4 kWh (Scheme 0).

Table 8. The annual irrigation water consumption of each sub-district and irrigation district in each scheme (10^4 m^3).

Sub-District	Scheme			
	0	**1**	**2**	**3**
1	212.38	249.15	186.86	227.43
2	1399.08	1586.89	1230.82	1498.02
3	4030.66	4313.07	3548.41	4203.41
4	1540.65	1627.97	1356.39	1374.17
5	541.71	572.35	476.49	481.40
6	2851.84	2742.33	2511.52	2537.29
7	2094.69	1798.37	1876.01	1516.21
8	1539.00	1244.76	1356.60	618.17
Irrigation district	14,210.00	14,134.89	12,543.09	12,456.10

Table 9. The annual energy consumption of each sub-district and irrigation district in each scheme (10^4 kWh).

Sub-District	Scheme			
	0	**1**	**2**	**3**
1	182.92	214.43	163.07	195.81
2	1321.48	1498.18	1176.29	1414.57
3	4284.74	4583.95	3811.72	4467.88
4	1800.65	1902.30	1599.55	1606.76
5	695.96	735.27	617.01	618.72
6	3950.96	3798.38	3502.69	3515.21
7	3718.20	3230.09	3292.12	2635.25
8	2456.77	1987.51	2177.22	1059.39
Irrigation district	18,411.69	17,950.12	16,339.66	15,513.59

3. Adjustment and Evaluation of the Spatial Patterns of Crops and Irrigation Technologies

The spatial patterns of crops and irrigation technologies in the ID will be adjusted based on the present situation (Scheme 0). Different adjustment schemes of the spatial patterns of crops and irrigation technologies will be formed according to certain adjustment principles. Taking Scheme 0 as the baseline, the effect of water saving and energy saving of each adjustment scheme will be evaluated. This research provides a basis for optimizing the spatial patterns of crops and irrigation technologies in the CPSID.

3.1. The Principles of the Adjustment

- Principle 1: The area of each sub-district remains unchanged after adjustment.

This principle is to avoid the deterioration of the ecological environment in arid regions caused by blindly expanding irrigation areas. The area of each sub-district shall meet Equation (8):

$$\sum_{k=1}^{8} s_{i1k} + \sum_{k=1}^{5} s_{i2k} = S_i \tag{8}$$

where S_i is the area of the sub-district (ha), as shown in Table 2.

- Principle 2: The adjustment is integrated with existing irrigation facilities.

In the process of adjustment, to reduce the project investment, the WCP&C and CPS remain the status quo, and the pre-existing crop types and areas of drip irrigation in the DIU in each sub-district remain unchanged.

- Principle 3: Adjusting the spatial pattern based on the net irrigation quotas.

Different crops use different irrigation technologies; their net irrigation quotas are also different. The net irrigation quota is ranked in ascending order, as shown in Table 3. In the process of adjusting the spatial patterns of crops and irrigation technologies, the crops with the smallest net irrigation quota for drip irrigation are placed in the sub-district with the highest cumulative head, and the crops with the largest net irrigation quota for surface irrigation are placed in the sub-district with the lowest cumulative head. According to this principle, the spatial patterns of each sub-district are adjusted to reduce the water and energy consumption in the CPSID.

3.2. Adjustment Modes

The ID is composed of several sub-districts (Figure 2). Each sub-district has an SIU and DIU; each unit contains several crops with a different irrigated area (Figure 3). To achieve water and energy savings, the following adjustment modes are formed.

- Mode 1: Adjust the spatial patterns among sub-districts.

Following Principles 1, 2, and 3, adjust the spatial patterns of crops and irrigation technologies among sub-districts.

- Mode 2: Adjust the crop planting structure within the unit in each sub-district.

According to Principles 1 and 2, part or all of the crop areas with the higher net irrigation quota are transferred to those with the lower net irrigation quota within the unit (SIU or DIU) in each sub-district.

- Mode 3: Adjust crop irrigation technology between the units in the sub-district.

According to Principles 1 and 2, change part or all of the crop areas in the SIU to the DIU in the sub-district.

3.3. Evaluation Indexes of Water-Saving and Energy-Saving

To analyze and evaluate the effects of water and energy savings of each scheme, the following evaluation indexes of water and energy savings are proposed based on the present situation (Scheme 0).

The water-saving rate of each sub-district for Scheme r (r is the number of spatial patterns schemes, r = 1,2,3) is calculated as:

$$\theta_{ri} = \frac{w_{ri} - w_{0i}}{w_{0i}} \tag{9}$$

where θ_{ri} is the water-saving rate of sub-district i in Scheme r (%); w_{ri} is the irrigation water consumption of sub-district i in Scheme r (m^3); w_{0i} is the irrigation water consumption of sub-district i in Scheme 0 (m^3).

The water-saving rate of the ID for Scheme r is calculated as:

$$\Theta_r = \frac{W_r - W_0}{W_0} \tag{10}$$

where Θ_r is the water-saving rate of the ID in Scheme r (%); W_r is the irrigation water consumption of the ID in Scheme r (m^3); W_0 is the irrigation water consumption of the ID in Scheme 0 (m^3).

The energy-saving rate of each sub-district is calculated as:

$$\varphi_{ri} = \frac{E_{ri} - E_{0i}}{E_{0i}} \tag{11}$$

where φ_{ri} is the energy-saving rate (%) of sub-district i in Scheme r (%); E_{ri} is the annual energy consumption of sub-district i in Scheme r (kWh). E_{0i} is the annual energy of sub-district i in Scheme 0 (kWh).

The energy-saving rate of the ID in each scheme is calculated as:

$$\Phi_r = \frac{F_r - F_0}{F_0} \tag{12}$$

where Φ_r is the energy-saving rate of the ID in Scheme r (%); F_r is the annual energy consumption of the ID in Scheme r (kWh); F_0 is the annual energy consumption of the ID in Scheme 0 (kWh).

4. Results and Discussion

4.1. Results Analysis

Three different schemes of spatial patterns were formed based on the different combinations of the three modes above.

4.1.1. Scheme 1 (Mode 1)

According to Mode 1, Scheme 1 is adjusted based on Scheme 0 (Table 5). The adjustment starts from sub-district 8 with a cumulative head of 479.10 m (the highest). According to Principles 2 and 3, SN (sequence number) 1–5 of the net irrigation quotas (Table 3) are the crops of the DIU in Scheme 0, which already satisfy the requirements. All 1845 ha of pear trees (SN 6) in the SIU are transferred to sub-district 8, while the 73 ha of apple trees (SN 7) in the SIU are transferred to sub-district 8, and 148 ha of vegetables in the DIU of Scheme 0. The sum of these three terms is 2066 ha, which is equal to the area of sub-district 8 (Table 2) and meets the requirement of Principle 1 and Equation (8). Then sub-district 7 with the cumulative head of 451.99 m is adjusted. According to Principles 2 and 3, the following adjustments are made: transfer all the other 1402 ha of apple trees (SN 7) of the SIU to sub-district 7, transfer the 1208 ha of flax (SN 8) of the SIU to sub-district 7, transfer the 595 ha of potatoes (SN 9) to sub-district 7, as well as 100 ha of pear trees and 149 ha of potatoes in the SIU of Scheme 0. The sum of the above five items is the area of sub-district 7, totaling 3454 ha (Table 2), which meets the requirement of Principle 1. Following the same principles, the spatial patterns of crops and irrigation technologies in sub-districts 1–6 are adjusted. Thus, the spatial patterns of Scheme 1 are formed (Table 10). To obtain the annual irrigation water consumption in each sub-district and the whole ID for Scheme 1, the data in Tables 5 and 6 are substituted into Equations (2) and (3) (Table 8). The data in Tables 5 and 7 are substituted into Equations (6) and (7) to obtain the annual energy consumption of each sub-district and the whole ID for Scheme 1 (Table 9). The data in Table 8 are substituted into Equations (9) and (10) to obtain the water-saving rate of each sub-district and the whole ID for Scheme 1 (Table 11). Substitute the data in Table 9 into Equations (11) and (12) to obtain the energy-saving rate of each sub-district and the whole ID for Scheme 1 (Table 12). The irrigation water consumption and energy consumption in sub-districts 6–8 of Scheme 1 are all smaller than that in Scheme 0, while the irrigation water consumption and energy consumption in sub-districts 1–5 are both larger than that in Scheme 0. The water-saving rate and energy-saving rate in the ID for Scheme 1 are 0.53% and 2.51%, respectively (Tables 11 and 12).

Table 10. The spatial patterns of crops and irrigation technologies of Scheme 1 (ha).

Sub-District	Surface Irrigation Unit								Drip Irrigation Unit				
	W	**M**	**F**	**A**	**P1**	**V**	**P2**	**O**	**A**	**P1**	**V**	**P2**	**O**
1	0	0	0	0	0	331	0	0	26	0	0	0	0
2	0	813	0	0	0	1327	0	0	0	166	0	0	0
3	0	6063	0	0	0	0	0	0	0	0	200	270	0
4	2166	38	0	0	0	0	0	0	0	0	0	0	171
5	748	0	0	0	0	0	0	0	0	58	0	0	0
6	1038	0	0	0	0	0	1618	1106	182	0	110	0	0
7	0	0	1208	1402	0	0	595	0	0	100	0	149	0
8	0	0	0	73	1845	0	0	0	0	0	148	0	0

Note: Crop abbreviation as shown in Table 3.

Table 11. Water-saving rate of each sub-district and irrigation district in each scheme (%).

Sub-District	Scheme		
	1	**2**	**3**
1	−17.31	12.02	−7.09
2	−13.42	12.03	−7.07
3	−7.01	11.96	−4.29
4	−5.67	11.96	10.81
5	−5.66	12.04	11.13
6	3.84	11.93	11.03
7	14.15	10.44	27.62
8	19.12	11.85	59.83
Irrigation district	0.53	11.73	12.34

Table 12. Energy-saving rate of each sub-district and irrigation district in each scheme (%).

Sub-District	Scheme		
	1	2	3
1	−17.22	10.85	−7.05
2	−13.37	10.99	−7.04
3	−6.98	11.04	−4.27
4	−5.65	11.17	10.77
5	−5.65	11.34	11.10
6	3.86	11.35	11.03
7	13.13	11.46	29.13
8	19.10	11.38	56.88
Irrigation district	2.51	11.25	15.74

4.1.2. Scheme 2 (Mode 2 + Mode 3)

According to Modes 2 and 3, Scheme 2 is adjusted based on Scheme 0 (Table 5). First, according to Mode 2, the 50% area of corn with the highest net irrigation quota (SN 12) is adjusted to flax (SN 8) in the SIU of each sub-district, and the rest sub-districts are adjusted accordingly. Then, according to Mode 3, all the areas of apple trees and vegetables in the SIU in each sub-district of Scheme 0 are adjusted to the DIU in the same sub-district. Then form the spatial patterns of Scheme 2 (Table 13). The results show that synchronous adjustment of crop and irrigation technology can achieve a more obvious effect of water and energy savings than a single adjustment of the crop planting structure or irrigation technology. The water-saving rate and energy-saving rate in each sub-district of Scheme 2 are positive (Tables 11 and 12).

Table 13. The spatial patterns of crops and irrigation technologies of Scheme 2 (ha).

Sub-District	Surface Irrigation Unit								Drip Irrigation Unit				
	W	M	F	A	P1	V	P2	O	A	P1	V	P2	O
1	64	56	76	0	30	0	36	18	50	0	27	0	0
2	415	363	490	0	194	0	233	116	155	166	174	0	0
3	1176	1029	1388	0	549	0	659	329	439	0	694	270	0
4	428	374	505	0	199	0	239	120	160	0	179	0	171
5	145	127	171	0	68	0	81	41	54	58	61	0	0
6	730	638	862	0	341	0	409	204	454	0	416	0	0
7	622	544	734	0	290	0	348	174	232	100	261	149	0
8	372	326	439	0	174	0	208	104	139	0	304	0	0

Note: Crop abbreviation as shown in Table 3.

4.1.3. Scheme 3 (Mode 2 + Mode 3 + Mode 1)

According to Modes 2, 3, and 1, Scheme 3 is adjusted based on Scheme 2. According to Mode 1, the crops with the smallest net irrigation quota in Scheme 2 are adjusted downward from the sub-district with the highest cumulative head, then form the spatial patterns of Scheme 3 (Table 14). Compared with Scheme 0, the water-saving rate and energy-saving rate in sub-districts 1–3 of Scheme 3 are negative, while the water-saving rate and energy-saving rate in sub-districts 4–8 of Scheme 3 are positive. The water-saving rate and energy saving rate in the ID are 12.34% and 15.74%, respectively (Tables 11 and 12), which are superior to Scheme 2. The results showed that coordinated adjustment of the spatial patterns of crops and irrigation technologies among the sub-districts has a more significant effect on water and energy savings.

Table 14. The spatial patterns of crops and irrigation technologies of Scheme 3 (ha).

Sub-District	Surface Irrigation Unit								Drip Irrigation Unit				
	W	M	F	A	P1	V	P2	O	A	P1	V	P2	O
1	0	331	0	0	0	0	0	0	26	0	0	0	0
2	0	2140	0	0	0	0	0	0	0	166	0	0	0
3	3952	986	0	0	0	0	19	1106	0	0	200	270	0
4	0	0	10	0	0	0	2194	0	0	0	0	0	171
5	0	0	748	0	0	0	0	0	0	58	0	0	0
6	0	0	3762	0	0	0	0	0	182	0	110	0	0
7	0	0	145	0	1845	0	0	0	0	100	1215	149	0
8	0	0	0	0	0	0	0	0	1475	0	591	0	0

Note: Crop abbreviation as shown in Table 3.

4.2. Discussion

In some large-scale IDs, to achieve the purpose of reducing irrigation water consumption, pressure pipes are used to replace open channels, and water-saving irrigation systems (such as sprinklers or drip irrigation systems) are taken for irrigation [26,27], but it increases the energy consumption and cost [6,28,29]. To reduce the energy consumption of the irrigation pressure pipe networks, a large amount of research has been carried out [30–32]. The research in this paper shows that drip irrigation technology can reduce the consumption of water and energy in the high lift CPSIDs.

There are two main reasons for drip irrigation to save water in the CPSIDs. One reason is that the net irrigation quota of surface irrigation is higher than that of drip irrigation for the same crop, because the wetting range of drip irrigation is limited to the soil near the crop root layer, while the soil evaporation of drip irrigation is much less than that of surface irrigation. For example, for an apple tree, the net irrigation quotas of surface irrigation and drip irrigation are 3226 m^3/ha and 1784 m^3/ha, respectively (Table 3). The net irrigation quota of drip irrigation is 45% lower than that of surface irrigation. The other reason is that the leakage and evaporation loss of the irrigation water by surface irrigation and drip irrigation are different in water transportation. For the same crop in the same sub-district, the gross irrigation quota of surface irrigation is much higher than that of drip irrigation. The water loss during the transportation is divided into two parts. The first part is the water loss from the water source to the sub-district in each WCP&C segment. According to Equation (1) and Table 3, the loss ratio of the two irrigation technologies is the same. The second part is to send water from the WCP&C segment to the field; in this part, the loss ratios of the two irrigation technologies are very different because the irrigation water of the SIU is sent to the field through the channel system, while that of the DIU is sent to the crops through the pressurized pipe network and drip emitters. For example, in sub-district 1 (the cumulative head is 270.80 m), the gross irrigation quotas of surface irrigation and drip irrigation for the apple tree are 5227 m^3/ha and 2168 m^3/ha, respectively (Table 6). The gross irrigation quota of drip irrigation is 58% lower than surface irrigation. The higher the cumulative head of the sub-district, the greater the difference in the gross irrigation quota between the surface and drip irrigation technology for the same crop. Because the higher the cumulative head of the sub-district to which the water is sent, the more WCP&C segments are traversed, the longer the distance of water delivery and the higher the proportion of water is lost. For example, in sub-district 8 (the cumulative head is 479.10 m), the gross irrigation quotas of surface irrigation and drip irrigation for apple trees are 6474 m^3/ha and 2657 m^3/ha, respectively (Table 6). The gross irrigation quota of drip irrigation is 59% lower than surface irrigation.

Drip irrigation saves energy mainly because it saves water. In the high lift CPSIDs, water saving means energy saving. The process of lifting the irrigation water from the source to the field through the pump station can be divided into two stages. The first stage is from the water source to the sub-districts. The second stage is to transfer water from the WCP&C segment of each sub-district to the fields of the SIU and the crops of the DIU, respectively. According to the data in Tables 3 and 6, the net irrigation quota or gross irrigation quota for the same crop irrigated by drip irrigation technology is less than surface irrigation; therefore, in the first stage, water is lifted from the water source to a certain sub-district through CPSs; surface irrigation will increase more water per unit area than drip irrigation, so the energy consumption of surface irrigation will be higher. In the second stage, water flows through the channel system into the field by the SIU. As shown in Equation (4), to ensure the normal operation of the drip irrigation system, the irrigation water from the WCP&C segment should be pressurized 50 m through the pump stations.

Although the drip irrigation system requires pressure, it consumes far less energy than surface irrigation in the CPSID. There are two reasons: (1) drip irrigation saves a lot of energy compared to surface irrigation. (2) The amount of water required by drip irrigation is much lower than that of surface irrigation. Although the drip irrigation system requires an increase of 50 m water head, its proportion in the cumulative head is relatively low. The 50 m water head required by drip irrigation is 18.46% of the cumulative head (270.80 m) in sub-district 1. The annual energy consumption per unit area of surface irrigation and drip irrigation for the apple tree in sub-district 1 is 4481 kWh/ha and 2188 kWh/ha, respectively. Drip irrigation is 51.17% lower in energy consumption than surface irrigation. In sub-district 8, the 50 m head is 10.43% of the cumulative head (479.10 m). The energy consumption per unit area of surface irrigation and drip irrigation for apple trees is 10,302 kWh and 4602 kWh, respectively. Drip irrigation is 55.33% lower than surface irrigation, which also indicates that a higher cumulative head of drip irrigation in the sub-district is more energy efficient.

It is necessary to increase the investment to expand the drip irrigation area in the CPSID [12,13]. Changing surface irrigation to drip irrigation and adjusting the crop planting structure will improve the crop output value in the CPSID [14]. Water and energy savings in the CPSID will also produce economic and ecological environmental benefits. The benefit analysis of the input and output of the CPSID caused by the above reasons should be further studied.

5. Conclusions

Based on the water–energy nexus of the Jingdian Phase I Irrigation District, two methods to reduce the consumption of energy and irrigation water in the ID are proposed: the first method is to adjust the planting pattern of crops, that is, to change the crops with high water consumption to the crops with low water consumption; the second method is to adjust the pattern of irrigation technologies, which means to change surface irrigation to drip irrigation. According to the two methods proposed, combined with the characteristics of the CPSIDs, three regulating principles and three modes are proposed to regulate the spatial patterns of crops and irrigation technologies. Three adjustment schemes have been formed by the combination of the three modes. The proposed mathematical model for energy consumption and irrigation water consumption, as well as water and energy-saving evaluation indicators, are the basis for the adjustment of the spatial patterns of crops and irrigation technologies in the CPSIDs. The application of drip irrigation technology in the CPSIDs saves both water and energy. In the CPSIDs, the higher the cumulative head, the more significant the water-saving and energy-saving effect of drip irrigation technology. Simultaneously, adjusting the spatial pattern of crops and irrigation technologies in each sub-district has a better effect than adjusting crop planting structure alone or expanding drip irrigation area alone. According to Principle 3, adjusting the spatial patterns of crops and irrigation technologies among the sub-districts of the ID is better than adjusting the spatial pattern within the sub-districts. The results of this research show that adjusting the spatial patterns of crops and irrigation technologies has great potential for water and energy savings in the CPSIDs, which is of great significance to the sustainable development of the CPSIDs.

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Abbreviations

CPSID	cascade pump station irrigation district
CPS	cascade pump station
ID	irrigation district
WCP&C	water conveyance pipe and channel
WDP&CS	water distribution pipe and channel system
SIU	surface irrigation unit
DIU	drip irrigation unit
SN	sequence number

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