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Evaluation of the Water Allocation and Delivery Performance of Jiamakou Irrigation Scheme, Shanxi, China

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Abstract: Irrigation performance assessment is an important step in ensuring sustainable agricultural development and improving the capacity of irrigation water management. In this paper, we examined irrigation water management in the Jiamakou Irrigation Scheme in the province of Shanxi (China) using four typical indicators, namely adequacy, efficiency, dependability, and equity. These indicators were calculated both globally and by grouping the data according to different irrigation processes (water allocation and water delivery). Results show that water was poorly allocated, and crop water requirements calculated through the FAO56 Penman-Monteith method was not met timely by scheduled water. They indicate that the overall performance of the scheme was relatively poor, owing to dismal water allocation. Nevertheless, water delivery performance was good, indicating that the scheme was able to deliver adequate and dependable water in an equitable and efficient manner. Our findings suggest that farmers should be trained in allocating irrigation water. The study provides insights into the current behavior of the irrigation scheme and may be used as a base for improvement of irrigation performance.

Keywords: water management; assessment; performance indicators; irrigation scheme; water allocation; water delivery

1. Introduction

Water resources in China are becoming increasingly scarce because of the growing demands of agriculture, industry, society, and the environment. In particular, water shortage has led to high competition among users and has hindered sustainable development. Irrigation schemes, which are highly productive in agricultural areas, have the largest water demand in the country. Therefore, improving water management in irrigation schemes is vital to national food and water security.

The success of irrigation water management can be measured by how well water delivery meets crops' demand in both time and space [1,2]. Therefore, analyzing the current condition of irrigation schemes and assessing the level of the objective that can be achieved are necessary, and measures can then be taken to reduce the gap between the potential and actual performance of the irrigation scheme. Assessment is considered a useful tool in evaluating and improving the performance of the irrigation scheme [3,4]. Different performance indicators and evaluation perspectives have been proposed or used to evaluate various irrigation schemes in recent decades.

Performance evaluation of the irrigation scheme has been carried out for different purposes, such as performing diagnostic analysis [5,6], understanding irrigation behavior and general irrigation

trends [7], and comparing the performance of one irrigation scheme with another [8,9]. Evaluation indicators can be categorized into two main groups: external and internal performance. Most irrigation performance assessment studies in China have focused on external performance, especially in crop production, economic output, water use efficiency, and environmental effect [10–12]. However, few studies have measured internal performance, such as adequacy, efficiency, equity, and dependability because of the lack of water measurement or poor quality of records.

Adequacy, efficiency, equity, and dependability are performance objectives considered when evaluating irrigation schemes from the perspective of supply and demand services. Adequacy can be defined as the ability of a system to meet the demand, and it is the fundamental objective of a system. Efficiency expresses the ability of conservation of resources. When a system delivers a greater-than-adequate supply, it cannot be considered efficient. Equity is a measure of the fairness of resource supply and can be defined as spatial uniformity of the ratio of supply and demand. Dependability embodies the ability to supply resource at the right time and expresses the degree of temporal uniformity of the ratio of supply and demand [1].

Irrigation performance evaluation using these four indicators found in literature is mostly conducted by analyzing crop water requirements and actual water supply. For instance, Unal et al. [13] used these four indicators to evaluate the water delivery performance of the Menemen Left Bank Irrigation System in Turkey. They highlighted that factors causing poor irrigation performance derived in part from management, and in part from physical structure. Vandersypen et al. [14] evaluated the irrigation performance of the Office du Niger (Mali) in 1995 and 2004 using these four indicators. They found that the physical rehabilitation of the irrigation network made the irrigation delivery service excellent. Aly et al. [15] calculated the indicators of adequacy, equity, and dependability from the amount of irrigation water supply and demand. Their results indicated that users' association had a positive effect on managing of the tertiary canal. In fact, the evaluation of irrigation performance should not only be based on the analysis of the relationship between crop water requirement and the actual water supply, but also on the relationship between crop water requirement, scheduled water, and actual water supply, that is, the performance of water allocation and water delivery can be assessed separately.

In this study, the Jiamakou Irrigation Scheme (JMIS) was selected as a pilot project for performance assessment. Irrigation performance was assessed and the contributions of water allocation and water delivery to the overall performance were evaluated by using four indicators, namely, adequacy, efficiency, dependability, and equity. Required, scheduled, and delivered amounts of water were used in the calculation of the four indicators. We aim to evaluate the current situation and identify the main causes affecting irrigation performance of JMIS. The contribution of this study is the study of irrigation performance indicator discrimination by water allocation and water delivery. This study enables the determination of the influence of each process on irrigation to consequently improve irrigation performance.

2. Materials and Methods

2.1. Description of JMIS

JMIS is in Yuncheng City, Shanxi Province, at a latitude of 35°00'–35°10' N, longitude of 110°22'–110°51' E, and elevation from 360–450 m. The irrigation scheme has a semi-arid climate condition, characterized by cold and dry winters, hot and rainy summers, and a mean annual precipitation of 500 mm. The main crops in JMIS are apple and cotton. Irrigation water is usually applied 4–6 times a year under surface irrigation. The irrigation water delivery system in JMIS consists of a pump station, management stations, control structures, a main canal, secondary canals, and tertiary canals, as shown in Figure 1. A total of 11 secondary canals were selected to evaluate the irrigation performance in 2012, 2014, and 2015. The characteristics of the selected secondary canals in

this study area, such as the location, the irrigated area, the length of canal, and planting crop, are given in Table 1.

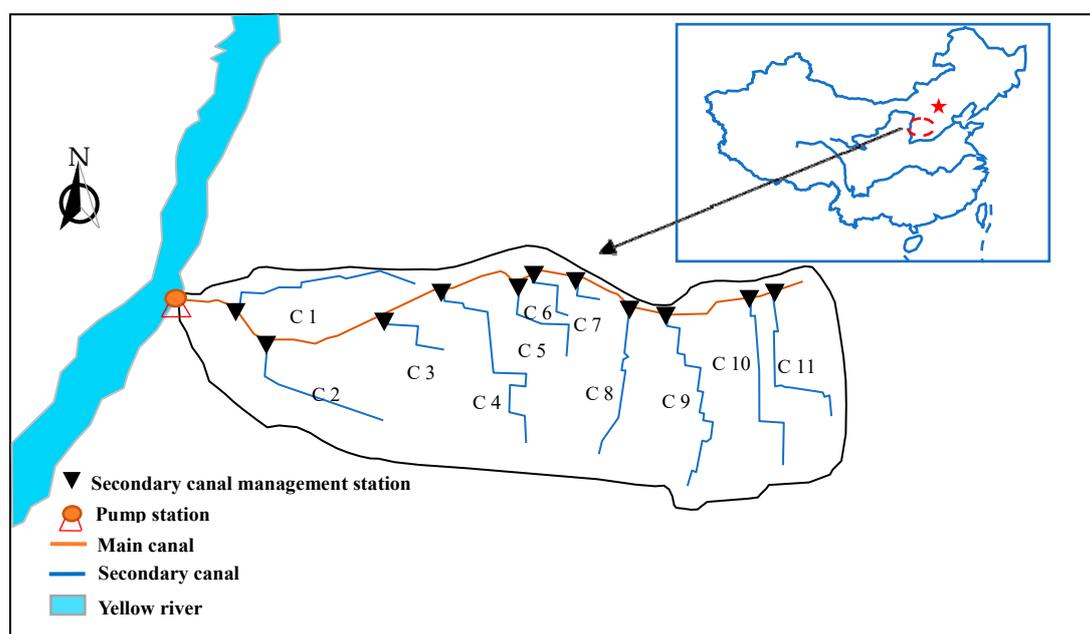


Figure 1. Distribution of main and secondary canals in Jiamakou Irrigation Scheme.

Table 1. Characteristics of selected secondary canals in the study area.

No.	Secondary Canal Name	Distance from Pump Station (m)	Irrigated Area (ha)	Total Length of Canal (m)	Cropping Pattern (Apple: Cotton)
C 1	Puli	2664	1139	11,117	0.32:0.68
C 2	Secondary canal 1	5267	2235	26,274	0.55:0.45
C 3	Secondary canal 3	13,093	595	4693	0.85: 0.15
C 4	Secondary canal 4	16,655	1729	21,600	0.55:0.45
C 5	Secondary canal 5	20,569	989	10,800	0.67:0.33
C 6	Secondary canal 6	21,274	209	2788	0.74:0.26
C 7	Secondary canal 7	24,252	229	3928	0.79:0.21
C 8	Secondary canal 8	29,300	665	9200	0.24:0.76
C 9	Secondary canal 9	30,100	754	1400	0.74:0.26
C 10	Secondary canal 10	35,062	980	19,488	0.57:0.43
C 11	Secondary canal 11	36,321	995	28,500	0.68:0.32
Total	-	-	10,517	-	-

The timely availability of water for crops has greatly contributed to local agricultural and economic development in JMIS, and the irrigation scheme has formed a systematic irrigation water management mode. The irrigation water management in JMIS includes two procedures, namely water allocation and water delivery. Water allocation refers to the process where farmers allocate irrigation water to crops according to traditional irrigation experience and submit their orders to the managers of the irrigation scheme. Water delivery refers to the process where the managers of the irrigation scheme operate the irrigation water delivery system to supply water to crops according to farmers' water orders, and it is mainly affected by the physical system and operational decision of canals.

JMIS is managed by the Irrigation Scheme Administration Bureau (ISAB), and the following departments conduct the management of irrigation water: Pump Management Station, Main Canal Management Center, Secondary Canal Management Station, and Tertiary Canal Operating Organization.

Figure 2 shows the relationship between these departments. During the irrigation period, farmers submit daily orders directly to the Tertiary Canal Operating Organization. The Secondary Canal Management Station then receives these orders and passes the information on to the Main Canal Management Center. According to this information and water-use efficiency in the canal system, the Main Canal Management Center issues instructions of pump operation (run number, setting time) to the Pump Management Station. The four departments simultaneously control their own hydraulic structures to supply water to the lower canals; and they check, monitor, and record the water delivered. Flow measurement is at the core of irrigation water management. Each canal in JMIS is equipped with accurate flow measuring facilities: Parshall flume for the secondary canal and non-throat flume for the tertiary canal.

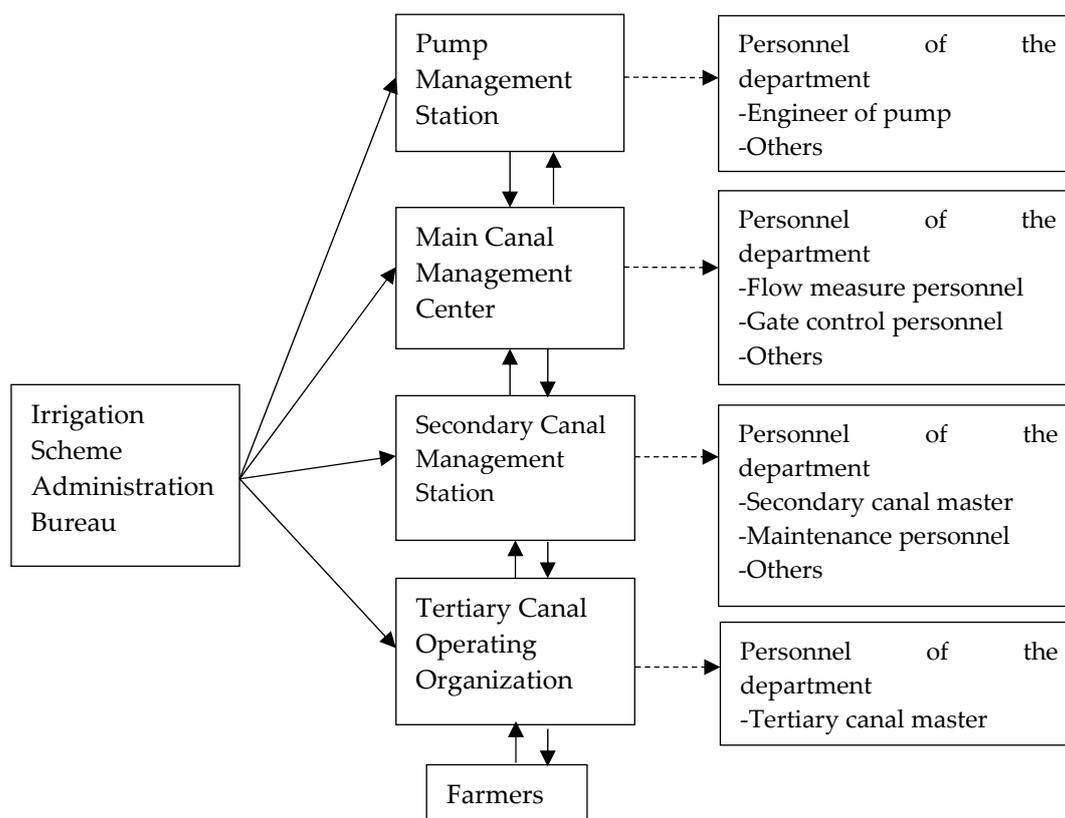


Figure 2. Organization chart in the process of irrigation water delivery management.

2.2. Crop Evapotranspiration and Irrigation Water Requirement

Crop evapotranspiration is calculated by correcting the reference evapotranspiration with the crop coefficient as shown in Equation (1):

$$ET_c(t) = k_c(t)ET_0(t) \tag{1}$$

where ET_c is crop evapotranspiration, t is time, and k_c is crop coefficient, the value of which can be obtained from the results of two experimental areas near the study area (see Figure 3) [16,17]. The distance between the two experimental areas and the study area is approximately 200 km. Similar climatic conditions, soil, and farmland management make it possible to use the k_c values of the two experimental areas in this study area. Meanwhile, ET_0 is reference evapotranspiration and can be calculated by the FAO56 Penman–Monteith method according to climate data observed at meteorological stations near JMIS [18].

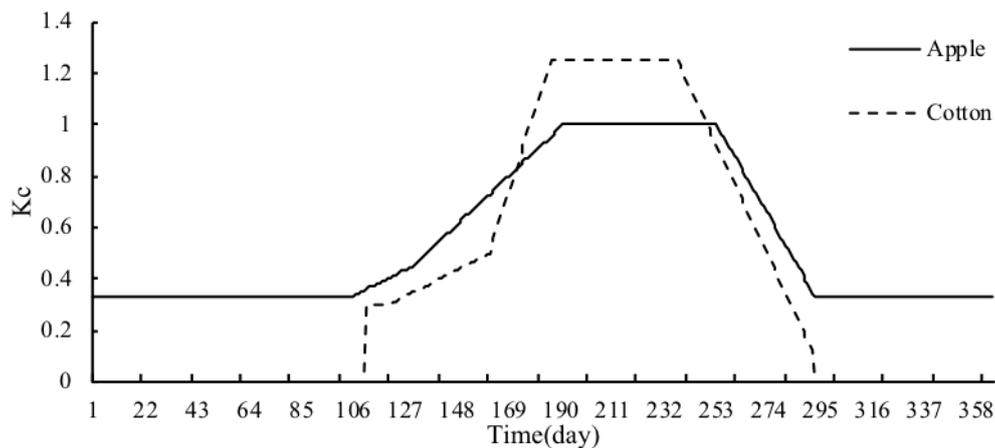


Figure 3. Crop coefficients of apple and cotton in JMIS.

Net irrigation water requirement of crop and irrigation water requirement for the secondary canals are formulated as Equations (2) and (3):

$$Q_{Rnet}(t) = (ET_{ca}(t) - EP(t))A_a + (ET_{cc}(t) - EP(t))A_c \quad (2)$$

$$Q_R(t) = Q_{Rnet}(t) / (WUE_f \times WUE_c) \quad (3)$$

where Q_{Rnet} is net irrigation water requirement, ET_{ca} is ET_c of apple, ET_{cc} is ET_c of cotton, and EP is defined as the effective precipitation in crop-growing season and is equal to the total precipitation minus the loss from surface runoff. If EP is greater than ET_c , Q_{Rnet} is considered equal to zero. The variables A_a and A_c represent the planting areas of apple and cotton within the secondary canal control area, respectively. Q_R is irrigation water requirement, WUE_f and WUE_c represent water use efficiency in the field and canal system, respectively. According to the experiments in this irrigation scheme, water efficiency in the field and canal systems is, respectively, assumed to be 0.95 and 0.85.

The variable EP is mainly related to precipitation amount at a rainfall event, topography, soil infiltration rate, and field management. It is regarded as an invalid precipitation when the rainfall is extremely small. In contrast, surface runoff will occur if precipitation is excessive. In this study, EP is formulated as Equation (4):

$$EP = \alpha P \quad (4)$$

where P is the total amount of precipitation at a time, and α is the coefficient of effective precipitation. Generally, $\alpha = 0$ when $P < 5$ mm, $\alpha = 1.0$ when $5 \text{ mm} \leq P \leq 50$ mm, and $\alpha = 0.8$ when $50 \text{ mm} > P$ [19].

2.3. Scheduled Water and Delivered Water

We define the amount of scheduled water as the amount of water allocated to the secondary canal at a time, which is determined by the water requested by the farmers and the water use efficiency in the canal system. Scheduled water is formulated as Equation (5):

$$Q_s(t) = Q_r(t) / WUE_c \quad (5)$$

where Q_s is the scheduled water, and Q_r is water requested by farmers. As previously mentioned, the farmers' water orders are submitted to ISAB daily, so the data of requested water in 2012, 2014, and 2015 was collected directly from ISAB.

The actual amount of delivered water to the secondary canal at a time, denoted herein as Q_D , was measured by the Parshall flume managed by the Secondary Canal Management Station. Water levels were measured and recorded at 1 h intervals during the irrigation season and converted into

discharges using the flow formula of Parshall flume. Similar to Q_r , Q_D was collected directly from ISAB of JMIS (Table 2).

Table 2. EP , Q_R , Q_S , and Q_D values during 2012, 2014, and 2015.

Year	Month	EP (mm)	Q_R (10^4 m ³)	Q_S (10^4 m ³)	Q_D (10^4 m ³)
2012	Total	329	3923	4314	4265
	January	0	53	0	0
	February	0	101	91	85
	March	14	51	627	598
	April	9	256	648	651
	May	32	315	850	889
	June	12	1679	1173	1180
	July	131	134	181	157
	August	43	1197	534	497
	September	66	0	0	0
	October	16	0	0	0
	November	7	45	202	199
December	0	93	9	9	
2014	Total	557	2110	3578	3636
	January	0	123	0	0
	February	6	18	0	0
	March	0	221	791	785
	April	73	0	109	115
	May	57	0	160	167
	June	90	136	965	1009
	July	57	1285	945	898
	August	85	327	176	229
	September	174	0	0	0
	October	4	0	0	0
	November	11	0	401	392
December	0	0	31	42	
2015	Total	481	2832	3421	3310
	January	0	92	0	0
	February	0	151	0	0
	March	24	0	756	757
	April	52	0	19	17
	May	52	0	645	647
	June	87	88	677	731
	July	47	1112	744	511
	August	26	1389	535	582
	September	84	0	45	65
	October	65	0	0	0
	November	43	0	0	0
December	0	0	0	0	

2.4. Determination of Performance Indicators

The overall performance of the irrigation scheme was calculated by the indicators of adequacy, efficiency, equity, and dependability (Equation (6a–d)) and was considered satisfactory only when the performance levels of water allocation and water delivery were high. The performance of water allocation and water delivery were also determined according to the four indicators and were used in the analysis of the farmers' capacity to allocate water and the manager's capacity to deliver the same. The performance indicators of water allocation were calculated by the scheduled water and

the required water. Meanwhile, the performance indicators of water delivery was calculated by the amount of delivered water and scheduled water.

$$P_A = \frac{1}{T} \sum_T \left(\frac{1}{R} \sum_R P_{A\text{single}} \right), \begin{cases} P_{A\text{single}} = Q_D/Q_R \text{ if } Q_D \leq Q_R \\ P_{A\text{single}} = 1 \text{ if } Q_D > Q_R \end{cases} \tag{6a}$$

$$P_F = \frac{1}{T} \sum_T \left(\frac{1}{R} \sum_R P_{F\text{single}} \right), \begin{cases} P_{F\text{single}} = Q_R/Q_D \text{ if } Q_R \leq Q_D \\ P_{F\text{single}} = 1 \text{ if } Q_R > Q_D \end{cases} \tag{6b}$$

$$P_D = \frac{1}{R} \sum_R CV_T(Q_D/Q_R) \tag{6c}$$

$$P_E = \frac{1}{T} \sum_T CV_R(Q_D/Q_R) \tag{6d}$$

$P_{A\text{single}}$ represents the indicator of adequacy in a secondary canal and a month, and P_A represents the indicator of adequacy in the irrigation scheme and can be calculated by the spatial and temporal average of $P_{A\text{single}}$. When P_A is close to or equal to one, the delivered water was sufficient for crop water requirement. T is the time (12 months in total) in which performance was evaluated. R represents the secondary canals (11 canals in total), the performance of which was to be determined. $P_{F\text{single}}$ represents the indicator of efficiency in a secondary canal and a month, and P_F represents the indicator of efficiency in the irrigation scheme and can be calculated by the spatial and temporal average of $P_{F\text{single}}$. $P_F = 1$ reveals that irrigation water was efficient and no water was wasted. Meanwhile, P_D and P_E represent indicators of dependability and equity, respectively, which show the fairness and reliability of water supply in the irrigation scheme by comparing the adequacy of different secondary canals and months. When P_D and P_E values were close to or equal to zero, this indicates that water delivery was uniform from canal to canal and month to month. $CV_T(Q_D/Q_R)$ is temporal coefficient of variation of Q_D/Q_R over the period T . Similarly, $CV_R(Q_D/Q_R)$ is the spatial coefficient of variation of Q_D/Q_R over the region R . When we calculate Q_D/Q_R or Q_R/Q_D in this paper, we assume that the ratio is 1 if the denominator is zero.

In general, P_A , P_F , P_D , and P_E represent the relationship between the actual water supply and crop water requirement as the comprehensive reflection of performance in the irrigation scheme. The evaluation standard for performance indicators was formed by Molden and Gate as shown in Table 3 [1]. According to the evaluation standard, the performance can be classified as good, fair, or poor.

Table 3. Evaluation standard for performance indicators.

Measure	Performance Classes		
	Good	Fair	Poor
P_A	$0.90 \leq P_A \leq 1.00$	$0.80 \leq P_A < 0.9$	$P_A < 0.8$
P_F	$0.85 \leq P_F \leq 1.00$	$0.70 \leq P_F < 0.85$	$P_F < 0.70$
P_D	$0 \leq P_D \leq 0.10$	$0.10 < P_D \leq 0.25$	$P_D > 0.25$
P_E	$0 \leq P_E \leq 0.10$	$0.10 < P_E \leq 0.20$	$P_E > 0.2$

The calculation of Equation (6a–d) shown that the result of the performance indicators were affected by the calculation unit (time and space). Due to the persistence of crop water requirements and the intermittent trait of irrigation, it was easy to find that if the calculation unit is small, the performance of irrigation will be poor, and vice versa. However, if the calculation unit is too small or too large, it will have no practical significance on the performance evaluation of the irrigation scheme. In related papers [13–15,20], most of the studies used the month as the unit of time, and the canal

control area as the unit of space. Therefore, in this paper, the month and the secondary canal control area were chosen as the time unit and the space unit, respectively.

When the performance of water allocation is analyzed, P_{AA} , P_{AF} , P_{AD} , and P_{AE} are selected to represent the performance of water allocation with respect to adequacy, efficiency, dependability, and equity in the irrigation scheme. The calculation method of P_{AA} , P_{AF} , P_{AD} , and P_{AE} is similar to that of P_A , P_F , P_D , and P_E (Equation (6a–d)). The difference between the two methods is that the former is based on the ratio Q_S/Q_R , whereas the latter is based on the ratio Q_D/Q_R . P_{AA} , P_{AF} , P_{AD} , and P_{AE} represent the relationship between the scheduled water and crop water requirement. The amount of scheduled water in JMIS is determined directly by the farmers' order without the intervention of the managers of the irrigation scheme. Therefore, the performance of water allocation is mainly characterized by the cultivation level of farmers in this irrigation scheme.

Similarly, when the performance of water delivery is analyzed, P_{DA} , P_{DF} , P_{DD} , and P_{DE} are selected to represent the performance of water delivery with respect to adequacy, efficiency, dependability, and equity, reflecting the capability of the irrigation scheme to deliver water. P_{DA} , P_{DF} , P_{DD} , and P_{DE} can also be calculated using the method in Equation (6a)–(6d). The difference is that P_{DA} , P_{DF} , P_{DD} , and P_{DE} are calculated based on the ratio Q_D/Q_S . These indicators can effectively express whether the scheduled water can be delivered to the field by the physical system and canal operation decision. Thus, P_{DA} , P_{DF} , P_{DD} , and P_{DE} signify a series of indicators for the capacity of the irrigation scheme to provide services to the farmers.

3. Results and Discussion

3.1. Performance of Water Allocation and Water Delivery

The performances of water allocation and water delivery of this irrigation scheme are summarized in Table 4. These indicators indicate a poor performance with respect to the objectives of adequacy, efficiency, dependability, and equity in the water allocation process. The calculated crop water requirement based on the FAO56 Penman–Monteith method cannot be met by the scheduled water in a timely manner. Although this situation is believed to occur because of the continuous water demand for crop and intermittent irrigation, it also partly reflects on the incompetence of farmers in establishing an irrigation schedule.

The values of P_{AD} show that the allocation performance with respect to dependability was extremely poor, indicating that the relative water allocation was uneven over time. Through the values of Q_R and Q_S in Table 2, we can intuitively sense a mismatch between scheduled water and required water over time. From the total amount of the year, the scheduled water was greater than the required water, especially in 2014 (wet year). The amount of scheduled water was 1.7 times that of required water in 2014, but the crop water requirement was met only in some months under the influence of the unscientific water allocation. These results may indicate that the farmers' water orders were mainly influenced by traditional and fixed irrigation ideas, and the scientific method of water allocation that allocates water according to the crop water requirement was not reasonably considered.

As shown in Table 4, P_{DA} values were above 0.9, P_{DF} values were above 0.85, P_{DD} values were between 0.1 and 0.25, and P_{DE} values were between 0.1 and 0.2 in the selected years. According to the evaluation criteria, the performances of delivery contribution were good with respect to adequacy and efficiency and were fair with respect to dependability and equity. The operation and management of the irrigation water delivery system in this irrigation scheme was good, and the system could deliver adequate and dependable water to meet the scheduled water in an equitable and efficient manner in most cases. The results also indicate that this irrigation scheme can provide good service to farmers. Some studies have shown that a flexible water delivery system and good water delivery service capacity are important ways to improve water use efficiency and promote modernization of irrigation schemes [21–23]. In recent years, the Chinese government has made efforts to promote the

modernization of irrigation schemes. The good water delivery management and service capabilities of JMIS can serve as a reference for the modernization of other irrigation schemes in the country.

Table 4. Summary of performance for the irrigation scheme.

	Objective	Indicator	2012	2014	2015	Average
Adequacy	Overall performance	P_A	0.61	0.73	0.65	0.66
	Water allocation	P_{AA}	0.62	0.71	0.66	0.66
	Water delivery	P_{DA}	0.93	0.98	0.93	0.95
Efficiency	Overall performance	P_F	0.77	0.47	0.49	0.58
	Water allocation	P_{AF}	0.71	0.48	0.48	0.56
	Water delivery	P_{DF}	0.97	0.88	0.90	0.92
Dependability	Overall performance	P_D	1.48	1.26	1.64	1.46
	Water allocation	P_{AD}	1.52	1.25	1.56	1.44
	Water delivery	P_{DD}	0.21	0.21	0.25	0.23
Equity	Overall performance	P_E	0.69	0.17	0.12	0.32
	Water allocation	P_{AE}	0.69	0.18	0.12	0.33
	Water delivery	P_{DE}	0.17	0.18	0.12	0.16

3.2. Overall Performance of the Irrigation Scheme

The values of P_A , P_F , P_D , and P_E in 2012, 2014, and 2015 are listed in Table 4. According to the evaluation standard in Table 3, the values of P_A were less than 0.8, indicating that the delivered water was insufficient to satisfy the crop water requirement in the selected years. The efficiency indicator was fair in 2012 and poor in 2014 and 2015. These results show that the delivered water was greater than the crop water requirement in some cases. The values of P_D were much greater than 0.25 in 2012, 2014, and 2015, and thus irrigation water was not supplied to the secondary canals at the right time. The secondary canal received more water than required in some months and received less water in some months. The equity indicator was poor in 2012 and fair in 2014 and 2015, showing that the delivered water was uneven in various secondary canals in 2012, and some secondary canals received too much water, whereas some did not receive enough.

Table 5 lists a comparison of the evaluation results that were reported in other studies. Compared to other studies, the results of this study showed that the overall performance of JMIS was generally poor, especially with respect to dependability. The two processes of irrigation water allocation and water delivery determined the overall performance in JMIS. The above analysis shows that compared to water delivery, water allocation had a greater contribution to the poor performance of this irrigation scheme. Although the scheduled water could be supplied by delivered water with good water delivery performance, the overall performance of this irrigation scheme was relatively poor because of the poor performance of water allocation. These results suggest that additional efforts are needed to improve the performance of water allocation and the overall performance of this irrigation scheme. These efforts include the use of modern field-monitoring equipment and technology and the use of a guide for the establishment of farmers' water orders under different climatic conditions. In addition, communication between irrigation scheme managers and farmers must be strengthened, especially in periods of peak water demand.

Table 5. Comparison of the evaluation results reported in other studies.

Categories	Country	Year	Crop	Adequacy	Efficiency	Dependability	Equity
Unal et al. [13]	Turkey	1999	Cotton and vegetable	0.93	0.83	0.81	0.67
Vandersypen et al. [14]	Mali	2004	paddy rice	0.91	0.59	0.71	0.54
Aly et al. [15]	Egypt	2003	Paddy rice, cotton and maize	0.66	-	0.26	0.18
Nam et al. [20]	South Korea	2013	paddy rice	0.87	0.86	0.21	0.22

4. Conclusions

The current irrigation behavior and irrigation performance in JMIS was analyzed and evaluated quantitatively by using adequacy, efficiency, dependability, and equity. The overall performance of this irrigation scheme was classified as poor. Indicators of the overall performance show that the water supply of this irrigation scheme was inadequate and inefficient, and the required water was not supplied at the right time in an equitable manner. Further, analysis found that the performance of this irrigation scheme was poor in terms of water allocation, but good in terms of water delivery, indicating that this scheme had an unscientific water allocation method. Therefore, the allocation method could be the main cause affecting the irrigation performance of JMIS and matching the amount scheduled water delivered to the crop water requirement requires additional effort.

By calculating performance indicators according to water allocation and water delivery, it is possible to determine the influence of each individual process on irrigation management and take subsequent measures to improve irrigation performance.

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