

OPTIMIZING ROTATIONAL IRRIGATION STRATEGIES AND ENHANCING WATER-USE EFFICIENCY IN THE HOULI CANAL SYSTEM: AN OPTIMIZATION MODEL BASED ASSESSMENT

OPTIMISATION DES STRATEGIES D'IRRIGATION PAR ROTATION ET AMELIORATION DE L'EFFICIENCE DE L'UTILISATION DE L'EAU DANS LE RESEAU DE CANAUX DE HOULI : EVALUATION FONDEE SUR UN MODELE D'OPTIMISATION

Yun Wei Tan¹, Ming-Che Hu² and Feng Wen Chen³

ABSTRACT

The Houli Canal irrigation district, located on the southern bank of the Daan River in Taichung, is one of the most important rice-producing regions in central Taiwan. Due to its extensive service area and high crop water demand, the district has frequently experienced irrigation shortages, particularly under the long-term reduction of agricultural water rights and increasing competition from domestic and industrial water uses. To maintain agricultural production under constrained water supply conditions, the Houli Canal has implemented a rotational irrigation scheme operated by three work stations—TZJ, YM, and ZY. In current practice, the rotation cycle is fixed at 5.5 days (132 hours), with station-specific rotation durations of 18 hours for TZJ, 62 hours for YM, and 52 hours for ZY. While this system has been effective in sustaining irrigation operations, fixed rotation intervals and static station allocations may not fully reflect seasonal variability in crop water demand, conveyance time, and conveyance losses. This study develops an optimization-based analytical framework to evaluate the performance of the existing rotational irrigation regime and to explore opportunities for improving water-use efficiency. The analysis is primarily based on the 2024 planned water allocation and conveyance discharge data for the three work stations. Planned flows exhibit clear intra-annual variability, particularly at YM and ZY, where a bimodal pattern reflects the double-cropping rice system. Peak planned discharges reach approximately 3~4 m³/s, and conveyance losses increase proportionally with flow magnitude, with maximum losses of about 1.3 m³/s observed at YM. Overall, annual conveyance loss rates across the stations are estimated to range between 30~40%, highlighting the importance of incorporating conveyance characteristics into irrigation scheduling. Conveyance times were estimated using the Manning equation, assuming a representative canal width of approximately 3.8 m and a uniform slope of 0.0019. Monthly flow data were used to derive reach velocities and travel times for each station. Estimated flow velocities range from approximately 0.94~1.44 m/s, resulting in average conveyance times of about 0.97 hours to TZJ, 1.7 hours to YM, and 3.35 hours to ZY. These results indicate that conveyance time is non-negligible relative to rotational irrigation operations, especially for downstream service areas. Crop water requirements were estimated using the FAO Penman-Monteith method to calculate reference evapotranspiration, combined with FAO crop coefficients and local cropping assumptions. Paddy rice cultivation was assumed from February to November, with short-term vegetable crops during December and January. Soil infiltration was incorporated to represent ponded paddy field conditions. Based on the predominance of sandy loam and loam soils, the area-weighted infiltration rate was estimated at approximately 10.23 mm/day, and seasonal crop water requirements ranged from about 1.95~14.64 mm/day. An optimization model was formulated on a 10-day periods (ten-day) time scale to identify the optimal rotation interval and station-specific rotation durations while accounting for conveyance time and operational constraints. Results indicate that the highest irrigation efficiency is achieved with two rotations, corresponding to a 5-day rotation interval, which is broadly consistent with the current 5.5-day cycle. The model further suggests

¹ Institute, Agricultural Engineering Research Center, Taoyuan 32061, Taiwan (R.O.C.) Email: tan0710@aerc.org.tw

² Institute, Department of Bioenvironmental System Engineering, National Taiwan University Email: mchu@ntu.edu.tw

³ Institute, Agricultural Engineering Research Center, Taoyuan 32061, Taiwan (R.O.C.), Email: chenfw@aerc.org.tw

that rotation durations should be adjusted dynamically on a 10-day periods basis to reflect seasonal demand variability. Optimized station-specific rotation durations were found to be close to current practice, indicating that the existing rotational irrigation system is generally well-structured, while modest seasonal adjustments could further enhance water-use efficiency under increasing supply constraints.

Keywords: Agricultural Water, Rotation Irrigation Mechanism, Optimization; Crop water requirements; Water-use efficiency.

RÉSUMÉ

Le périmètre irrigué du canal de Houli, situé sur la rive sud de la rivière Daan à Taichung, est l'une des principales régions rizicoles du centre de Taïwan. En raison de l'étendue de sa zone desservie et des besoins élevés en eau des cultures, le périmètre a fréquemment connu des pénuries d'eau d'irrigation, notamment dans un contexte de réduction à long terme des droits d'eau agricoles et de concurrence croissante des usages domestiques et industriels. Afin de maintenir la production agricole dans des conditions d'approvisionnement en eau limitées, le canal de Houli a mis en œuvre un dispositif d'irrigation par rotation exploité par trois stations de travail : TZJ, YM et ZY. Dans la pratique actuelle, le cycle de rotation est fixé à 5,5 jours (132 heures), avec des durées propres à chaque station de 18 heures pour TZJ, 62 heures pour YM et 52 heures pour ZY. Si ce système a permis de maintenir efficacement les opérations d'irrigation, les intervalles de rotation fixes et les allocations statiques entre les stations peuvent ne pas refléter pleinement les variations saisonnières des besoins en eau des cultures, du temps d'acheminement et des pertes de transport. Cette étude développe un cadre analytique fondé sur l'optimisation afin d'évaluer les performances du régime existant d'irrigation par rotation et d'examiner les possibilités d'amélioration de l'efficacité de l'utilisation de l'eau. L'analyse repose principalement sur les données de 2024 relatives aux allocations d'eau planifiées et aux débits d'acheminement des trois stations de travail. Les débits planifiés présentent une nette variabilité intra-annuelle, en particulier à YM et ZY, où une distribution bimodale reflète le système de double culture du riz. Les débits planifiés maximaux atteignent environ 3 à 4 m³/s, et les pertes de transport augmentent proportionnellement à l'importance du débit, les pertes maximales observées à YM étant d'environ 1,3 m³/s. Globalement, les taux annuels de pertes de transport dans les différentes stations sont estimés entre 30 % et 40 %, ce qui souligne l'importance de prendre en compte les caractéristiques d'acheminement dans la programmation de l'irrigation. Les temps d'acheminement ont été estimés à l'aide de l'équation de Manning, en supposant une largeur représentative du canal d'environ 3,8 m et une pente uniforme de 0,0019. Les données mensuelles de débit ont servi à calculer la vitesse d'écoulement et le temps de parcours pour chaque station. Les vitesses d'écoulement estimées varient d'environ 0,94 à 1,44 m/s, ce qui donne des temps moyens d'acheminement d'environ 0,97 heure jusqu'à TZJ, 1,7 heure jusqu'à YM et 3,35 heures jusqu'à ZY. Ces résultats indiquent que le temps d'acheminement n'est pas négligeable par rapport aux opérations d'irrigation par rotation, surtout pour les zones desservies en aval. Les besoins en eau des cultures ont été estimés à l'aide de la méthode FAO de Penman-Monteith pour calculer l'évapotranspiration de référence, combinée aux coefficients culturels de la FAO et aux hypothèses locales de culture. La riziculture inondée a été supposée de février à novembre, avec des cultures maraîchères à cycle court en décembre et janvier. L'infiltration du sol a été intégrée afin de représenter les conditions des rizières submergées. Compte tenu de la prédominance des sols sablo-limoneux et limoneux, le taux d'infiltration pondéré par la superficie a été estimé à environ 10,23 mm/jour, et les besoins saisonniers en eau des cultures variaient d'environ 1,95 à 14,64 mm/jour. Un modèle d'optimisation a été formulé sur une échelle temporelle de dix jours afin de déterminer l'intervalle de rotation optimal et les durées de rotation propres à chaque station, tout en tenant compte du temps d'acheminement et des contraintes opérationnelles. Les résultats indiquent que l'efficacité d'irrigation la plus élevée est obtenue avec deux rotations, ce qui correspond à un intervalle de rotation de 5 jours et concorde globalement avec le cycle actuel de 5,5 jours. Le modèle suggère en outre d'ajuster dynamiquement les durées de rotation tous les dix jours afin de refléter la variabilité saisonnière de la demande. Les durées de rotation optimisées pour chaque station se sont révélées proches de la pratique actuelle, ce qui indique que le système existant d'irrigation par rotation est généralement bien structuré, tandis que de modestes ajustements saisonniers pourraient encore

améliorer l'efficacité de l'utilisation de l'eau face à des contraintes croissantes sur l'approvisionnement.

Mots clés : Eau agricoles; Mécanisme de rotation d'Irrigation, Optimisation; Besoins en eau des cultures; Efficacité de l'utilisation de l'eau.

1. Introduction

The irrigation areas under the Taichung Management Office of the Irrigation Agency represent a critical agricultural zone in central Taiwan, spanning a vast area of nearly 25,702 hectares. The region is supplied by three major river systems from north to south: the Da'an River, Da'jia River, and Wu River. The largest irrigation system on the south bank of the Da'an River is the Houli Canal irrigation district.

However, due to global climate change and rapid socioeconomic development, water stress and competition among domestic, industrial, and agricultural sectors are on the rise worldwide, significantly threatening the stability of agricultural water supplies (van Schaik et al., 2017).

Under this context, the Houli Canal district faces severe challenges from shrinking water rights and strict limits on canal water diversion. Moreover, the primary crop in this district is paddy rice, which requires a continuous ponding depth during its growth stages. This traditional cultivation method leads to massive field water losses through evapotranspiration and soil percolation (Bouman and Tuong, 2001). Consequently, under the dual challenges of limited water supply and high crop water requirements, the available water volume of the Houli Canal is often insufficient to fully satisfy the irrigation demand across the entire district.

Additionally, the total length of the Houli Canal is nearly 14 kilometers. Transporting water over such a long distance significantly increases conveyance losses and travel times. To overcome these unfavorable factors, minimize ineffective water delivery, and achieve reasonable water allocation, water managers have long divided the district into three main workstations—TZJ (Tunzijiao), YM (Yuemei), and ZY (Ciyao)—implementing a rotation irrigation mechanism to coordinate water distribution. To effectively schedule such dynamic systems, utilizing optimization models that integrate crop water production, weather conditions, and water allocation time intervals has been recognized as a highly successful approach to maximizing water efficiency and regional agricultural benefits (Georgiou and Papamichail, 2008).

Considering the existing rotation mechanism of the Houli Canal, this study approaches the issue from the perspectives of crop water requirements and water conveyance time. Under the same water delivery timeframe, we explore the optimal number of rotations and investigate how to maximize irrigation time. Finally, while ensuring that crop water requirements are met, we propose practical recommendations for water allocation time within the rotation mechanism.

II. Methodology

2.1 Study Area

The study area is the Houli Canal rotation irrigation system, covering a total irrigation area of 2,196 ha. The system is operated via rotation by three workstations from upstream to downstream: TZJ (Tunzijiao), YM (Yuemei), and ZY (Ciyao). Their respective irrigation areas are 255 ha, 1,036 ha, and 905 ha (Taichung Management Office, 2025). YM has the largest irrigation area, while TZJ has the smallest.

In terms of the water intake system, the Houli Canal diverts water from the left bank of the Da'an River. It passes through a conveyance tunnel and irrigates lateral canals No. 1 to No. 8 along the route. Specifically, Branch 1~2 belong to TZJ, Branch 3~5 belong to YM, and Branch 6~8 belong to

ZY (Taichung Irrigation Association, 2018). The total length of the Houli Canal is nearly 14 km. Relative to the main intake of the Houli Canal, the water diversion points for the workstations are located at approximately 4.2 km for TZJ, 7 km for YM, and 13.8 km for ZY. A schematic diagram of the research area is shown in Figure 1.



Figure 1 Schematic Diagram of the Study Area ~ Houli Canal Irrigation District

2-2 Current Rotation Irrigation Mechanism

According to the 2025 rotation irrigation announcement by the Taichung Management Office, each rotation interval (cycle) lasts 5.5 days (132 hours). Within this cycle, the irrigation duration for TZJ is 18 hours, while YM and ZY receive 62 hours and 52 hours, respectively (Taichung Management Office, 2025). This shows that because the TZJ irrigation area is smaller, its overall water demand and allocated irrigation time are relatively shorter. Conversely, YM has the largest irrigation area and higher water requirements, resulting in a longer irrigation duration.

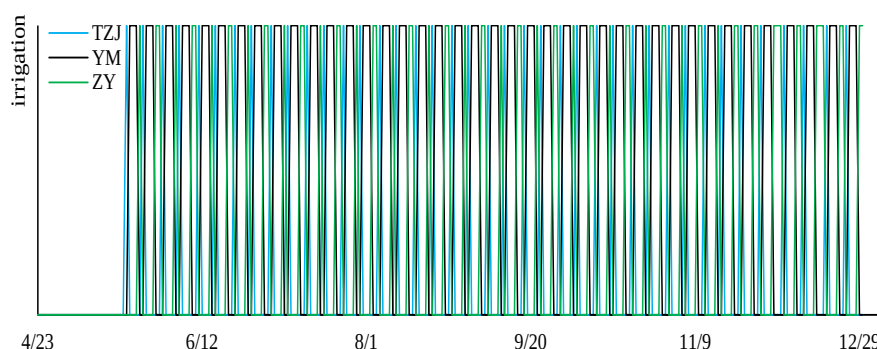


Figure 2 2024 Houli Canal Rotation Irrigation Schedule

2-3 Planned Irrigation Water Volume and Conveyance Loss

Based on the 2025 irrigation plan from the Taichung Management Office, the planned water consumption for the three workstations is plotted in Figure 3, illustrating the variations in planned flow rates for the early, middle, and late periods (decades) of each month. A clear double-peak pattern can be observed for YM and ZY, indicating that the primary crop in these areas is second-crop paddy rice, with a maximum planned flow rate of approximately 3~4 cms. In contrast, the annual planned water volume for TZJ remains relatively low.

Additionally, the water conveyance losses for the three stations are shown in Figure 4. The results indicate that water loss is proportional to the planned water volume, with the maximum conveyance loss occurring at YM at approximately 1.3 cms. By calculating the ratio of planned water volume to water loss, the annual conveyance loss rate for the three workstations remains fairly consistent, ranging from roughly 30% to 40%, as shown in Figure 5.

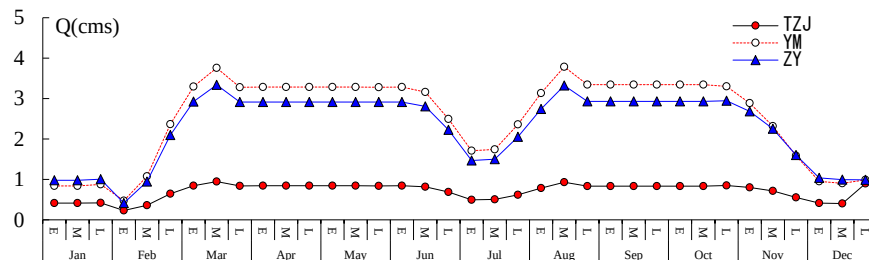


Figure 3 Planned Water Consumption of the Houli Canal Rotation Workstations in 2024

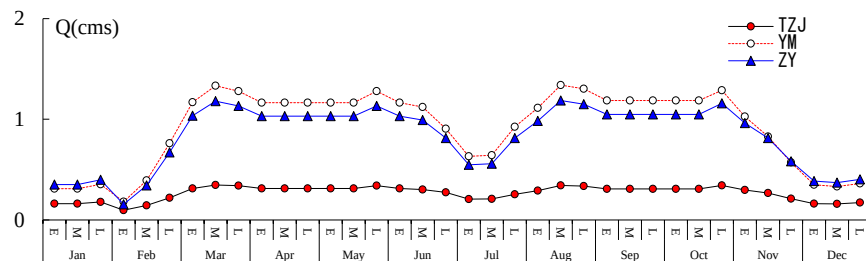


Figure 4 Water Conveyance Loss of the Houli Canal Rotation Workstations in 2024

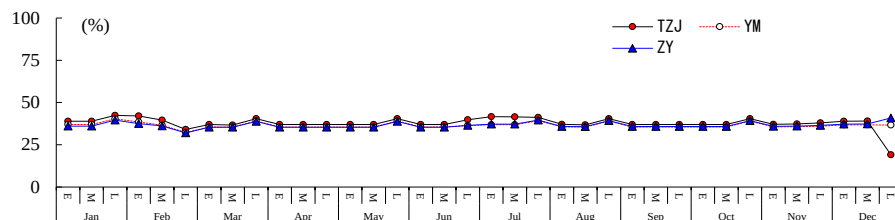


Figure 5 Water Conveyance Loss Rate of the Houli Canal Rotation Workstations in 2024

2.4 Assessment of Water Conveyance Time

Since the rotation mechanism involves water travel time, longer main canal routes lead to longer delivery times. To estimate the conveyance time, this project assumes that the channel width of the Houli Canal is uniform throughout its length (the measured upstream channel width is about 3.8 m), with a consistent slope of 0.0019 (calculated as the ratio of the elevation difference between the intake and the downstream end to the total length of the canal).

Using the monthly flow data and applying the Manning formula (Eq.1), the flow velocities corresponding to different monthly flow rates were estimated. The results indicate that the flow velocity in the TZJ section ranges from 0.98 to 1.44 m/s, the YM section ranges from 0.95 to 1.39 m/s, and the ZY section ranges from 0.94 to 1.4 m/s. Based on the distances from the main intake to each workstation, the water travel times were determined: the average conveyance time for TZJ is approximately 3,497 seconds (0.97 hr), YM is about 6,135 seconds (1.7 hr), and ZY is about 12,047 seconds (3.35 hr), as shown in Figure 6.

$$v = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \dots \dots \dots (1)$$

Where: v is the flow velocity (m/s), n is the Manning roughness coefficient, R is the hydraulic radius (m), and S is the channel slope.

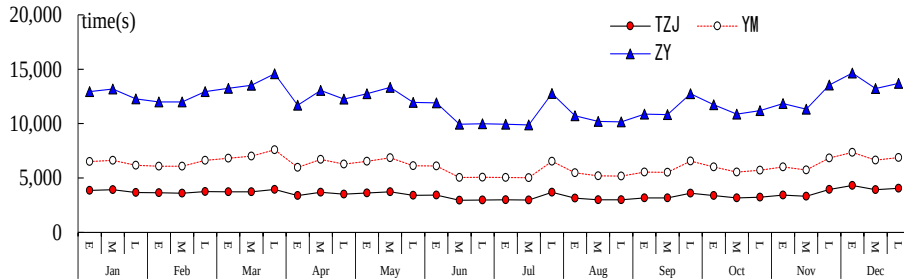


Figure 6 Water Conveyance Time Estimation for the Houli Canal Rotation Workstations in 2024

2.5 Estimation of Crop Water Requirement

This study utilizes the Penman-Monteith Method (Eq.2 and 3) to estimate the reference crop evapotranspiration (ET_o) in the Houli Canal irrigation district (Allen et al. (FAO), 1998; Kassam and Smith, 2001; AERC, 2022). It is assumed that the primary crop from February to November is paddy rice, while short-term vegetables are grown from December to January. Crop evapotranspiration was estimated using the crop coefficients recommended by the FAO.

Additionally, rice cultivation must account for soil infiltration under ponding conditions. According to the irrigation planning tables provided by the Taichung Management Office (2024), the irrigation district consists mainly of sandy loam (1,160 ha) and loam (1,036 ha). Based on the relationship between soil types and infiltration rates (Department of Agricultural Engineering, National Taiwan University, 1970), the weighted average soil infiltration rate for the Houli Canal district was calculated to be 10.23 mm/day. The total annual crop water requirement ranges from 1.95 to 14.64 mm/day.

$$ET_{crop} = K_c \times ET_o \dots \dots \dots (2)$$

$$ET_o = \frac{0.408 \times \Delta \times (R_n - S) + \gamma \times \frac{900}{T + 273} \times U_2 \times (e_a - e_d)}{\Delta + \gamma(1 + 0.34 \times U_2)} \dots \dots \dots (3)$$

$$\Delta = \frac{2504 \times \exp\left[\frac{17.27 \times T}{(T + 237.3)}\right]}{(T + 237.3)^2} \dots \dots \dots (4)$$

Where: ET_o is the reference crop evapotranspiration (mm/day), Δ is the slope of the saturation vapor pressure curve (kPa/°C), R_n is the net radiation (MJ/m²·day), G is the soil heat flux density (MJ/m²·day), γ is the psychrometric constant (kPa/°C), T is the mean daily air temperature (°C), u_2 is the wind speed at 2 m height (m/s), e_s is the saturation vapor pressure (kPa), and e_a is the actual vapor pressure (kPa).

Table 1 Crop Water Requirements in the Houli Canal Irrigation District (Unit: mm/day)

Water demand	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Paddy rice	0	2.14	2.75	3.45	3.21	3.90	4.41	4.33	4.36	3.55	2.59	0
Vegetable	1.95	0	0	0	0	0	0	0	0	0	0	2.07
Infiltration	0	10.23	10.23	10.23	10.23	10.23	10.23	10.23	10.23	10.23	10.23	0
ET_{crop}	1.95	12.37	12.98	13.68	13.44	14.13	14.64	14.56	14.59	13.78	12.82	2.07

Unit:mm/da

2.6 Model Construction

To maximize the effective use of irrigation water and reduce water losses caused by conveyance, the objective function of this study aims to maximize the total irrigation time within a fixed ten-day (per decade) period (Eq.5). Eq.6 ensures that the water volume delivered to each workstation during its irrigation period satisfies the water demands of the fields during non-irrigation periods; meaning, the water depth received during supply periods must meet the crop water requirements when water is turned off.

Furthermore, the actual water supply time must be proportional to the planned irrigation time, meaning the actual irrigation durations for the three rotating workstations should increase proportionally (Eq.7). In addition, the sum of the total irrigation time and water conveyance time must be less than the ten-day scale (Eq.8). The field irrigation depth must also be kept below 0.1 m (Eq.9) to avoid submerging the rice seedlings. Finally, the number of rotations must be a positive integer, as shown in Eq.10.

$$\text{Max } n \sum T \dots\dots\dots (5)$$

$$\hat{T} \geq \frac{A \cdot ET_{crop} \cdot \sum (T+t)}{n(Q + A \cdot ET_{crop})} \dots\dots\dots (6)$$

$$T = k\hat{T} \dots\dots\dots (7)$$

$$n \sum T+t \leq 864000 \dots\dots\dots (8)$$

$$T \leq \frac{0.1A}{Q} \dots\dots\dots (9)$$

$$n \geq 1, n \in Z \dots\dots\dots (10)$$

Where: n is the number of irrigation rotations, T is the irrigation time (s), T_{total} is the unallocated irrigation time (s), A is the irrigation area (ha), ET_{crop} is the crop water requirement (m/s), t is the water conveyance time (s), Q is the water conveyance volume of the corresponding workstation per decade (cms), and α is the allocation ratio.

III. Results and Discussion

The results of this study show that the maximum irrigation efficiency is achieved when the number of rotations (n) is set to 2, which corresponds to an irrigation interval (cycle) of 5 days per rotation, as illustrated in Figure 7. Because water demands vary across different growth stages—for instance, crop water requirements are relatively lower from mid-June to mid-July—the allocated irrigation time decreases accordingly. Therefore, rotation schedules should be adjusted dynamically every ten days to achieve optimal water resource efficiency. The estimated rotation times show that the annual optimal irrigation duration (including conveyance time) ranges from 11.2 to 17.3 hours for TZJ (average: 14.4 hours), 40 to 55.3 hours for YM (average: 51.7 hours), and 37 to 54.9 hours for ZY (average: 48.2 hours).

Given that the current Houli Canal system uses a fixed 5.5-day rotation interval, the comparison was conducted using the ratio of irrigation time (as shown in Figure 8). In the existing system, the irrigation time ratios for TZJ, YM, and ZY are 13.6%, 47%, and 39.4%, respectively. This study's optimized model suggests an optimal time ratio of 11.7%~14.2% for TZJ (average: 12.6%), 41%~45.8% for YM (average: 45.2%), and 41.6%~45.5% for ZY (average: 42.1%).

Comparing the optimized averages with the current system, the differences are -7.4% for TZJ, -3.8% for YM, and +6.9% for ZY. This indicates that the current system allocates slightly more time than necessary to TZJ and YM, while ZY is slightly under-allocated. However, because these differences are minor, the results confirm that the existing rotation irrigation system already possesses a highly reasonable and practical water distribution method.

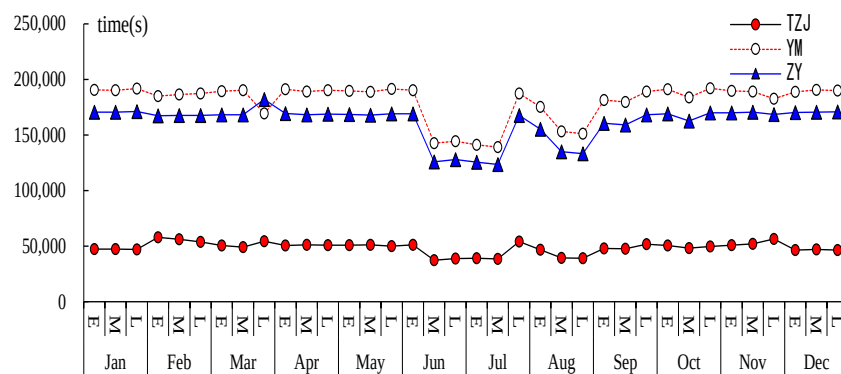


Figure 7 Estimated Results of Irrigation Rotation Time

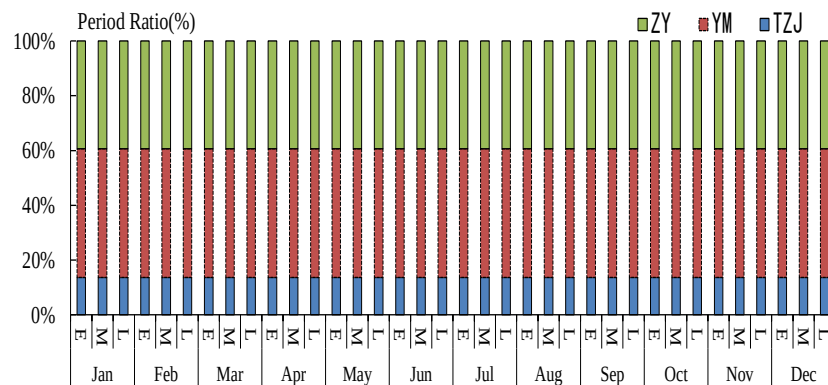


Figure 8 Estimated Results of Irrigation Time Ratios for Houli Canal Workstations

V. Conclusions and Suggestions

Based on the 2024 water conveyance and planned water allocation data of the Houli Canal, this study utilized a ten-day (per decade) time scale to analyze irrigation efficiency. The Manning formula was used to estimate water travel times, the Penman-Monteith method calculated crop water requirements, and an optimization model evaluated the differences between the optimal rotation schedule and the current system. The results show that executing 2 rotations per ten days provides the maximum irrigation time, which translates to a 5-day rotation interval. This is very close to the current 5.5-day interval.

Regarding irrigation hours, to satisfy the minimum crop water requirements while accounting for different growth stages, the optimal approach is to dynamically adjust irrigation hours on a ten-day

basis. Ideally, irrigation hours should be treated as a time-variable parameter. The model indicates that the annual optimal irrigation hours (including conveyance time) for TZJ should be 11.2~17.3 hours, where the maximum value aligns well with the current 18 hours. For YM, the optimal range is 40~55.3 hours, which is slightly lower than the current 62 hours. For ZY, the optimal range is 37~54.9 hours, with the maximum value slightly exceeding the current 52 hours.

In actual field operations, a fixed irrigation schedule is usually preferred for administrative and management convenience. Because this study's theoretical model focuses strictly on satisfying crop water needs and accounting for conveyance losses, the calculated optimal times and water volumes are slightly lower than current operational practices. Nevertheless, the analysis of irrigation time ratios among the three workstations demonstrates that the existing schedules closely match the optimized distribution. This validates the high completeness and long-term reliability of the water allocation mechanism in the Houli Canal system.

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