

FROM EXPERIENCE TO ALGORITHMS: ADAPTIVE GATE OPERATION FOR WATER-SCARCE IRRIGATION DISTRICTS

DE L'EXPÉRIENCE AUX ALGORITHMES: MANŒUVRE ADAPTATIVE DES VANNES DANS LES PÉRIMÈTRES IRRIGUÉS EN SITUATION DE PÉNURIE D'EAU

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ABSTRACT

Irrigation districts are increasingly exposed to water scarcity, supply variability, and operational uncertainty, making efficient water management difficult under fixed infrastructure and limited supply conditions. In many districts, gate operation and water distribution are still adjusted using experience-driven approaches, which limits systematic comparison of operating alternatives and identification of improved management strategies. Because irrigation performance involves multiple and often conflicting objectives—such as ponding stability, distribution equity, and operational safety—a structured optimization framework is required. This study presents a simulation-based multi-objective optimization framework for irrigation gate operation management in a small-scale irrigation district. An agricultural irrigation network was modeled using EPA-SWMM, constructed from field investigations of canal geometry, elevations, and channel lengths, together with management office records. Measured reservoir supply data provided by the Korea Rural Community Corporation (KRC) were used as boundary inputs. A structured indicator system was defined and applied to simulation outputs, covering ponding deficit characteristics, spatial discharge balance among upstream, midstream, and downstream zones, and gate operation variability. These indicators serve directly as objective functions in the optimization. Gate opening ratios were treated as weekly decision variables for multiple hydraulic control structures. A multi-objective evolutionary algorithm was used to generate a Pareto set of non-dominated operation schedules representing trade-offs among evaluation indicators. A decision-support procedure was then applied to rank Pareto solutions using nonlinear multi-criteria weights linked to water availability regimes, enabling adaptive selection of recommended operation schedules. The proposed framework was applied to the Geumseok irrigation district (55 ha), where optimization-based gate operation reduced all four performance indicators and improved spatial water distribution balance relative to the baseline operation.

Keywords: Adaptive irrigation management; Gate operation optimization; EPA-SWMM; Multi-objective optimization; Irrigation canal network; Water distribution efficiency

RÉSUMÉ

Les périmètres irrigués sont de plus en plus exposés à la rareté de l'eau, à la variabilité de l'approvisionnement et à l'incertitude opérationnelle, ce qui complique la gestion efficace de l'eau lorsque les infrastructures sont fixes et l'approvisionnement limité. Dans de nombreux périmètres, la manœuvre des vannes et la distribution de l'eau sont encore ajustées selon des approches fondées sur l'expérience, ce qui limite la comparaison systématique des différentes options d'exploitation et l'identification de meilleures stratégies de gestion. Comme les performances de l'irrigation reposent sur des objectifs multiples et souvent contradictoires — tels que la stabilité de la lame d'eau, l'équité de la distribution et la sécurité opérationnelle —, un cadre d'optimisation structuré est nécessaire.

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Cette étude présente un cadre d'optimisation multiobjectif fondé sur la simulation pour gérer la manœuvre des vannes dans un petit périmètre irrigué. Un réseau d'irrigation agricole a été modélisé au moyen d'EPA-SWMM, à partir de relevés de terrain portant sur la géométrie, l'altitude et la longueur des canaux, ainsi que des registres du bureau de gestion. Les données mesurées d'alimentation du réservoir, fournies par la Korea Rural Community Corporation (KRC), ont été utilisées comme données d'entrée aux limites. Un système structuré d'indicateurs a été défini et appliqué aux résultats de la simulation ; il couvre les caractéristiques du déficit de mise en eau, l'équilibre spatial des débits entre les zones amont, médiane et aval, ainsi que la variabilité de la manœuvre des vannes. Ces indicateurs servent directement de fonctions objectifs dans l'optimisation. Les taux d'ouverture des vannes ont été considérés comme des variables de décision hebdomadaires pour plusieurs ouvrages de régulation hydraulique. Un algorithme évolutionnaire multiobjectif a permis de générer un ensemble de Pareto de calendriers de manœuvre non dominés, représentant les compromis entre les indicateurs d'évaluation. Une procédure d'aide à la décision a ensuite été appliquée pour classer les solutions de Pareto au moyen de pondérations multicritères non linéaires liées aux régimes de disponibilité en eau, permettant ainsi de sélectionner de manière adaptative les calendriers de manœuvre recommandés. Le cadre proposé a été appliqué au périmètre irrigué de Geumseok (55 ha), où la manœuvre des vannes fondée sur l'optimisation a réduit les quatre indicateurs de performance et amélioré l'équilibre spatial de la distribution de l'eau par rapport au fonctionnement de référence.

Mots clés : Gestion adaptative de l'irrigation; Optimisation du fonctionnement des vannes; EPA-SWMM; Optimisation multi-objectifs ; Réseau de canaux d'irrigation; Efficacité de la distribution d'eau.

INTRODUCTION

Irrigation districts that supply water to paddy fields through reservoir–canal–field network systems face increasing challenges from growing water demand, declining supply reliability, and climate variability. In Korea, a large proportion of paddy irrigation relies on small- to medium-scale reservoirs with aging canal infrastructure, where the effective delivery of stored water to individual paddy zones depends on the timing and magnitude of gate operations throughout the irrigation season (Shin et al., 2024). Under such conditions, a key practical question is whether water shortages arise from insufficient supply or from operational inefficiencies within the canal network. Distinguishing between these two sources is essential for identifying management interventions that can improve district-level performance without requiring infrastructure expansion.

In many irrigation districts, gate operation is conducted based on field managers' experience or rule-based procedures. Opening schedules are typically determined by seasonal conventions and adjusted in response to observable field conditions such as ponding depth or visible crop stress. While such approaches have served conventional conditions, they rely on the judgment of individual operators and do not produce systematic records that allow comparison across operation strategies. As a result, it is difficult to evaluate whether current gate settings are near-optimal or whether alternative schedules could yield better outcomes, particularly when multiple performance criteria—such as ponding deficit reduction, equitable spatial distribution, and gate operation stability—must be considered simultaneously.

Previous research on irrigation performance evaluation has focused on single indicators such as irrigation efficiency, adequacy, or water supply vulnerability (Labadie, 2004; Reed et al., 2013). These indicators provide useful aggregate measures of water use performance but do not capture the spatial distribution of water within the canal network or the temporal dynamics of gate control. Hydraulic simulation models such as EPA-SWMM have been applied to agricultural canal systems to represent flow routing, gate operation, and field water balance in an integrated framework (Kim et al., 2016). Multi-objective optimization has been applied to irrigation water allocation at the district scale, and NSGA-III has demonstrated effectiveness in handling four or more conflicting objectives in water resources problems (Deb and Jain, 2014). However, gate-level operation optimization within a hydraulic canal network, using simulation-derived performance indicators as objective functions in a many-objective framework, remains less explored. In particular, structured approaches that link

hydraulic simulation outputs directly to multi-objective optimization and decision support for irrigation districts have not been widely reported.

This study presents a simulation-based multi-objective optimization framework for irrigation gate operation, integrating EPA-SWMM hydraulic network modeling, NSGA-III many-objective optimization, and TOPSIS-based decision support. Four performance indicators covering ponding deficit intensity, deficit duration, spatial discharge imbalance, and drainage ratio deviation were defined as objective functions and computed directly from EPA-SWMM simulation outputs. Gate opening ratios for ten hydraulic control structures were treated as weekly decision variables, and NSGA-III was used to generate Pareto-optimal operation schedules. TOPSIS was then applied to select a representative schedule under identified supply conditions. The framework is applied to the Geumseok irrigation district in Cheongju, Korea—a small-scale paddy district of 55 ha—using 2022 irrigation season data, to evaluate gate operation alternatives and identify improved management schedules based on quantitative performance indicators.

MATERIALS AND METHODS

Study Irrigation District and Canal Network

The Geumseok irrigation district is located in Eumseong-gun, Chungcheongbuk-do, Republic of Korea (Figure 1). The district is a small-scale paddy irrigation system with a total command area of 55 ha supplied by the Geumseok reservoir. Irrigation water is conveyed through a gravity-fed open canal network composed of main canals, branch canals, and field intake structures. Flow distribution is regulated by gate structures installed at key hydraulic junctions. The main characteristics of the irrigation district are summarized in Table 1.

Based on Farmmap boundaries, the paddy fields were classified into three spatial zones: upstream (U, 17.63 ha), midstream (M, 25.47 ha), and downstream (D, 6.82 ha).

The upstream zone is directly connected to the reservoir outlet through the main canal, whereas the midstream and downstream zones receive water sequentially through branch canal systems. Because water delivery to downstream areas depends on upstream gate operations, inappropriate gate control can induce spatial imbalance in water distribution and intensify irrigation water deficits in downstream areas during the irrigation season.

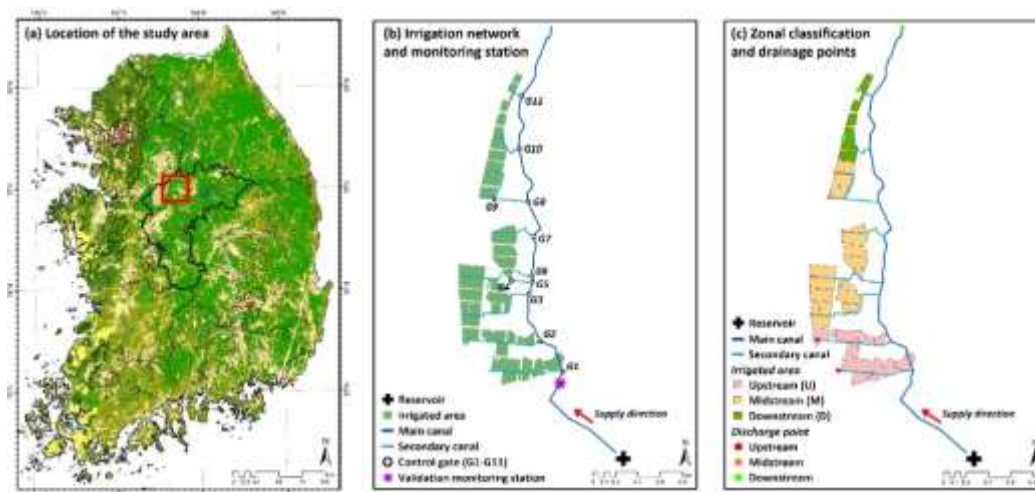


Figure 1. Geographic location, irrigation canal network, and zonal classification of the Geumseok irrigation district used for adaptive gate operation analysis.

Table 1. Characteristics of the study reservoir and irrigation district

Construction year	Watershed area (ha)	Irrigated area (ha)	Effective storage (10 ³ m ³)	Design drought frequency (year)	Number of hydraulic gates
1981	717	55	3,309	10	11

EPA-SWMM Hydraulic Simulation Model

The irrigation canal network was modeled using EPA-SWMM, a hydraulic-hydrological simulation model developed by the U.S. Environmental Protection Agency. Its storage-node and conduit-link framework can represent the hydraulic connectivity of reservoir-canal-paddy systems, including open channels, orifice gate structures, and field storage elements (Rossman, 2015). The model network includes storage nodes for the reservoir and paddy field ponding, conduit links for canal sections, and orifice elements for nine gate structures. Paddy field water balance incorporates rainfall, evapotranspiration, and percolation alongside canal supply.

The simulation period covered the 2022 irrigation season from May 1 to September 30 (153 days). Meteorological inputs were obtained from the Automated Synoptic Observing System (ASOS) operated by the Korea Meteorological Administration. Evapotranspiration was estimated using the modified Penman equation with crop coefficients. Percolation rates were set at 4.9 mm/day based on standard values from national irrigation planning guidelines (MAFRA, 2014). Initial ponding depth was set to 0 mm and the management ponding depth to 60 mm. Observed irrigation supply data for the 2022 season were provided by the Korea Rural Community Corporation (KRC) for the reservoir, with unit water demand applied for pumping stations and intake weirs, and used as time-varying boundary inputs to the simulation model.

Multi-Objective Optimization Framework

Four performance indicators were used for evaluating irrigation operation conditions (Table 2): PDI (Ponding Deficit Index), DDI (Deficit Duration Index), ZDI (Zone Discharge Imbalance Index), and DRDI (Discharge Ratio Deviation Index). PDI represents the cumulative volume of ponding deficit across the district (Eq. 1), while DDI indicates the frequency of deficit occurrence during the irrigation period (Eq. 2). ZDI was used to evaluate spatial differences in discharge distribution among the upstream, midstream, and downstream zones (Eq. 3). DRDI represents variability in drainage-to-supply ratios among hydraulic control structures (Eq. 4).

$$f_1 = (1/N) \sum D_i \quad (1)$$

$$f_2 = (1/N) \sum T_i \quad (2)$$

$$f_3 = \sum (R_z - 1/K)^2 \quad (3)$$

$$f_4 = (D/S - 0.50)^2 \quad (4)$$

A deficit condition was defined when the simulated sum of percolation and evapotranspiration was lower than the required daily demand value. The deficit magnitude was calculated as the difference between the required and simulated values. Gate opening ratios for ten hydraulic control structures were assigned as weekly operational variables during the 22-week irrigation season.

NSGA-III (Deb and Jain, 2014) was applied to explore alternative gate operation conditions considering the four indicators simultaneously. Optimization settings included a population size of 84 and 50 generations. TOPSIS was subsequently applied to the resulting solution set to identify a representative operation condition. Based on the baseline operation characteristics, weighting factors of PDI:DDI:ZDI:DRDI = 4:4:2:2 were applied to place relatively greater emphasis on deficit-related indicators. The overall analysis procedure is presented in Figure 2.

Table 2. Multi-objective performance indicators used in irrigation operation optimization

Acronym	Indicator	Description	Unit	Reference
PDI	Ponding Deficit Index	Mean deficit volume	1,000 m ³	Yevjevich (1967)
DDI	Deficit Duration Index	Average ratio of deficit days	Dimensionless	Mishra and Singh (2010)
ZDI	Zone Drainage Imbalance Index	Spatial imbalance of drainage distribution among irrigation zones	Dimensionless	Marin and Smith (1988); Mahdi et al. (2024)
DRDI	Drain-to-Supply Ratio Deviation Index	Deviation of the drainage-to-supply ratio from the target condition	Dimensionless	Yazdani and Jeffrey (2011); Çetin et al. (2021)

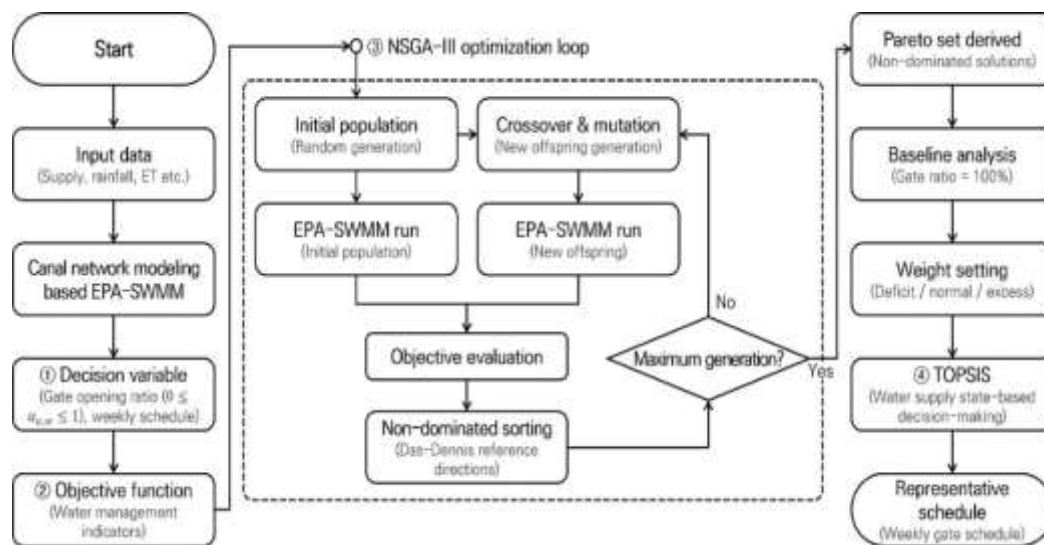


Figure 2. Simulation-based multi-objective optimization framework for adaptive irrigation gate operation.

RESULTS AND DISCUSSION

Baseline Irrigation Operation Characteristics

Under the baseline operation reflecting the 2022 management schedule, indicator values were: PDI = 0.073, DDI = 0.480, ZDI = 0.189, and DRDI = 0.030. The DDI value of 0.480 indicates that deficit conditions occurred on approximately 48% of irrigation days at the district level under the baseline schedule. The ZDI value of 0.189 reflects a pronounced imbalance in discharge distribution among the three spatial zones. Figure 3 shows the spatial discharge distribution and deficit frequency analysis results under the baseline operation. Spatial analysis indicated a strong upstream discharge concentration: the upstream zone accounted for 61% of total district discharge, the midstream zone for 39%, and the downstream zone received no discharge throughout the season. Downstream deficit frequency reached 59%, meaning that more than half of the irrigation days in the downstream zone did not meet the required ponding depth. The DRDI value of 0.030 indicates a relatively low deviation in the district-level drainage-to-supply ratio under baseline conditions.

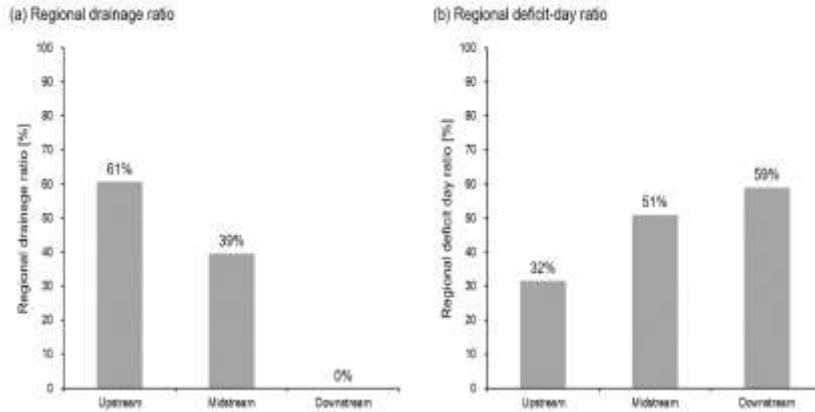


Figure 3. Baseline operational imbalance prior to optimization-based gate control.

Pareto Trade-Off Analysis and Representative Schedule Selection

NSGA-III produced a Pareto-optimal solution set over 50 generations. Figure 4 shows the convergence curves of all four objective functions across generations. Objective function values showed a generally decreasing trend that stabilized by approximately generation 40, indicating that the population reached a near-stable distribution of non-dominated solutions within the allocated computational budget. A trade-off between PDI and ZDI was observed across the Pareto front: solutions with lower ponding deficit tended to show higher spatial discharge imbalance, consistent with the hydraulic structure of the network in which upstream gates control the primary flow path. Concentrating discharge in the upstream zone reduces district-level deficit volume but simultaneously increases spatial imbalance among zones. DDI and ZDI showed a similar trade-off pattern, while DRDI values remained low across most Pareto solutions, indicating that the drainage-to-supply ratio was relatively stable regardless of gate configuration.

Table 3 presents the objective function values and TOPSIS rankings for the baseline and selected Pareto solutions. Among the boundary solutions, Sol. 13 achieved the minimum PDI (0.048) with a TOPSIS rank of 11 (score: 0.334), and Sol. 3 achieved the minimum ZDI (0.000) with a TOPSIS rank of 6 (score: 0.804). The low TOPSIS scores of these boundary solutions reflect the cost of optimizing a single indicator at the expense of others. Based on the water-deficit supply state identified from the baseline, TOPSIS was applied with weights (PDI:DDI:ZDI:DRDI = 4:4:2:2), assigning higher priority to deficit-related indicators. Solution 7 (Sol. 7) was selected as the representative operation schedule with a TOPSIS score of 0.898, the highest among all 84 Pareto solutions, indicating the most balanced performance across all four indicators under the applied weighting scheme. Although the minimum PDI solution achieved the lowest ponding deficit, the representative solution selected through TOPSIS provided a more balanced trade-off among all operational objectives.

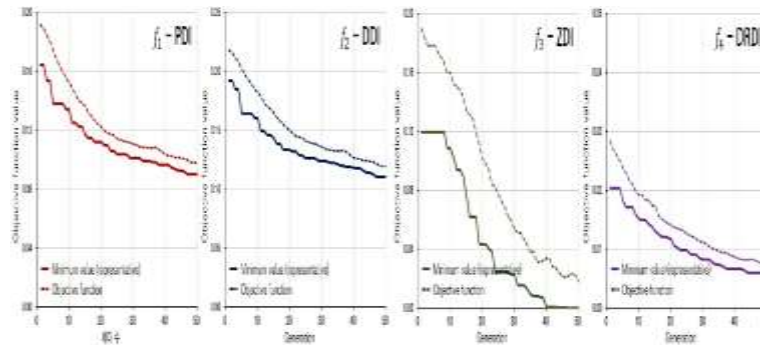


Figure 4. Convergence behavior of objective functions during NSGA-III optimization.

Table 3. Multi-objective trade-off analysis and TOPSIS-based representative solution selection

Scenario	PDI	DDI	ZDI	DRDI	TOPSIS rank (closeness score)
Baseline operation	0.073	0.480	0.189	0.030	Reference
Minimum PDI solution	0.048	0.315	0.016	0.004	11 (0.334)
Minimum ZDI solution	0.053	0.332	0.000	0.005	6 (0.804)
Representative solution	0.049	0.319	0.002	0.004	1 (0.898)

Spatial Redistribution under the Representative Operation

Under the representative schedule (Sol. 7), all four indicators showed improvement relative to the baseline: PDI decreased from 0.073 to 0.049 (33% reduction), DDI from 0.480 to 0.319 (34% reduction), ZDI from 0.189 to 0.002 (99% reduction), and DRDI from 0.030 to 0.004 (87% reduction). Figure 5 shows the spatial discharge distribution and deficit frequency analysis results under the representative operation. Among the four indicators, ZDI showed the largest relative reduction under the representative schedule. However, the results are dependent on the hydraulic configuration and operational assumptions applied in this study district.

The downstream zone showed the most notable change: discharge ratio increased from 0% to 30%, and deficit frequency decreased from 59% to 27%. The upstream zone discharge share decreased from 61% to 46%, while the midstream zone share remained relatively stable. These results indicate that the representative schedule shifted water supply toward the downstream zone, which had received no discharge under the baseline operation, while maintaining adequate supply in the upstream and midstream zones. The DRDI reduction from 0.030 to 0.004 indicates that the drainage-to-supply ratio across gates became more uniform under the representative schedule, reflecting a more consistent gate operation pattern across the district.

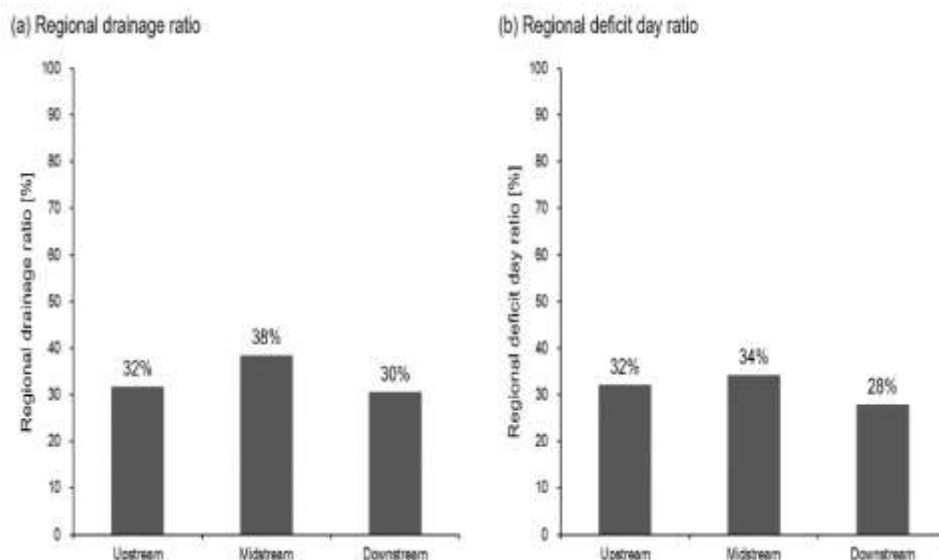


Figure 5. Improved regional balance under the representative optimized operation scenario.

Temporal Water Distribution under Baseline and Optimized Operations

Figures 6 and 7 show time-series comparisons of irrigation water supply, deficit, and water intake by zone under the baseline and representative operation, respectively. Under the baseline operation, the downstream zone consistently showed near-zero water intake throughout most of the irrigation season, with deficit episodes concentrated in the mid-to-late season period. The upstream zone received the majority of water intake throughout the season, while the midstream zone showed intermittent supply. The time-series pattern confirms that the spatial imbalance identified in the indicator values persisted across the full irrigation season rather than being limited to specific periods. Under the representative schedule, water intake in the downstream zone increased notably from the early season onward, and deficit episodes were reduced in both frequency and duration. The upstream zone water intake decreased relative to the baseline, reflecting a redistribution of gate-controlled supply toward the midstream and downstream zones. The overall district-level supply volume remained constant between the two scenarios, as the total reservoir input was unchanged; the improvement in indicator values reflects a reallocation of the same supply volume through adjusted gate opening ratios.

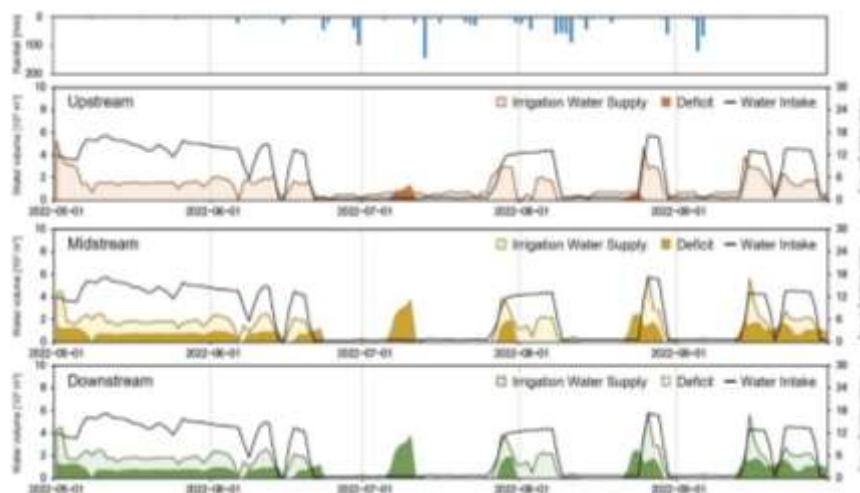


Figure 6. Evidence of spatial and temporal imbalance under the baseline irrigation operation scenario.

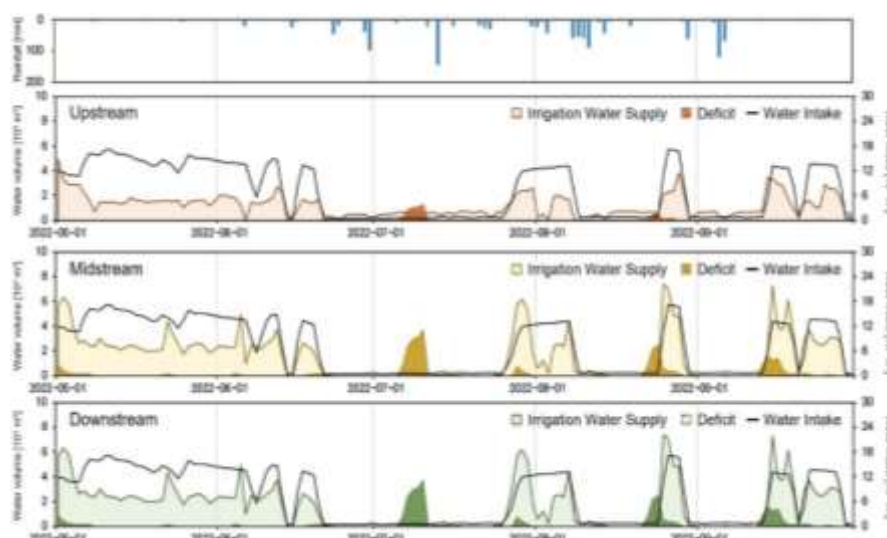


Figure 7. Improved temporal water distribution patterns under the representative optimized operation scenario.

CONCLUSIONS

This study evaluated adaptive irrigation gate operation in a small-scale agricultural irrigation district using coupled EPA-SWMM simulation and multi-objective optimization techniques. The proposed framework was applied to the Geumseok irrigation district to analyze operational characteristics and compare alternative gate operation schedules under the 2022 irrigation season conditions. The irrigation canal network of the Geumseok district (55 ha) was constructed in EPA-SWMM using field survey data, including canal geometry, elevations, and hydraulic structure information, together with observed reservoir supply records for the 2022 irrigation season. Four performance indicators were defined as objective functions: ponding deficit index (PDI), deficit duration index (DDI), zone drainage imbalance index (ZDI), and drainage-to-supply ratio deviation index (DRDI). These indicators were directly computed from EPA-SWMM simulation outputs and collectively represent water deficit conditions, spatial distribution equity among upstream, midstream, and downstream irrigation zones, and operational stability. Gate opening ratios for ten hydraulic control structures were treated as weekly decision variables throughout the 22-week irrigation season, resulting in a total of 220 decision variables for the optimization process.

Under the baseline operation, discharge was concentrated in the upstream zone, which accounted for 61% of total district discharge. The midstream zone accounted for the remaining 39%, and the downstream zone received no discharge throughout the season. Downstream deficit frequency reached 59%, indicating that the downstream zone did not meet the required ponding depth on more than half of all irrigation days. Indicator values under the baseline were: PDI = 0.073 ($\times 10^3$ m³), DDI = 0.480, ZDI = 0.189, and DRDI = 0.030. These values collectively indicate that while district-level deficit volume was moderate, the spatial distribution of water supply was highly imbalanced under the existing gate operation schedule.

NSGA-III generated a Pareto-optimal set of 84 solutions over 50 generations, with objective function values stabilizing by approximately generation 40. A trade-off between PDI and ZDI was identified across the Pareto front: solutions that minimized ponding deficit tended to concentrate discharge in the upstream zone, increasing spatial imbalance. This trade-off is consistent with the hydraulic structure of the network, in which upstream gates control the primary flow path to the district. TOPSIS-based ranking with water-deficit supply weights (PDI:DDI:ZDI:DRDI = 4:4:2:2) identified Sol. 7 as a representative operation schedule among the Pareto-optimal solutions.

Under the representative schedule, all four indicators improved relative to the baseline: PDI decreased from 0.073 to 0.049 (33% reduction), DDI from 0.480 to 0.319 (34% reduction), ZDI from 0.189 to 0.002 (99% reduction), and DRDI from 0.030 to 0.004 (87% reduction). The downstream zone discharge ratio increased from 0% to 30%, and downstream deficit frequency decreased from 59% to 27%. The upstream zone discharge share decreased from 61% to 46%, while the midstream zone share remained relatively stable. Time-series analysis confirmed that water intake in the downstream zone increased throughout the irrigation season under the representative schedule, with deficit episodes reduced in both frequency and duration relative to the baseline. The total district-level supply volume was maintained between scenarios, while differences in indicator values were associated with changes in gate operation patterns during the irrigation season. Although the representative schedule showed improved performance under the study conditions, additional validation under different hydrologic and operational environments is required before broader application.

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