

COST-EFFECTIVE INTEGRATED OPTIMIZATION OF IRRIGATION SCHEDULING AND PRESSURE REGULATION IN PRESSURIZED IRRIGATION NETWORKS UNDER WATER SCARCITY AND VARIABLE SUPPLY CONDITIONS

OPTIMISATION INTÉGRÉE ET RENTABLE DE LA PROGRAMMATION DE L'IRRIGATION ET DE LA RÉGULATION DE LA PRESSION DANS LES RÉSEAUX D'IRRIGATION SOUS PRESSION EN CONDITIONS DE PÉNURIE D'EAU ET D'APPROVISIONNEMENT VARIABLE

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ABSTRACT

Water scarcity and climate variability, intensified by climate change, are increasingly constraining irrigation systems and require adaptive and efficient management strategies at the farm scale. In pressurized irrigation networks, operational adaptations such as reducing water volumes, reducing irrigated areas, modifying cropping patterns, and adjusting water delivery schedules can significantly alter hydraulic behavior, often resulting in undesirable pressure fluctuations that affect system performance and equity.

This study develops an integrated simulation–optimization framework to control pressure fluctuations under such climate-stressed operational conditions. The model simultaneously optimizes irrigation scheduling, pressure reducing valve (PRV) settings, and PRV locations, while also considering the number of valves as a design parameter. EPANET is coupled with a genetic algorithm (GA) implemented in MATLAB to evaluate the interaction between operational decisions and hydraulic performance under variable reservoir water levels.

The proposed approach is applied to a real irrigation network. Results show that operational optimization significantly improves system performance, reducing pressure violations from 15 to 6 delivery points under the existing configuration. By incorporating PRV location optimization, this number is further reduced to only one point, while the objective function decreases to 119 under the most critical reservoir condition. Across different operating scenarios, objective function values of 395, 228, and 119 were obtained, confirming the effectiveness of the proposed framework.

Analysis of the number of PRVs indicates that increasing the number from two to three yields only marginal improvements (about 7–11%), suggesting that optimal placement and operation are more effective than infrastructure expansion.

Overall, the results demonstrate that data-driven simulation–optimization provides a practical and cost-effective decision-support tool for improving hydraulic performance and operational flexibility in water-stressed irrigation systems. The findings further emphasize the necessity of adaptive infrastructure management and re-evaluation of irrigation systems under climate change conditions.

Keywords: Water scarcity; Climate variability; Pressurized irrigation networks; Irrigation scheduling; Climate change conditions.

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RÉSUMÉ

La rareté de l'eau et la variabilité climatique, accentuées par le changement climatique, imposent des contraintes croissantes aux systèmes d'irrigation et exigent des stratégies de gestion adaptatives et efficaces à l'échelle de l'exploitation. Dans les réseaux d'irrigation sous pression, les adaptations opérationnelles, telles que la réduction des volumes d'eau et des superficies irriguées, la modification des plans de culture et l'ajustement des calendriers de distribution de l'eau, peuvent modifier considérablement le comportement hydraulique et provoquer souvent des fluctuations de pression indésirables qui nuisent aux performances et à l'équité du système.

Cette étude met au point un cadre intégré de simulation-optimisation destiné à maîtriser les fluctuations de pression dans de telles conditions d'exploitation soumises au stress climatique. Le modèle optimise simultanément la programmation de l'irrigation, les réglages et l'emplacement des réducteurs de pression (PRV), tout en considérant également le nombre de vannes comme un paramètre de conception. EPANET est couplé à un algorithme génétique (GA) mis en œuvre dans MATLAB afin d'évaluer l'interaction entre les décisions opérationnelles et les performances hydrauliques lorsque le niveau d'eau du réservoir varie.

L'approche proposée est appliquée à un réseau d'irrigation réel. Les résultats montrent que l'optimisation opérationnelle améliore sensiblement les performances du système, en faisant passer de 15 à 6 le nombre de points de livraison présentant des pressions non conformes dans la configuration existante. L'optimisation de l'emplacement des PRV ramène ensuite ce nombre à un seul point, tandis que la fonction objectif diminue jusqu'à 119 dans la situation la plus critique du réservoir. Pour différents scénarios d'exploitation, les valeurs de la fonction objectif obtenues sont de 395, 228 et 119, ce qui confirme l'efficacité du cadre proposé.

L'analyse du nombre de PRV indique que son passage de deux à trois n'apporte que des améliorations marginales (environ 7 à 11 %), ce qui laisse penser qu'une implantation et une exploitation optimales sont plus efficaces qu'une extension des infrastructures.

Dans l'ensemble, les résultats démontrent que la simulation-optimisation fondée sur les données constitue un outil pratique et rentable d'aide à la décision pour améliorer les performances hydrauliques et la souplesse d'exploitation des systèmes d'irrigation soumis au stress hydrique. Ils soulignent également la nécessité d'une gestion adaptative des infrastructures et d'une réévaluation des systèmes d'irrigation dans le contexte du changement climatique.

Mots clés : Rareté de l'eau; Variabilité climatique; Réseaux d'irrigation sous pression; Programmation de l'irrigation; Contexte du changement climatique.

1. Introduction

The operation of pressurized irrigation networks (PINs) is increasingly challenged by water scarcity, climate variability, and the growing need for efficient water management at the farm scale. Although these networks are typically designed to operate under peak demand conditions, in practice they function under dynamic and constrained environments due to fluctuations in water availability, variations in demand, and operational limitations. Consequently, significant pressure fluctuations arise within the network, leading to issues such as pipe bursts, leakage, inadequate pressure at delivery points, and reduced irrigation efficiency (Creaco and Pezzinga, 2015; Vicente et al., 2016; Gupta and Kulat, 2018). These challenges highlight the need for advanced management strategies that integrate both hydraulic and operational aspects of irrigation systems.

Pressure management is widely recognized as an effective approach for improving the performance of water distribution systems and reducing water losses (Lambert, 2002; AWWA, 2003; Lambert and Fantozzi, 2010). In PINs, maintaining pressure within a desirable range—typically between 20 and 40 meters—is essential for ensuring proper operation of irrigation equipment, particularly in drip systems. Excessive pressure can cause leakage and damage to network components, whereas insufficient

pressure leads to inadequate water delivery and poor irrigation uniformity. Therefore, effective pressure regulation is essential for achieving both hydraulic stability and irrigation adequacy.

Pressure reducing valves (PRVs) play a central role in pressure regulation. Numerous studies have investigated their optimal placement and setting to improve system performance. For example, Covelli et al. (2016), De Paola et al. (2017), and Pecci et al. (2019) focused on PRV optimization in urban water distribution systems, primarily targeting leakage reduction. Similarly, Price and Ostfeld (2022) proposed a graph theory-based approach for optimal PRV layout design. In irrigation contexts, Gupta and Kulat (2018) emphasized the importance of pressure control strategies for mitigating operational issues. However, most existing studies focus on urban networks, which are typically looped and operate under on-demand conditions, whereas irrigation networks are generally branched and operate under rotational delivery schedules, resulting in fundamentally different hydraulic behavior.

In parallel, extensive research has addressed irrigation scheduling, particularly in open irrigation networks (OINs). Studies by Monem and Namdarian (2005), Pawde et al. (2013), Darvishi et al. (2019), Liu and Yang (2021), and Zhang et al. (2022) applied various optimization techniques, including genetic algorithms (GAs), particle swarm optimization (PSO), and ant colony optimization, to enhance water delivery efficiency, reduce operational costs, and optimize irrigation cycles. Although these approaches are effective in OINs, their direct application to PINs is limited due to the strong coupling between flow and pressure in pressurized systems.

Despite its importance, irrigation scheduling has received relatively limited attention in PINs. Recent studies have begun to address this gap. For instance, Pardo et al. (2022) proposed a minimum variance scheduling approach to stabilize inlet flow rates, while Navarro-González et al. (2023) and Pang et al. (2024) focused on energy-efficient scheduling strategies. Lima et al. (2018) and Alonso Campos et al. (2020) also examined the relationship between scheduling and energy consumption. However, these studies generally consider pressure constraints indirectly or rely on simplified hydraulic assumptions. In large-scale PINs, changes in irrigation scheduling can significantly alter flow distribution in sub-branches, leading to substantial pressure variations at delivery points. Therefore, without explicitly incorporating hydraulic behavior into scheduling, achieving stable and reliable operation remains challenging.

In addition to operational strategies, several studies have addressed the design optimization of PINs. Masoumi et al. (2016) optimized pipe sizing and layout using ant colony algorithms, achieving notable cost reductions. Monem and Sami Kashkooli (2016) applied particle swarm optimization for design improvement. Jafari-Asl et al. (2020) developed a simulation–optimization framework for PRV placement and control, demonstrating significant leakage reduction. More recently, Jafari-Asl et al. (2024) proposed an advanced framework for reducing the environmental footprint of water conveyance systems. While these studies provide valuable insights, they often treat design and operation as separate problems and rarely consider their combined effects under real operating conditions.

A comprehensive review by Mala-Jetmarova et al. (2018) highlighted that most optimization studies focus on urban water systems, with limited attention given to irrigation networks. The review further emphasized that system performance depends on the interaction among multiple components, including pipes, valves, pumps, and operational strategies. This underscores the need for integrated approaches that simultaneously consider hydraulic behavior and operational decisions in irrigation systems.

In a previous study by the authors (Ketabi & Monem, 2025), a simulation–optimization model was developed for the joint optimization of irrigation scheduling and PRV settings in PINs. The model, integrating a GA with the EPANET hydraulic simulator, demonstrated that coordinated optimization significantly improves pressure regulation and reduces deviations from desired pressure levels. However, the results also indicated that the existing number and locations of PRVs may limit

achievable performance, as some pressure deficiencies and excesses could not be fully resolved through operational adjustments alone.

Building on these findings, the present study extends the previous work by incorporating PRV location as an additional decision variable and analyzing the number of PRVs as a design parameter. This extension enables a more comprehensive evaluation of both operational and structural strategies for pressure management. Integrating irrigation scheduling, PRV settings, and PRV locations within a unified framework allows for systematic exploration of their interactions under varying hydraulic conditions, including fluctuations in reservoir water levels.

The proposed model couples the EPANET hydraulic simulation tool (Rossman, 2000; Vegas Niño et al., 2017) with a GA implemented in MATLAB. It simultaneously determines optimal irrigation schedules, PRV settings, and PRV locations to minimize pressure deviations while ensuring compliance with allowable pressure limits. Unlike many previous studies, this approach explicitly captures the dynamic behavior of the system under real operating conditions and provides a practical decision-support tool for network managers.

The main contribution of this study is the integrated consideration of operational (irrigation scheduling and PRV settings) and structural (PRV location and number) factors within a single simulation–optimization framework. This enables more effective pressure management compared to conventional approaches that treat these aspects separately. Furthermore, by evaluating multiple reservoir scenarios, the model provides insights into the robustness of optimal solutions under varying supply conditions.

The remainder of this paper is organized as follows: Section 2 presents the methodology, Section 3 discusses the results, and Section 4 concludes the study and outlines future research directions.

2 Materials and Methods

2.1 Integrated Simulation–Optimization Framework

This study presents an integrated simulation–optimization framework aimed at improving irrigation scheduling and pressure management in PINs. The proposed framework couples a GA with the EPANET hydraulic simulation model within a MATLAB environment.

The model is formulated to simultaneously optimize irrigation scheduling, pressure reducing valve (PRV) settings, and PRV locations within the network, while the number of PRVs is considered as a design parameter to evaluate its impact on system performance.

By integrating hydraulic simulation with optimization, the proposed framework enables the analysis of complex interactions between operational decisions and hydraulic behavior under variable reservoir water levels. This integration provides a realistic representation of actual field operating conditions and allows for systematic exploration of the solution space.

2.2 Optimization Model Formulation

2.2.1 Decision Variables

The optimization problem is defined in terms of three main decision variables:

1. Irrigation scheduling pattern, representing the selection of active delivery points during each irrigation cycle.
2. PRV settings, representing the outlet pressure assigned to each valve.
3. PRV locations, representing the placement of valves within the network.

These variables directly influence the hydraulic conditions of the system and are evaluated through the coupled simulation–optimization framework.

2.2.2 Constraints

The optimization model incorporates both hydraulic and operational constraints, defined as follows:

- Flow constraint $\leq Q_c$
- Irrigation duration constraint $T \leq T_d$
- Pressure limits in the network
- $0 \leq h_j \leq 60$
- Pressure limits at delivery points
- $20 \leq h_i \leq 40$
- Cavitation constraint for PRVs $\alpha \leq h_{in}/h_{out}$

where q_i is the flow rate at node i , Q_c is the system capacity, h_j is the pressure at node j , and h_i is the pressure at delivery point i . The pressure-related constraints are treated as soft constraints and incorporated into the objective function through penalty terms. In contrast, the flow, irrigation duration, and cavitation constraints are enforced as hard constraints during the optimization process.

2.2.3 Objective Function

The objective function is formulated to minimize pressure deviations from the target value (30 m) while penalizing violations of allowable pressure limits:

$$\begin{aligned} \text{Minimize } Z = & \sum_{i=1}^n |(h_i - 30)| + \alpha_1 \sum_{j=1}^m (\max(h_j/60 - 1, 0)) - \alpha_2 \sum_{j=1}^m (\min(h_j, 0)) \\ & + \alpha_3 \sum_{i=1}^n (\max(h_i/40 - 1, 0)) - \alpha_4 \sum_{i=1}^n (\min(h_i/20 - 1, 0)) \end{aligned}$$

This formulation ensures that the optimization process simultaneously:

- promotes uniform pressure distribution,
- avoids excessive and insufficient pressure, and
- improves overall irrigation performance.

2.2.4 GA Configuration

The parameters of the GA, including population size, number of generations, crossover rate, and mutation rate, were determined through sensitivity analysis to ensure both convergence reliability and computational efficiency.

The penalty coefficients associated with constraint violations were calibrated through iterative testing to achieve an appropriate balance between constraint satisfaction and optimization performance.

2.3 Hydraulic Simulation, Case Study, and Model Application

Hydraulic simulations were conducted using the EPANET model, which enables analysis of flow and pressure distribution in pressurized pipe networks. The hydraulic model incorporates head loss calculations based on the Hazen–Williams equation and represents key network components, including pipes, nodes, valves, and reservoirs. EPANET was dynamically coupled with the optimization model through the MATLAB environment to enable iterative evaluation of candidate solutions during the optimization process.

Model calibration was performed using field-measured pressure data collected from 21 delivery points in the study network. The calibration process involved minimizing discrepancies between simulated and observed pressures through adjustment of the Hazen–Williams roughness coefficients. Model performance was evaluated using statistical indicators, resulting in RMSE values ranging from 1.6 to 1.8 and a coefficient of determination (R^2) of approximately 0.99. These results indicate a high level of accuracy and reliability of the hydraulic simulation model.

To evaluate the performance of the proposed framework, both hypothetical and real irrigation networks were analyzed. The hypothetical network was developed under controlled conditions and consisted of one reservoir, nine pipes, ten nodes, and one PRV. The simplified layout of the hypothetical network is presented in Figure 1, while the main pipeline specifications are summarized in Table 1. The network configuration and operational parameters were designed to represent typical pressurized irrigation systems.

Table 1. Main pipeline specifications of the hypothetical irrigation network (reproduced from Ketabi & Monem (2025)).

Parameter	Pipeline Number								
	1	2	3	4	5	6	7	8	9
ID	P1	P2	P3	P4	P7	P8	P9	P5	P6
Length (m)	5	3000	500	600	2000	500	600	500	200
Diameter (m)	0.4	0.4	0.2	0.16	0.315	0.2	0.16	0.2	0.16
Elevation Difference (m)	0	10	5	6	10	5	3	3	2

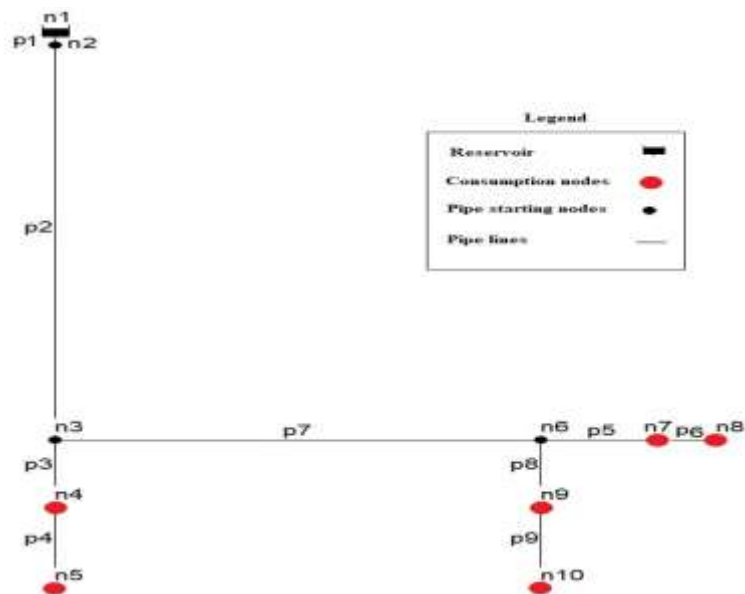


Figure 1 - Simplified layout of the hypothetical PIN used for model evaluation (reproduced from Ketabi & Monem (2025)).

The real case study corresponds to the Kinevars irrigation network, located downstream of the Kinevars Dam in Iran. The network includes an irrigated area of approximately 450 hectares operating under a drip irrigation system, with 21 delivery points, three existing PRVs, and a three-day irrigation cycle. The layout of the irrigation sectors and the locations of the existing PRVs are illustrated in Figure 2.

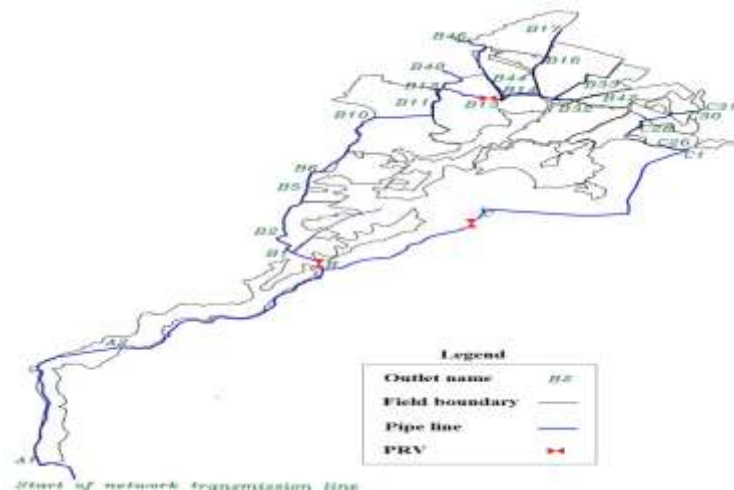


Figure 2 – Layout of the Kinevars irrigation network, including irrigation sectors and locations of the existing pressure reducing valves (PRVs) (reproduced from Ketabi & Monem (2025)).

Since the network operates under variable reservoir water levels, three representative scenarios were considered: 1732 m (low level), 1740 m (intermediate level), and 1747.5 m (high level). For each reservoir scenario, the model determines the optimal irrigation schedule and PRV settings while evaluating pressure distribution throughout the network. In addition, PRV locations were optimized, and different numbers of PRVs (two and three) were analyzed to assess their influence on hydraulic performance.

The model was implemented in two sequential stages. In the first stage, irrigation scheduling and PRV settings were optimized while maintaining fixed valve locations. In the second stage, irrigation scheduling, PRV settings, and PRV locations were simultaneously optimized, and the effect of varying the number of PRVs was evaluated.

This strategy enables systematic comparison with previous studies and demonstrates the additional benefits of incorporating valve placement into the optimization process.

Model performance was assessed using several hydraulic and operational indicators, including the objective function value, the number of delivery points outside the acceptable pressure range, maximum and minimum pressure values, and the stability of pressure distribution throughout the network. These indicators provide a comprehensive evaluation of the effectiveness of the proposed simulation–optimization framework.

3. Results and Discussion

The performance of the developed simulation–optimization framework was evaluated at two levels. First, the model was applied to a hypothetical network to verify its functionality under controlled conditions. Subsequently, the model was implemented for the real Kinevars irrigation network under different reservoir water level scenarios in order to evaluate the effects of irrigation scheduling, PRV settings, and PRV locations on network hydraulic performance.

The model was initially tested on the hypothetical network assuming a single PRV, an inlet pressure of 30 m, and a three-day irrigation cycle. The convergence behavior of the objective function during the optimization process is illustrated in Figure 3. As shown, the objective function decreases progressively and converges to a minimum value of approximately 16.2 after nearly 2800 objective function evaluations (NFE). The optimal values of the decision variables, including the irrigation schedule, PRV setting, and optimal PRV location, are presented in Table 2.

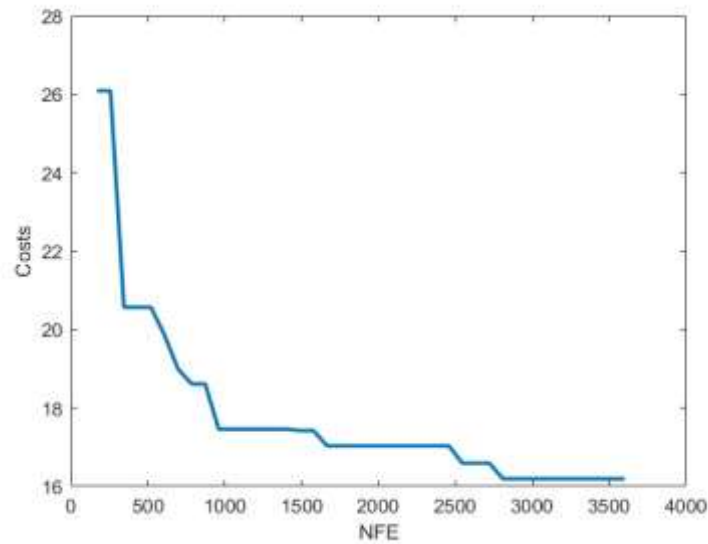


Figure 3 – Convergence behavior of the objective function during optimization of the hypothetical network.

Table 2 – Optimal decision variables and objective function components for the hypothetical network.

Objective Function Value		Decision Variables	Value	Day	Active Inlets						Pressure in active inlets in sequence (meters)		
					1	2	3	4	5	6			
16.2		Pipe Number of PRV Location	2	Day 1	0	1	1	0	0	1	25.6	30.4	37.8
		PRV Distance from Pipe Start (meters)	411	Day 2	1	0	0	0	0	0	29.3		
		PRV Setting (meters)	16	Day 3	0	0	0	1	1	0	32.8	29.9	

The results indicate that appropriate scheduling of delivery points combined with optimal PRV operation maintains pressure at all consumption points within the desirable range of 20–40 m. Furthermore, none of the penalty terms were activated in the final solution, indicating that all hydraulic constraints were satisfied. Consequently, the objective function value was governed solely by pressure deviations from the target value. These findings confirm the correct functionality of the proposed model under simplified conditions and demonstrate its capability to identify feasible and hydraulically efficient solutions.

Following model verification, the framework was applied to the Kinevars irrigation network under three reservoir water level scenarios: 1732 m (low level), 1740 m (intermediate level), and 1747.5 m (high level). In the first stage, irrigation scheduling and PRV settings were optimized while maintaining fixed PRV locations. Detailed results of this operational optimization stage were previously reported by Ketabi and Monem (2025).

Briefly, under the existing operating condition at the reservoir level of 1732 m, the objective function value was reduced from 1080 to 476 after optimization, while the number of delivery points outside the acceptable pressure range decreased from 15 to 6, indicating a substantial improvement in network

pressure regulation. For the reservoir levels of 1740 m and 1747.5 m, the corresponding objective function values obtained from operational optimization were 359 and 301, respectively.

In the second stage of the present study, PRV locations and the number of PRVs were incorporated into the optimization framework in order to evaluate the additional benefits of structural optimization compared to operational optimization alone.

At the reservoir level of 1747.5 m, optimization with two PRVs reduced the objective function value from 301 to 119, corresponding to an improvement of approximately 60%, as summarized in Table 3. This substantial reduction highlights the critical importance of optimal PRV placement in pressure management. A comparison between the existing and optimized PRV locations is presented in Figure 5, while the resulting pressure distribution is illustrated in Figure 4.

It should be noted that PRV location optimization was performed only for the reservoir level of 1747.5 m, which represents both the most frequently occurring and the most hydraulically critical operating condition. In the other reservoir scenarios (1732 m and 1740 m), only irrigation scheduling and PRV settings were optimized while PRV locations were kept fixed, since PRV relocation is considered a long-term structural decision that cannot be adjusted for each operating condition.

Table 3 – Hydraulic performance indicators after optimization of PRV locations at reservoir level 1747.5 m.

Objective Function Value		Decision Variables Description																Variable Value				
		PRV Number																1	2	-		
119		Pipe Number of PRV Location																75	53	-		
		PRV Distance from Pipe Start (meters)																36	130	-		
		PRV Setting (meters)																7	11	-		
Optimum Irrigation Program and Pressure at Active Inlets (m)																						
Inlet Number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Day 1	Active Inlets	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	1	1	1	0	0	1
	Pressure (m)	-	-	-	-	-	-	-	30	29	28	41	29	28	-	-	34	30	30	-	-	40
Day 2	Active Inlets	1	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
	Pressure (m)	29	-	-	-	24	23	-	-	-	-	-	-	-	-	23	-	-	-	23	-	-
Day 3	Active Inlets	0	1	1	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0
	Pressure (m)	-	36	25	23	-	-	38	-	-	-	-	-	-	39	-	-	-	-	-	24	-

Comparison of results across different reservoir levels indicated that the effectiveness of PRV location optimization strongly depends on hydraulic boundary conditions. At the lower reservoir level of 1732 m, incorporation of PRV location optimization reduced the objective function value from 476 to 395, corresponding to an improvement of approximately 17%, as presented in Table 4. This relatively limited improvement was mainly due to the persistent low-pressure condition at consumption point 19. Detailed analysis indicated that this deficiency is primarily associated with the topographic characteristics of the network. This point is located close to the reservoir and near the upstream section of the system, where the elevation difference relative to the reservoir is limited. Under gravity-driven operating conditions, reductions in reservoir water level directly decrease the available pressure head at this location. Consequently, even optimal PRV placement cannot fully compensate for insufficient hydraulic head under low reservoir conditions.

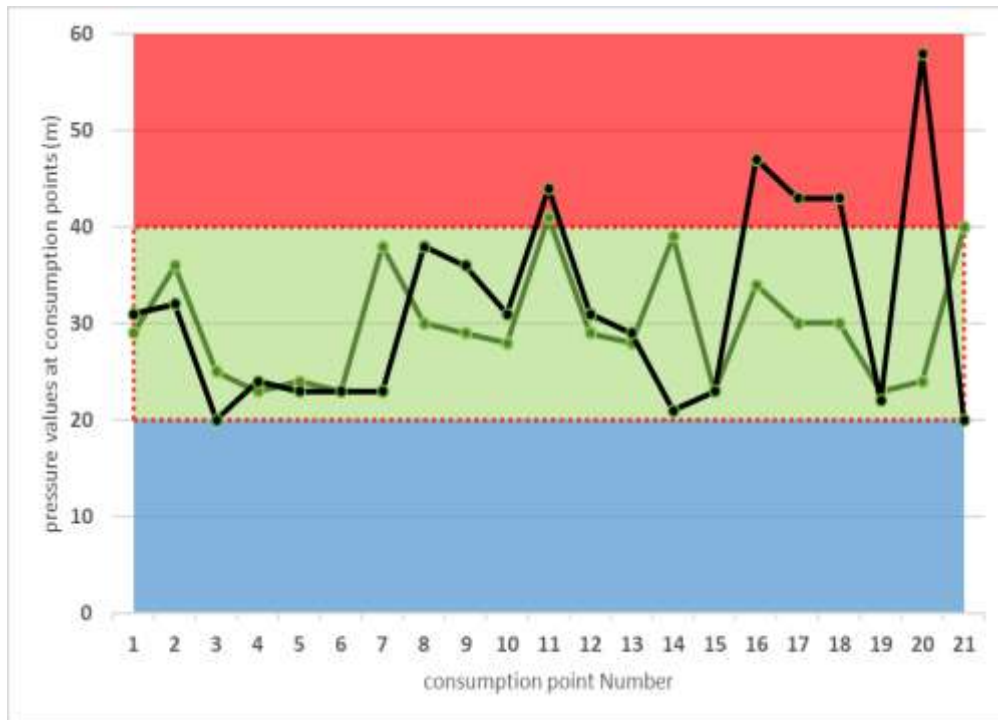


Figure 4 – Comparison of pressure values at consumption points in the Kinevars irrigation network obtained from the first-stage optimization results with fixed PRV locations (black line) and the second-stage optimization results with optimized PRV locations (green line), considering two PRVs and a reservoir water level of 1747.5 m.

Table 4 – Effect of PRV location optimization on hydraulic performance at reservoir level 1732 m.

Objective Function Value			Decision Variables Description															Variable Value				
			PRV Number															1	2	-		
395			Pipe Number of PRV Location															75	53	-		
			PRV Distance from Pipe Start (meters)															36	130	-		
			PRV Setting (meters)															6	11	-		
Optimum Irrigation Program and Pressure at Active Inlets (m)																						
Inlet Number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Day 1	Active Inlets	0	1	0	0	0	0	0	1	1	1	1	1	1	0	0	1	1	1	0	0	1
	Pressure (m)	-	32	-	-	-	-	-	28	28	27	40	27	26	-	-	33	29	29	-	-	40
Day 2	Active Inlets	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
	Pressure (m)	-	-	-	-	-	26	-	-	-	-	-	-	-	-	26	-	-	-	7	-	-
Day 3	Active Inlets	0	1	1	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1
	Pressure (m)	-	24	21	20	-	37	-	-	-	-	-	-	37	-	-	-	-	-	24	-	29

Table 5 presents the effect of increasing the number of PRVs on system performance at the reservoir level of 1747.5 m. The results show that increasing the number of PRVs from two to three reduces the objective function value from 119 to 111, indicating only a marginal improvement in hydraulic performance. A similar trend is observed at other reservoir levels, where the objective function values for the three-PRV configuration are 371 and 204 at reservoir levels of 1732 m and 1740 m, respectively, compared to 395 and 228 for the corresponding two-PRV cases. These results confirm that increasing the number of PRVs has a limited impact on system performance compared to optimal PRV placement and operational adjustments, as illustrated in Figure 5.

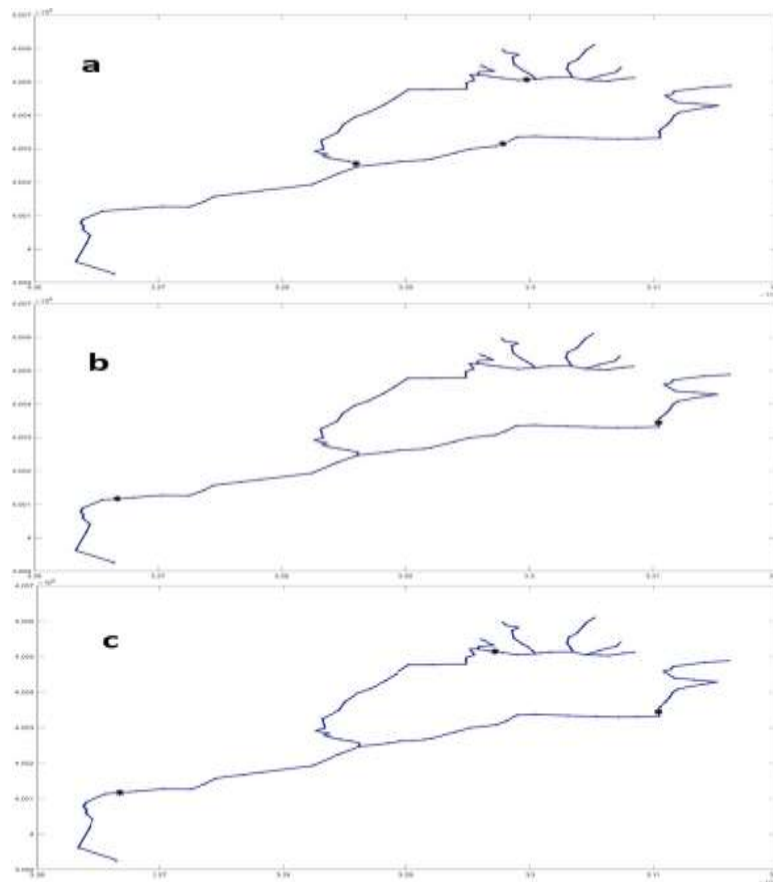


Figure 5 – Comparison of PRV layouts in the Kinevars irrigation network: (a) existing configuration, (b) optimized configuration with two PRVs, and (c) optimized configuration with three PRVs

Table 5 – Objective function results for the three-PRV configuration at the reservoir level of 1747.5 m.

Objective Function Value		Decision Variables Description														Variable Value						
		PRV Number														1	2	3				
111		Pipe Number of PRV Location														75	53	33				
		PRV Distance from Pipe Start (meters)														36	130	54				
		PRV Setting (meters)														7	14	23				
Optimum Irrigation Program and Pressure at Active Inlets (m)																						
	Inlet Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1 Day	Active Inlets	1	1	1	0	0	0	1	1	0	1	1	1	0	0	0	1	1	1	0	1	1
	Pressure (m)	32	35	23	-	-	-	30	34	-	29	42	29	-	-	-	34	30	30	-	27	43
2 Day	Active Inlets	0	0	0	1	1	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0
	Pressure (m)	-	-	-	27	27	-	-	-	37	-	-	-	28	-	26	-	-	-	-	-	-
3 Day	Active Inlets	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0
	Pressure (m)	-	-	-	-	-	25	-	-	-	-	-	-	-	20	-	-	-	-	23	-	-

Overall, the results demonstrate that the proposed framework effectively integrates irrigation scheduling, PRV settings, and PRV placement to improve pressure regulation in PINs. The findings further indicate that substantial performance improvements can be achieved without major structural modifications, primarily through coordinated operational optimization. In addition, the results emphasize the significant influence of reservoir water levels and topographic conditions on network hydraulic performance, highlighting the importance of considering these factors in both the design and operation of irrigation systems.

Conclusion

This study developed an integrated simulation–optimization framework for improving the hydraulic performance and operational resilience of PINs under increasing water scarcity and climate variability. The proposed model couples a GA with the EPANET hydraulic simulator to simultaneously optimize irrigation scheduling, PRV settings, and PRV locations, while also evaluating the influence of the number of PRVs as a design parameter.

The results demonstrate that operational optimization alone (irrigation scheduling and PRV settings) significantly enhances system performance under variable and climate-stressed operating conditions. Under existing operating conditions at a reservoir water level of 1732 m, the objective function was reduced to 395, accompanied by a reduction in the number of delivery points operating outside the acceptable pressure range (20–40 m) from 15 to 6, indicating improved pressure regulation and irrigation equity.

Further improvements were achieved by incorporating PRV location optimization under the most critical hydraulic condition (1747.5 m). In this case, the objective function decreased from 301 to 119 (approximately 60%), highlighting the significant contribution of optimal valve placement under high-head conditions. At intermediate and low reservoir levels, the corresponding objective function values were 228 and 395, respectively, confirming the effectiveness of the proposed framework across varying hydraulic scenarios.

An additional important finding relates to the effectiveness of the proposed optimization in reducing pressure violations. While operational optimization reduced the number of delivery points outside the acceptable pressure range from 15 to 6, the incorporation of PRV location optimization further reduced this value to only one point. This remaining violation corresponds to node 11, where the pressure is approximately 41 m, only slightly above the upper acceptable limit (40 m). This minor deviation is a direct consequence of the penalty structure, which assigns higher weight to under-pressure conditions compared to over-pressure conditions, reflecting the practical importance of avoiding insufficient pressure for irrigation performance.

The analysis also showed that the effectiveness of the proposed optimization is strongly influenced by topographic constraints. In particular, certain delivery points (e.g., point 19) remain hydraulically deficient under low reservoir levels due to limited elevation differences relative to the reservoir. These limitations cannot be fully eliminated through either operational or structural optimization, emphasizing the importance of physical constraints in irrigation system performance under climate variability.

In addition, increasing the number of PRVs from two to three resulted in only marginal improvements in system performance (approximately 7–11%), indicating that optimal placement and coordinated operation of a limited number of valves are more effective than infrastructure expansion from both hydraulic and economic perspectives.

Overall, the findings confirm that substantial improvements in pressure regulation and system performance can be achieved without major structural interventions, primarily through coordinated operational and limited structural optimization. The proposed framework provides a practical and cost-effective decision-support tool for irrigation managers operating under water-scarce and climate-uncertain conditions.

The results further emphasize the strong coupling between irrigation scheduling and hydraulic behavior in PINs, where proper scheduling not only ensures equitable water distribution but also contributes to stabilizing pressure fluctuations throughout the network. This reinforces the importance of integrated operational management in modern irrigation systems.

Finally, in the context of climate change and increasing water scarcity, the study highlights the necessity of re-evaluating existing irrigation infrastructure and adopting adaptive, data-driven management strategies to improve system resilience, efficiency, and sustainability at the farm scale.

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