Water Resources Management (2022) 36:6073–6092
https://doi.org/10.1007/s11269-022-03342-7

Investigation of Infrastructural and Management Actions to Increase the Resilience of Existing Pressurized Irrigation Networks

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Received: 31 January 2022 / Accepted: 28 September 2022 / Published online: 24 October 2022

Abstract

In recent decades, on-demand irrigation systems have been promoted to increase water use efficiency. This study focused on the assessment of two traditional rotational pressurized irrigation systems with a central pumping station in the Foggia Province (Italy). Irrigation system A has an area of 564 ha with 319 pipelines and 251 hydrants, and irrigation system B has an area of 445 ha with 280 pipelines and 214 hydrants. The nominal discharge of each hydrant is 10 l/s. In each of the two irrigation systems, 1000 different operation scenarios were investigated using the COPAM model. To evaluate the performance of the systems, the indices of Relative Pressure Deficit (*RPD*) and Reliability (*RI*) were used. Results showed that the systems are quite flexible and allow the required flow rate to be increased by 1.6 times the peak period flow rate, if necessary. With such increased discharges, it is impossible to guarantee the *RPD* ($RPD \geq 0$) and *RI* ($RI = 1$) indices in 47% of the hydrants in the irrigation system A and in 36.9% of the hydrants in the irrigation system B. An updated methodology for optimizing the pipe diameters starting from the current situation was also implemented. Around 23% of pipelines in each system were changed with such methodology. After the new optimization, the number of unsatisfied hydrants in both systems decreased by 94.1% (from 118 to 7 hydrants) and 82.3% (from 79 to 14 hydrants), respectively. Thus, with this methodology, the irrigation system performance can be improved.

Keywords Performance improvement · On-demand operation · COPAM · Relative pressure deficit · Reliability indicator

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1 Introduction

Pressurized irrigation networks have higher performance and guarantee better distribution efficiency than open channels (Lamaddalena and Sagardoy 2000; Khadra and Lamaddalena 2006; Daccache et al. 2010a, b; Ferrarese et al. 2021). While allowing the production of crops with high economic value, the modernization of open channels to pressurized irrigation networks can reduce the amount of water delivered by the network by up to 40% (Díaz et al. 2012). Pressurized irrigation networks can operate with three main delivery schedules: i) continuous flow, ii) rotational and iii) on-demand (Replogle and Gordon 2007; Anwar and Haq 2013). In the continuous flow approach, the irrigation network is constantly operated, and the discharge varies according to the irrigation requirements during the growing season. In the rotational approach, the discharge into the network is constant and assigned by the management agency. However, the duration and frequency of irrigation supply from the network change according to the requirements during the growing season. In the on-demand approach, the discharge into the network varies occurs according to farmers' demand.

Nowadays, on-demand pressurized irrigation networks have become very common and can be a good alternative to irrigation networks with different water-delivery schedules (Calejo et al. 2008; Fouial et al. 2017). Traditional irrigation networks with rotational irrigation schedule are more prone to inefficient management than on-demand irrigation networks (Moreno et al. 2010; Maqbool et al. 2021; Monserrat and Alduan 2020). Other advantages of on-demand irrigation networks over rotational delivery schedules include high flexibility and freedom of action for farmers (Stefopoulou and Dercas 2017). Therefore, changing the management of pressurized irrigation networks from rotational to on-demand can be very useful in improving the performance and satisfaction of farmers. There are, however, many challenges and problems in this regard for on-demand networks. One of these challenges is the high cost of the network, and there are many studies on this issue to reduce or optimize it (Córcoles et al. 2015; Fernández García et al. 2017; Sheibani et al. 2019; Monserrat and Alduan 2020; Bajany et al. 2021). Another major problem is the calculation of the flow rate required by the pressurized irrigation network, which is highly dependent on the cropping pattern, climatic conditions, farm irrigation efficiency, and farmers' behavior (Daccache et al. 2010b). The most widely used method for calculating flow rates is the probabilistic method (Clément 1966; Clément and Galand 1979; Calejo et al. 2008; Khadra et al. 2013). Another important issue in converting networks from rotation schedule to on-demand delivery is to provide the minimum pressure required by each hydrant. If the pressure at the hydrants is less than the minimum required pressure, on-farm irrigation efficiency and crop yield will be affected. Moreover, actual operating conditions in on-demand networks may differ from those assumed during the design phase because of management decisions, on-farm irrigation scheduling, and changes in farmers' behavior. These can alter the pressure required at each hydrant (Pereira et al. 2003; Moreno et al. 2007; Salvador et al. 2011; Kanakis et al. 2014). Another major challenge in on-demand networks is the variation in the number and location of hydrants that operate simultaneously (called "configuration"). For this reason, the performance assessment of an on-demand irrigation network is predictable only on a probabilistic basis (Daccache et al. 2010b). The above-said variation can sometimes lead to low hydraulic performance even when the required upstream flow rate in the entire network does not exceed the design flow rate (Lamaddalena and Pereira 2007). According to the above-mentioned points, the question arises as to whether it is possible and convenient to convert pressurized networks from rotational water-delivery schedule into on-demand networks or not. Therefore, the main aim of this study is to investigate the possibility of converting the management of a traditional rotational pressurized irrigation network into an on-demand irrigation network. Many existing pressurized irrigation networks have a central pumping station, and the pressure required of all network hydrants supply by this station. Few studies have reported the possibility of converting the water delivery management of these networks from a traditional rotational into on-demand. For this purpose, two irrigation networks with a central pumping station in Italy have been studied: their performance has been assessed based on defined evaluation indices, for rotational and on-demand water delivery schedules. Such indicators have been used to improve the optimization of the networks.

2 Materials and Methods

2.1 Case Study

In the present study, two pressurized irrigation networks in the province of Foggia (Puglia region, Southern Italy) were investigated. The irrigation network A has 319 sections, 251 hydrants over an area of 564 ha; the irrigation network B has 280 sections, 214 hydrants over an area of 445 ha. Both networks are pressurized. The nominal discharge of each hydrant is 10 l/s. The irrigation season starts on April 1st and ends on September 30th. The energy required for both networks is guaranteed by a pumping station which, for each network, consists of three parallel horizontal electric pumps and an emergency pump. The minimum required pressure head for all hydrants of the two networks is $H_{\min} = 20m$. Table 1 shows some information on the two irrigation networks studied and Fig. 1 shows their schematic view, provided by the Management Agency.

Table 1 Some specifications of the two pressurized irrigation networks studied

Information	Irrigation Network	
	A	B
Area (ha)	564	445
Nominal discharge of each hydrant (l/s)	10	10
Upstream pressure head (m)	65	43
Pumping station elevation (m.a.s.l)	206	206
Upstream piezometric elevation (m.a.s.l)	271	249
Number of sections	319	280
Number of hydrants	251	214
Specific continuous discharge (l/s/ha)	0.327	0.327
Clément's use coefficient (r)	0.667	0.667
Number of terminal open hydrants	4	4
Operation quality ($U_p(q)$)	1.645	1.645

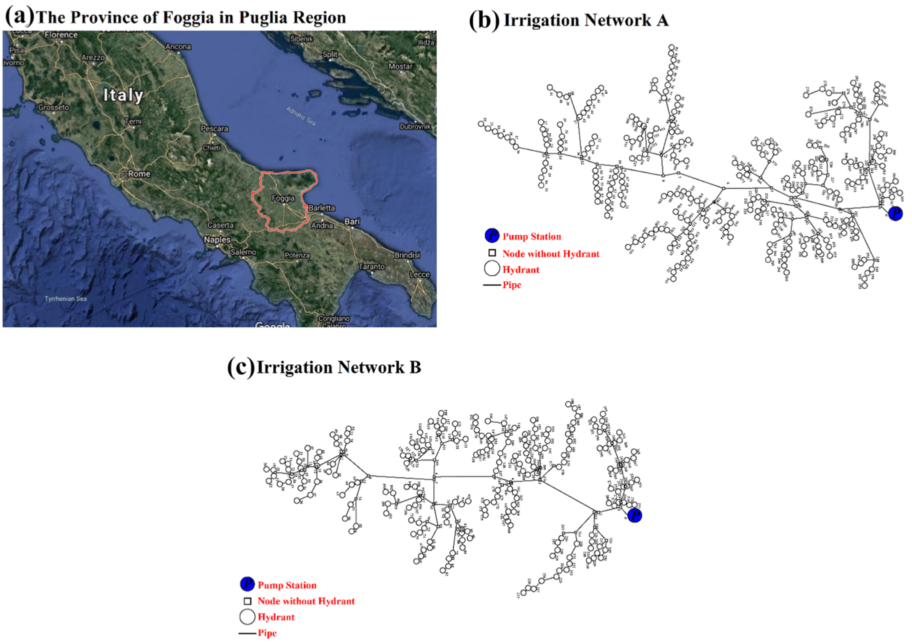

Fig. 1 Schematic view of the two pressurized irrigation networks under study; **a** Study area; **b** Irrigation network A; **c** Irrigation network B

2.2 Performance Analysis of on-demand Pressurized Irrigation Networks

Two models called ICARE (CTGREF 1979; Béthery et al. 1981; Béthery 1990) and AKLA (Lamaddalena and Sagardoy 2000) are commonly used to evaluate the performance of on-demand pressurized irrigation networks. The ICARE model was developed to estimate the entire generated sets of hydrants' configurations, assuming the hydrant discharge is constant. The limitation of this model is that it is not capable of detecting pressure-deficient hydrants, so the AKLA model was developed, which allows the detection of hydrants with pressure deficits (Lamaddalena and Pereira 2007). Lamaddalena and Sagardoy (2000) presented a software package (called COPAM) where the two models, ICARE and AKLA, along with a procedure for the optimization of the pipe network diameters, are integrated. The COPAM software package (Ver. 1.01, FAO, I&D Paper No 59) was used for the assessment of the two abovementioned Italian irrigation systems. Further details of this study are provided below.

2.2.1 Maximum Possible Inflow to the Network and Pipelines

`The maximum possible inflow into the networks was calculated on the basis of Clément's first model (Lamaddalena and Sagardoy 2000):

$$Q = \sum R_i P_i d_i + U\left(P_q\right)\sqrt{\sum R_i P_i (1 - P) d_i^2} \quad \text{(Clément's first equation)} \qquad (1)$$

in which, Q is the discharge (l/s); R is the number of hydrants, d is the nominal discharge of each hydrant (l/s), $U\left(P_q\right)$ is the operation quality, P is the elementary probability of each hydrant, which is calculated using Eq. (2):

$$P = \frac{q_s A}{rRd} \tag{2}$$

where, q_s is the network hydro module (l/s/ha), A is the irrigated area (ha) and r is the coefficient of utilization. A hydrant configuration refers to the number of hydrants that are open simultaneously. The number of possible configurations is given by Eq. (3).

$$C_R^K = \frac{R!}{K!(R-K)!} \tag{3}$$

where, C_R^K is the number of possible configurations when delivering the discharge Q corresponding to the K hydrant in simultaneous operation. In the present study, 1000 different random configurations were considered for the network evaluation and further optimization.

Clément's second formula was also used in this study to calculate the peak discharge. It allows the different approaches to be compared.

Clément's second model is:

$$Q = \sum R_i P_i d_i + u' \sqrt{\sum R_i P_i (1-P) d_i^2} \text{ (Clément's second equation)} \tag{4}$$

2.3 Performance Indicators

Two models (ICARE and AKLA) were used to analyze and evaluate the irrigation networks under study. A configuration is defined as a group of hydrants in operation (j) corresponding to a fixed value of the discharge upstream of the network $(Q(l/s))$. A hydrant configuration is considered to be satisfied and without problems when the following equation is true for all hydrants in operation:

$$\left(H_j\right)_r \geq H_{\min} \tag{5}$$

where, $\left(H_j\right)_r$ is the hydraulic height of the hydrant in configuration r and $H_{\min}$ is the minimum required pressure of the hydrant (m). This model indicates only that the irrigation network under study has some problems and is not able to identify the location of the failing hydrants. To solve this problem, AKLA model was used. In this model, two indicators were defined: ii) the relative pressure deficit, and ii) the reliability. Both are used to evaluate the performance of the irrigation network. The relative pressure deficit (RPD) index for each hydrant is defined as follows (Lamaddalena and Sagardoy 2000):

$$\Delta H = \frac{H_{j,r} - H_{\min}}{H_{\min}} \tag{6}$$

The reliability index of each hydrant is also calculated using Eq. (7):

$$\alpha_j = \frac{\sum_{R=1}^{C} Ih_{j,r} Ip_{j,r}}{\sum_{R=1}^{K} Ih_{j,r}} \tag{7}$$

where, α_j is the reliability of the hydrant j, if the hydrant is open in configurations r : $Ih_{j,r} = 1$, if the hydrant is closed in configurations r: $Ih_{j,r} = 0$, if the pressure height in the open hydrant j in the composition r is higher than the minimum pressure height required $Ip_{j,r} = 1$, if the pressure height in the open hydrant j in the configurations r is lower than the minimum pressure height required $Ip_{j,r} = 0$ and C is the total number of configurations.

3 Results and Discussion

3.1 Inflow to Irrigation Network

Figure 2 shows the results of calculations of the inflow discharge for both pressurized irrigation networks A and B. Differences are in the range between -10% and + 10%. Clément's second equation estimates a higher upstream discharge than the first equation. The discharges calculated by Clément's second equation in the networks A and B are, respectively, 15.65% and 17.64% greater than the values estimated by the first equation. The reason is attributed to the difference between two parameters of operating quality coefficient ($U_P(q)$) in the first equation and the saturation coefficient (u') in the second equation. Most researchers use Clément's first formula, which is also used in this study. The maximum upstream required discharges for the network A and B are, respectively, 300 l/s and 230 l/s. Therefore, the operating point $P_{New,A}(300l/s, 271m.a.s.l)$ in irrigation network A, and the operating point $P_{New,B}(230l/s, 249m.a.s.l)$ in irrigation network B, are considered as new base points for on-demand operation. Such points are very different from those computed during the design stage: i.e., Points $P_{old,A}(184.4l/s, 271m.a.s.l)$ and $P_{old,B}(145.5\ l/s, 249m.a.s.l)$.

Such differences are mainly due to the change in the cropping pattern, which is currently more water demanding than the design pattern, due to the impact of climate change and to the change in farmers' behavior. These are the main causes of some performance failures recorded in the two irrigation systems.

3.2 Current Status of Irrigation Networks

The Indexed Characteristic Curves were drawn for 1000 random hydrant configurations for upstream discharges ranging as: $30l/s \le Q \le 600l/s$ and $30l/s \le Q \le 500l/s$, respectively, for irrigation networks A and B (Fig. 3). The Indexed Characteristic Curves analysis shows that the old operating points $P_{old,A}(184.4l/s, 271m.a.s.l)$ and $P_{old,B}(145.5l/s, 271m.a.s.l)$ for both networks are located on the upper envelope area. It indicates that both networks in the initial management conditions can provide the minimum pressure head required by most hydrant configurations. New base points in irrigation networks A and B ($P_{0,A}(300l/s, 271m.a.s.l)$ and $P_{0,B}(230l/s, 249m.a.s.l)$), are respectively located on indexed

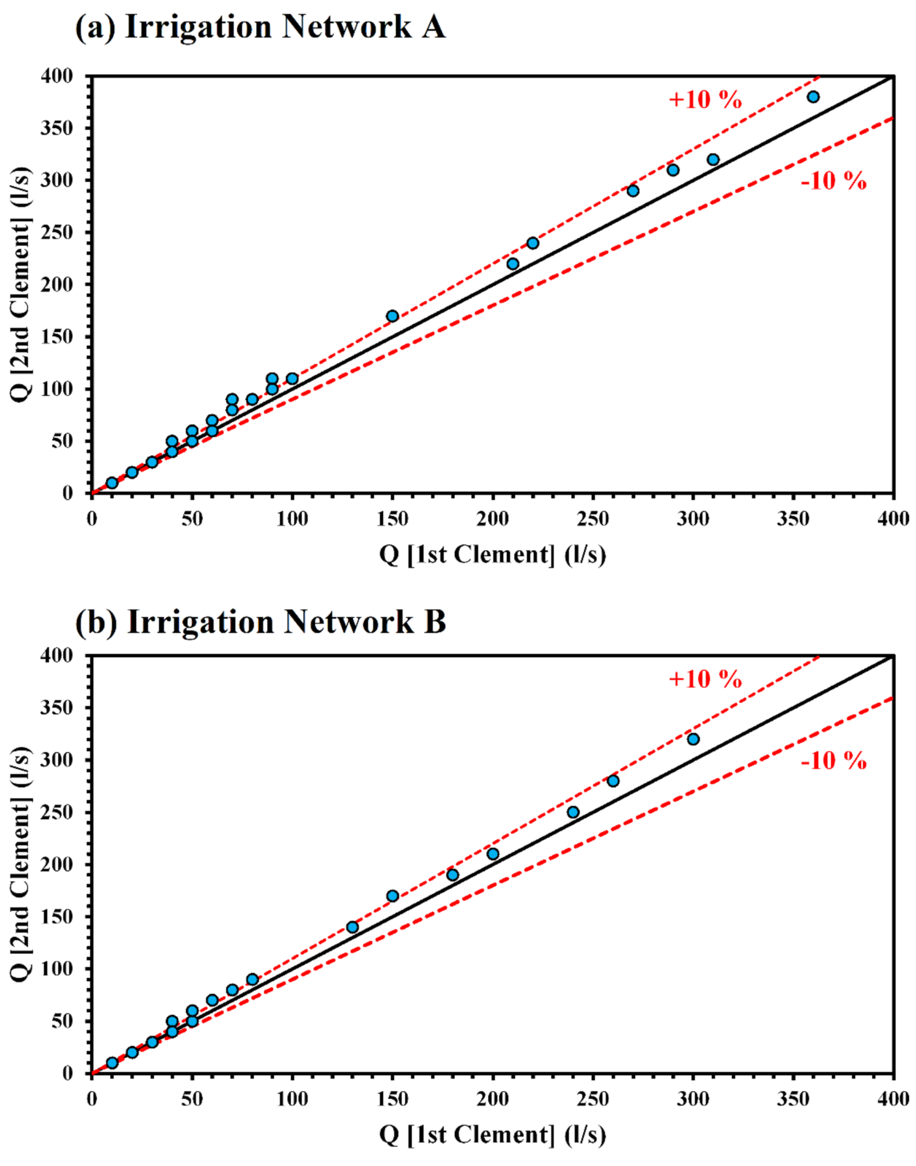

Fig. 2 Comparison of discharges calculated based on Clément's first and second equations **a** Irrigation network A **b** Irrigation network B

characteristic curves of 70% and 83%. In other words, for the irrigation networks A and B, the minimum pressure head ($H_{min} = 20m$) is satisfied in 70% and 83% of configurations at the discharges of 300 l/s and 230 l/s respectively. Such performance is still acceptable for both networks and indicates a very good flexibility of the designed systems.

Figure 4 shows the changes in the relative pressure deficit indicator as well as its envelope curves at 100%, 90% and 10%, for each hydrant at the new base points for 1000 random configurations. In both networks, the hydrants that are most exposed to

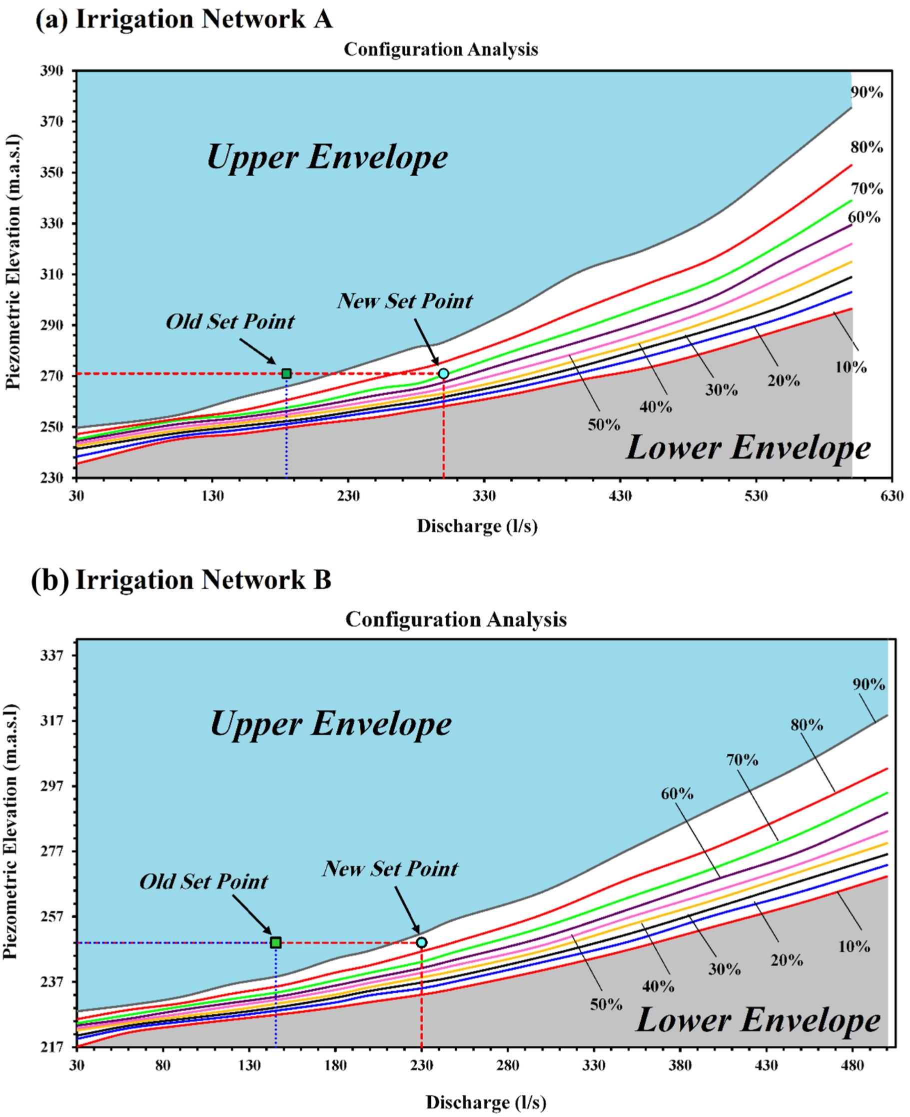

Fig. 3 Indexed characteristic curves in the current situation for **a** Irrigation network A and **b** Irrigation network B

insufficient pressure are identified. Based on the lower curve, in irrigation network A, 47% of hydrants do not provide the minimum required pressure. Of these, 10.9% of hydrants have less than zero pressure (meaning that water cannot flow from those hydrants), 10.3% have a pressure in the range of 0–10 m and 25.8% have a pressure in the range of 10–20 m. Also, in irrigation network B, the amount of pressure in 36.9% of hydrants is lower than the minimum required pressure: 6.6% have less than zero pressure, 8.2% have the pressure in the range of 0–10 m and 22.1% in the range of 10–20 m. Based on the curve 90% (except for 10% of the minimum pressure of each hydrant),

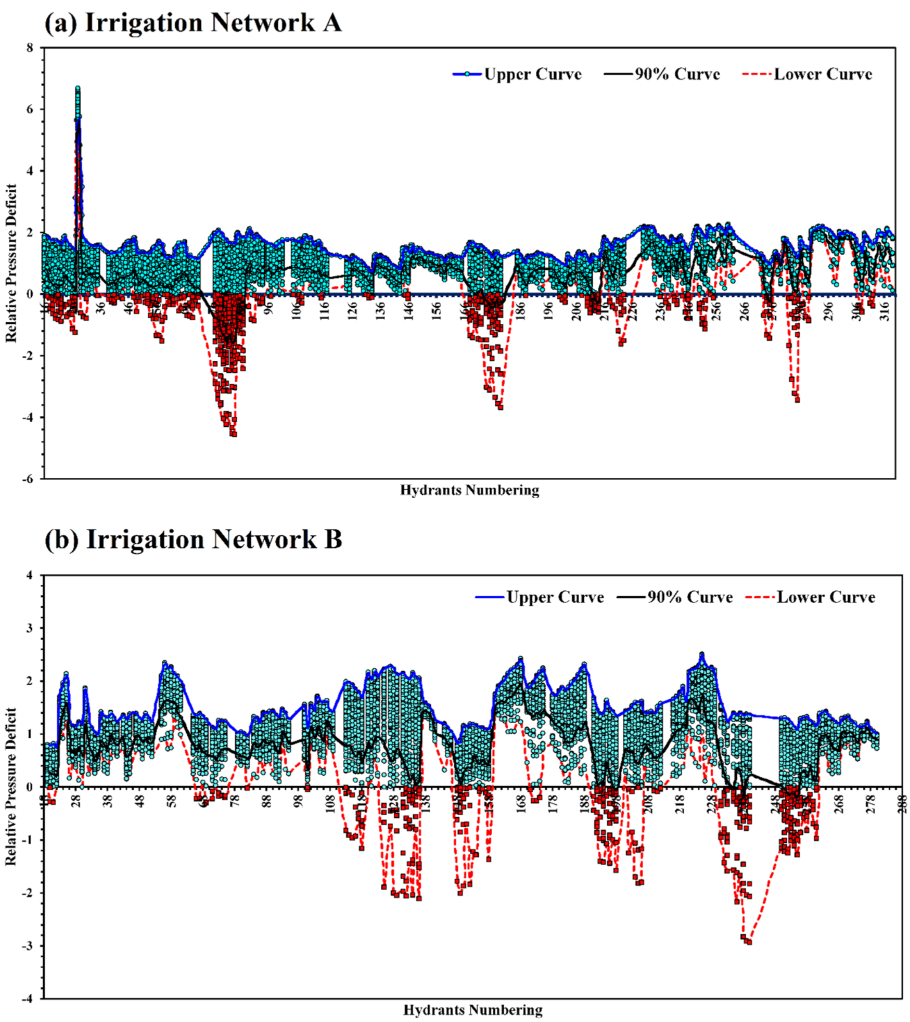

Fig. 4 Changes in the relative pressure deficit index and its curves at three levels (upper, 90% and lower) in each hydrant obtained from 1000 random configurations at the new base point **a** Irrigation network A and **b** Irrigation network B

in irrigation networks A and B, in 10.7% and 3.0% of hydrants, the minimum required pressure is not satisfied.

Figure 5 also shows the changes in the reliability indicator (*RI*) of hydrants at the new base points for 1000 random configurations. The closer the index is to 1, the better the hydrant performance and the minimum required pressure is satisfied. In irrigation networks A and B, respectively, 9 and zero hydrants (3.5% and 0%) are in the range of $RI \leq 0.8$; 14 and 10 hydrants (5.6% and 4.7%) are in the range of $0.8 < RI < 0.9$ and 228 and 204 hydrants (90.8% and 95.3%) are in the range $RI \geq 0.9$. Figure 6a shows the changes in the percentage of unsatisfied hydrants (PUH) against the discharge for the existing piezometric pressure heights (271 for irrigation network A and 249 for irrigation network B). At the new base points, in irrigation networks A and B, respectively, there is the possibility of not

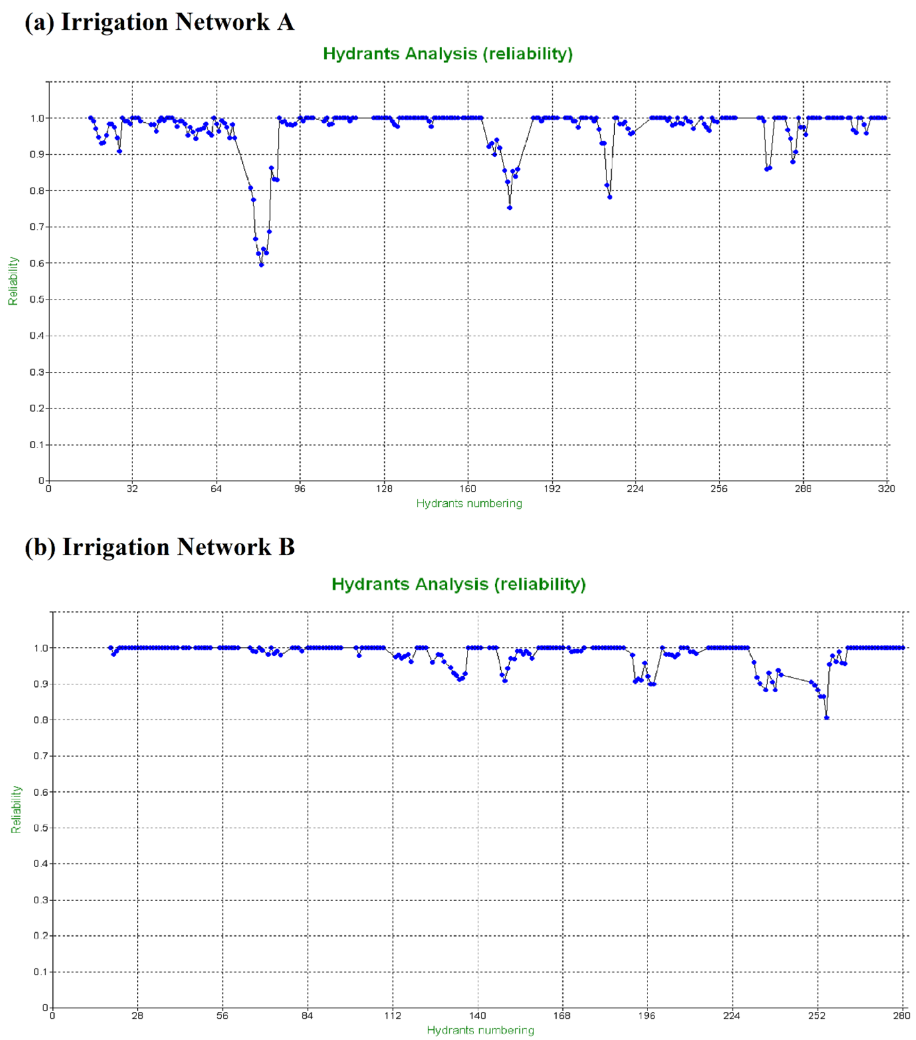

Fig. 5 Changes in reliability indicator for each hydrant obtained from 1000 random configurations at the new base point **a** Irrigation network A and **b** Irrigation network B

supplying the required pressure to 10% and 8% of the hydrants, with 90% probability of occurrence.

In summary, the irrigation network A at a discharge of 300 l/s with a piezometric elevation of 271 m.a.s.l and from 1000 random configurations can supply water at the required pressure to all configurations with a 60% probability of occurrence. Similar conditions are achieved for the irrigation network B with a probability of occurrence of 60% (Fig. 6a). Figure 6b shows the changes in the number of random configurations versus the required pressure head. As the number of random configurations increases, the pressure head required by the network (while maintaining maximum efficiency)

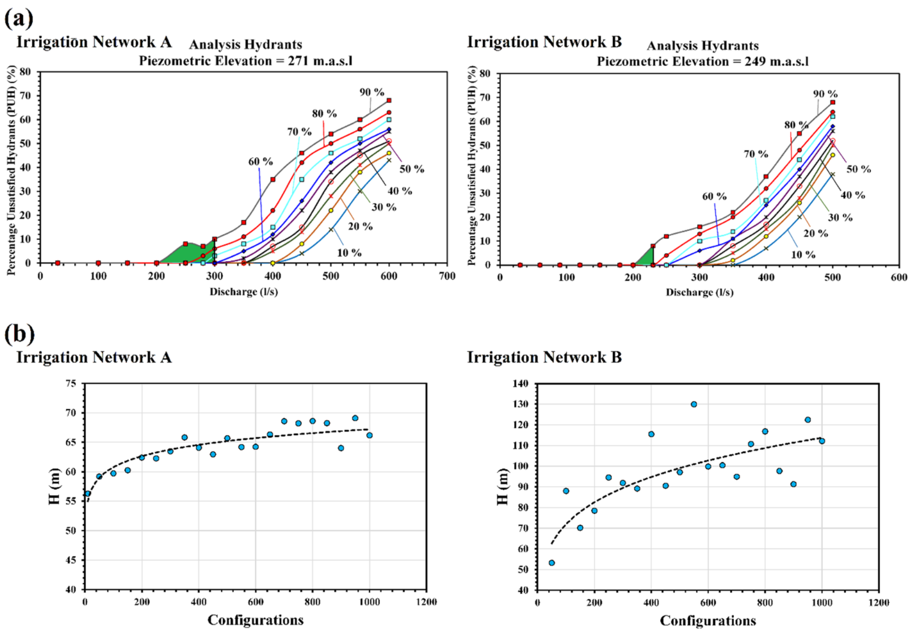

Fig. 6 **a** Percentage probability of occurrence of unsatisfied hydrants (PUH), calculated using 1000 random configurations, for new base points **b** Changes in the number of random configurations against the required water head to supply pressure to all hydrants for both studied irrigation networks

increases too. For the two irrigation networks A and B, the available pressure heads (65 and 43 m, respectively for the two networks A and B) can satisfy the minimum pressure head at hydrants up to 480 and 500 random configurations, respectively. Therefore, to improve the network's performance and, consequently, to increase the hydrant pressure head, the approaches described below are reported.

3.3 Optimization of Studied Irrigation Networks and Re-evaluation of their Performance

By changing the network operation management from the initial design to the current on-demand situation, the network base points change to new ones. The maximum possible discharge required for networks A and B is 300 l/s and 230 l/s, respectively. To provide the required discharge with the minimum pressure head at hydrants, different approaches can be introduced. The use of electric booster pumps and increased pressure at the central pumping station are among the suggested solutions. Still, one of the main drawbacks of these solutions is the high construction, hydromechanical and energy costs.

Another approach to supply the minimum required pressure in failure hydrants is to reduce their nominal discharge. Adopting this approach depends on the on-farm network management. The degree of freedom of hydrants indicates the freedom of farmers to irrigation schedule. The lowest degree of freedom should be not less than 2 times

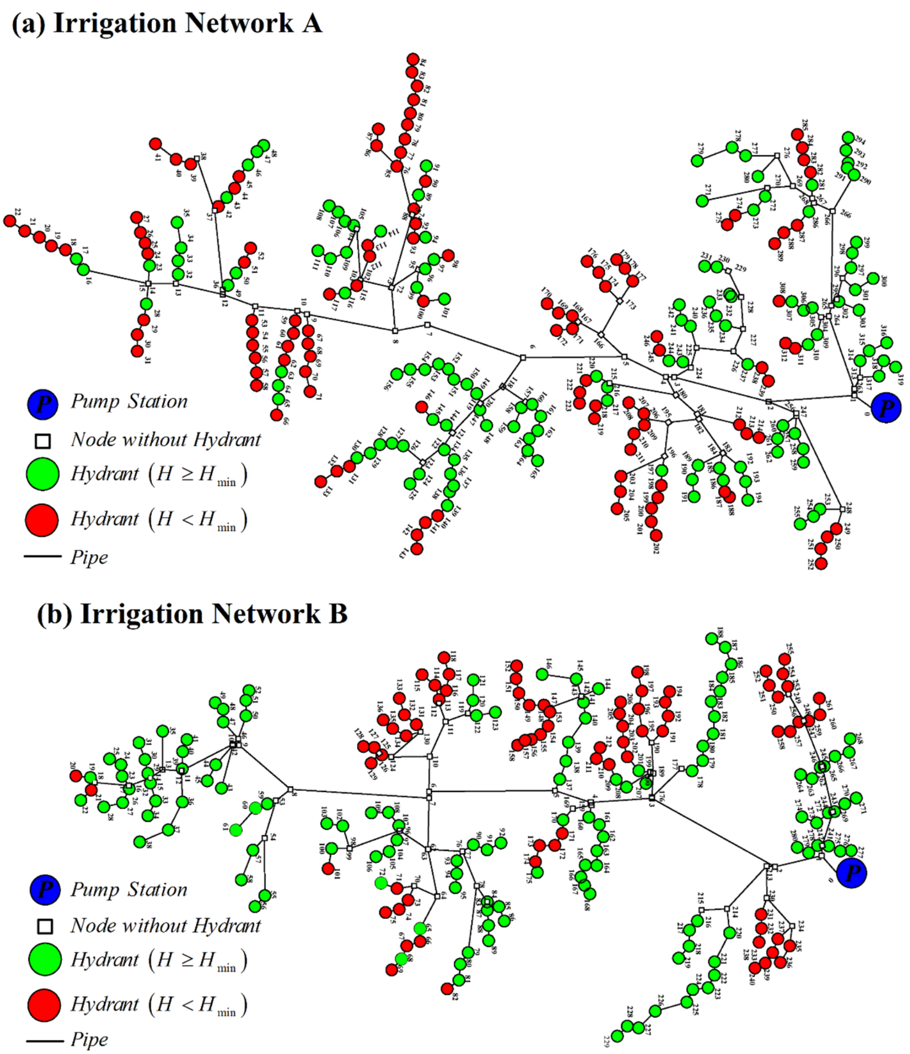

Fig. 7 Identification of unsatisfied pressure hydrants in the operating conditions of the new base point; **a** Pressurized irrigation network A **b** Pressurized irrigation network B

the continuous specific discharge, q_s, (FAO I&D paper n. 44). The actual degree of freedom of the hydrants for both networks is more than 12 times q_s, which is very high. In this regard, the nominal discharge of unsatisfied hydrants (as shown in Fig. 7) was reduced from 10 l/s to 6 l/s and the networks were re-evaluated. In both irrigation networks, the new base point was obtained in the upper envelope area (Fig. 8a). Also, the percentage of unsatisfied hydrants in both networks reached zero percent after reducing the nominal discharge (Fig. 8b). Also, by examining the RPD index, the number

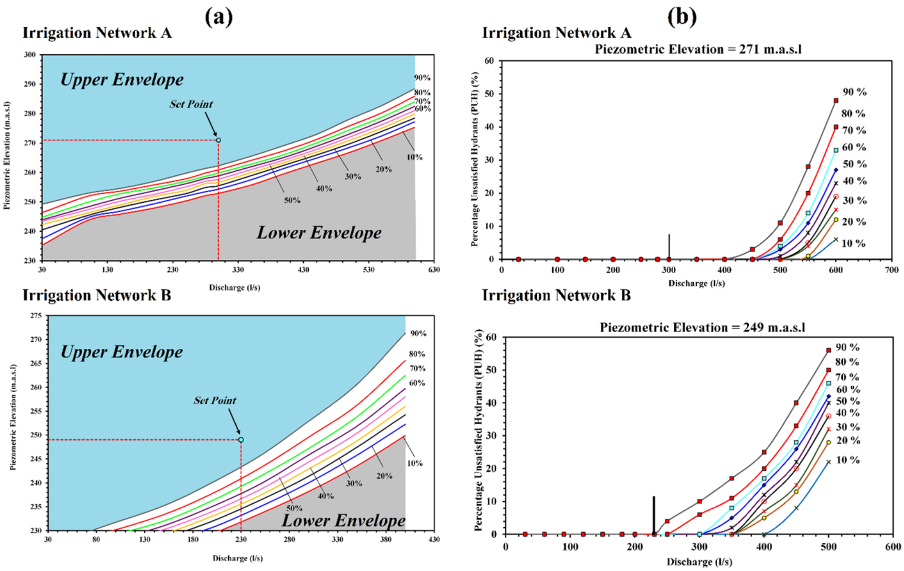

Fig. 8 **a** Indexed characteristic curves after reducing the nominal discharge of low-pressure hydrants **b** Percentage probability of occurrence of unsatisfied hydrants (PUH), calculated using 1000 random configurations, after reducing the nominal discharge of low-pressure hydrants

of hydrants with a pressure below the minimum required pressure in the mentioned networks was reduced from 118 and 79 hydrants to zero and 46 hydrants, respectively (Fig. 9). Moreover, despite cost savings and no change in the structure of the network, except for the flow regulators into the hydrants, this approach could reduce comfort for farmers and could make operation managers skeptical about the application of this approach. But the most stable method can be diameter reduction based on COPAM software, which will be fully described below.

3.3.1 Modification and Optimization of Network Pipe Diameters

In this session, the rehabilitation of the two networks A and B is proposed by using the optimization process available through this methodology; in irrigation networks A and B, the diameters of 72 and 65 pipelines (respectively, 22.6% and 23.2% of the total network) were changed (Fig. 10). After optimization, the pressure head in all nodes became higher than the minimum required pressure ($H_{min} = 20m$). Also, the new base points for both irrigation networks have been moved from the intermediate area to the upper envelope area (Fig. 11). It is also possible to reduce the upstream piezometric elevation in both irrigation networks A and B, from 271 and 249 m.a.s.l to 265 and 240.5 m.a.s.l, respectively. This reduction in piezometric elevation will reduce energy costs. Energy costs typically account for 55 to 70 percent of total network operation and maintenance costs (FAO 59). Therefore, the costs of changing the diameter of the pipes, after a certain period of time, will be compensated by reducing the costs related to energy consumption (Córcoles et al. 2015).

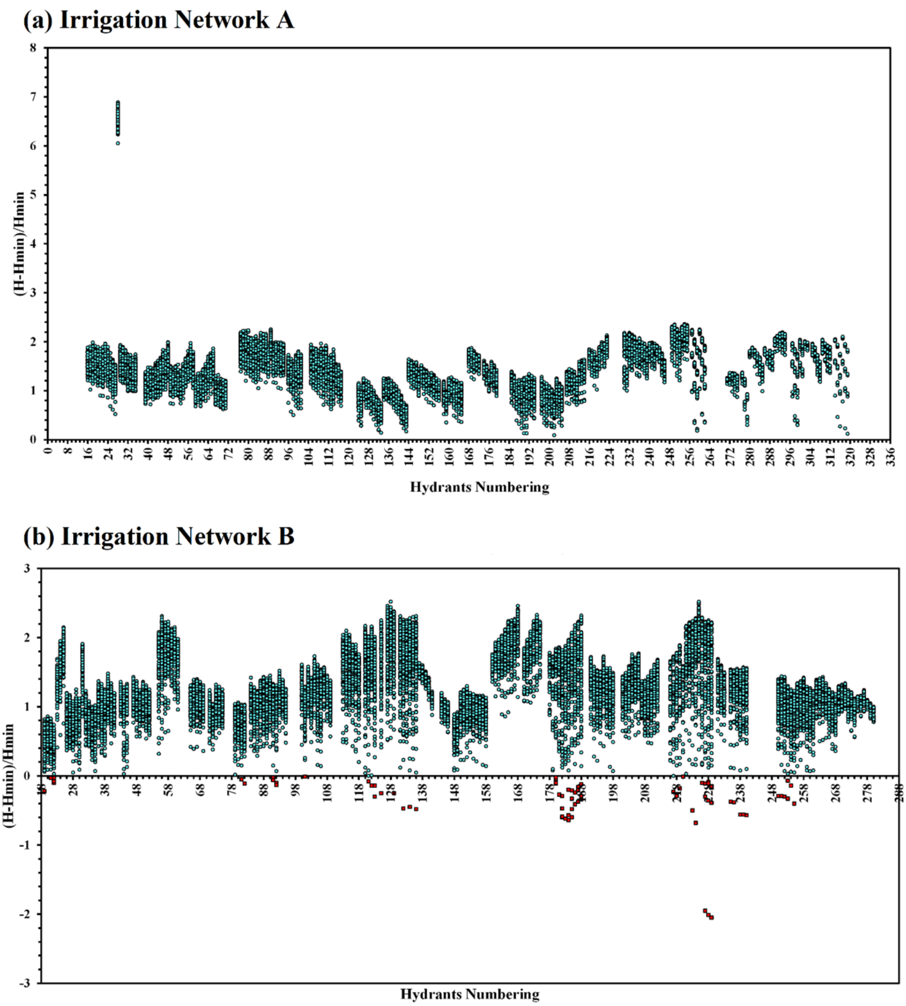

Fig. 9 Changes in the relative pressure deficit index in each hydrant obtained from 1000 random configurations, after reducing the nominal discharge of low-pressure hydrants; **a** Irrigation network A and **b** Irrigation network B

After optimization, the number of hydrants that do not supply the minimum required pressure is reduced to 7 and 14 hydrants for networks A and B, respectively (2.8% and 6.5% of the total network) (Fig. 12). Figure 13 also shows the condition of the hydrants of both irrigation networks. The *RI* index in all hydrants, except in very few cases, has reached 1 (the most desirable condition).

3.4 Initial Design of on-demand Networks

If the studied irrigation networks were designed from the beginning by using COPAM model, the costs of the pipes would have been less than the costs for the rehabilitation of the networks.

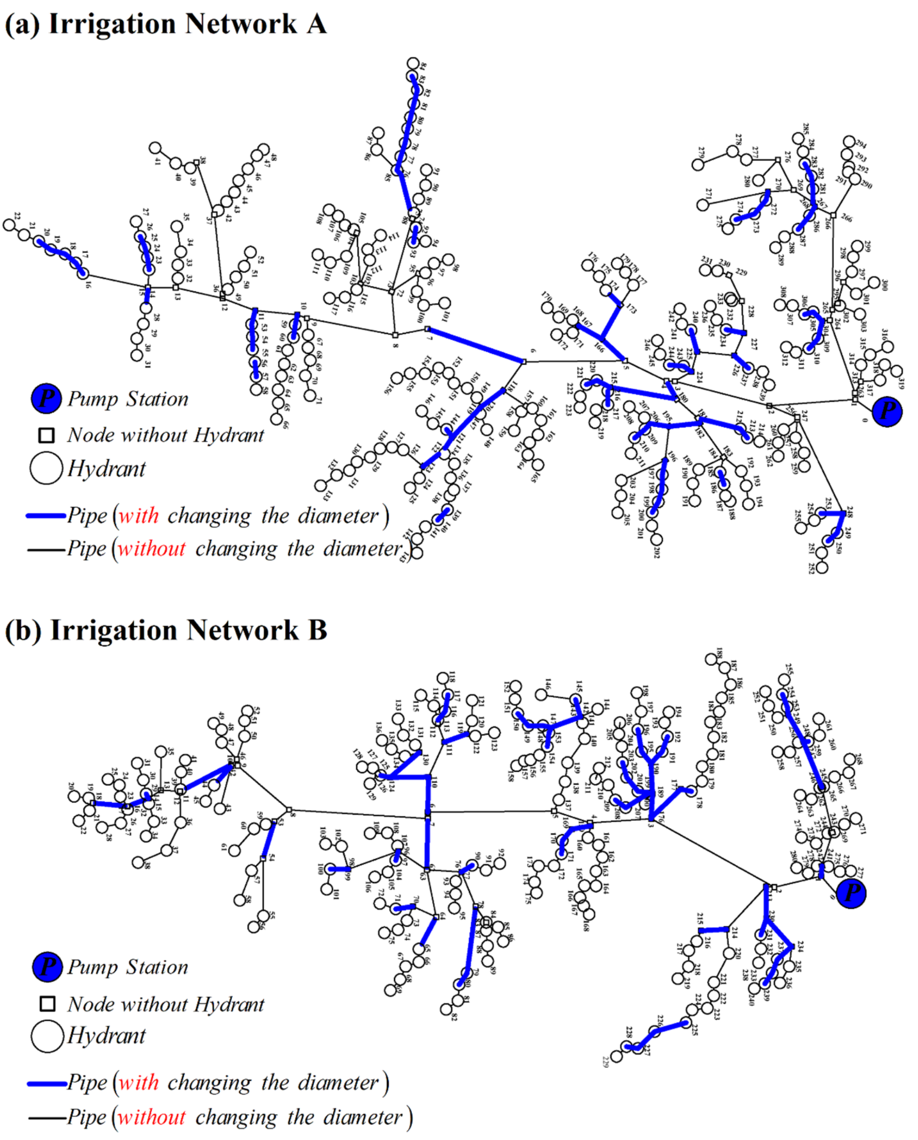

Fig. 10 Changes in pipelines diameter in the optimization stage; **a** Irrigation network A and **b** Irrigation network B

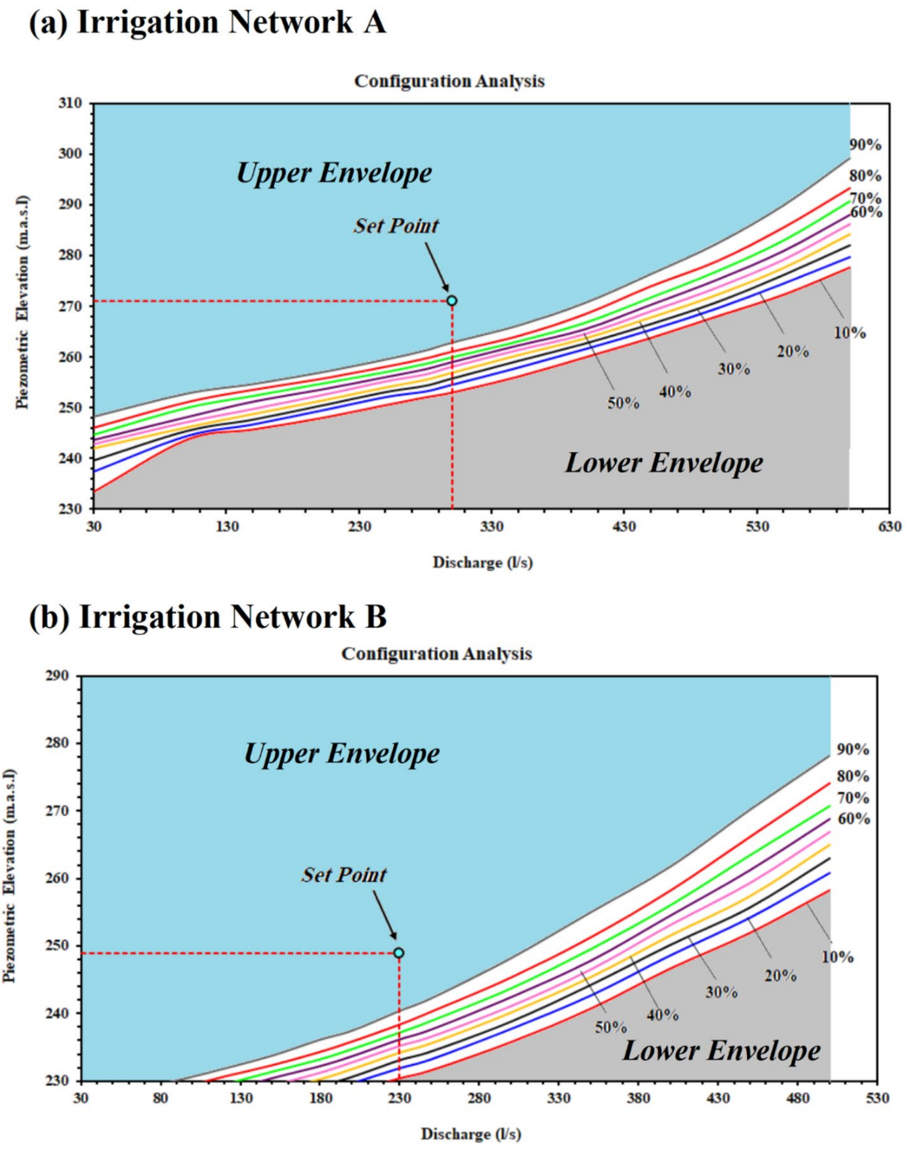

Fig. 11 Indexed characteristic curves after optimization of pipelines **a** Irrigation network A and **b** Irrigation network B

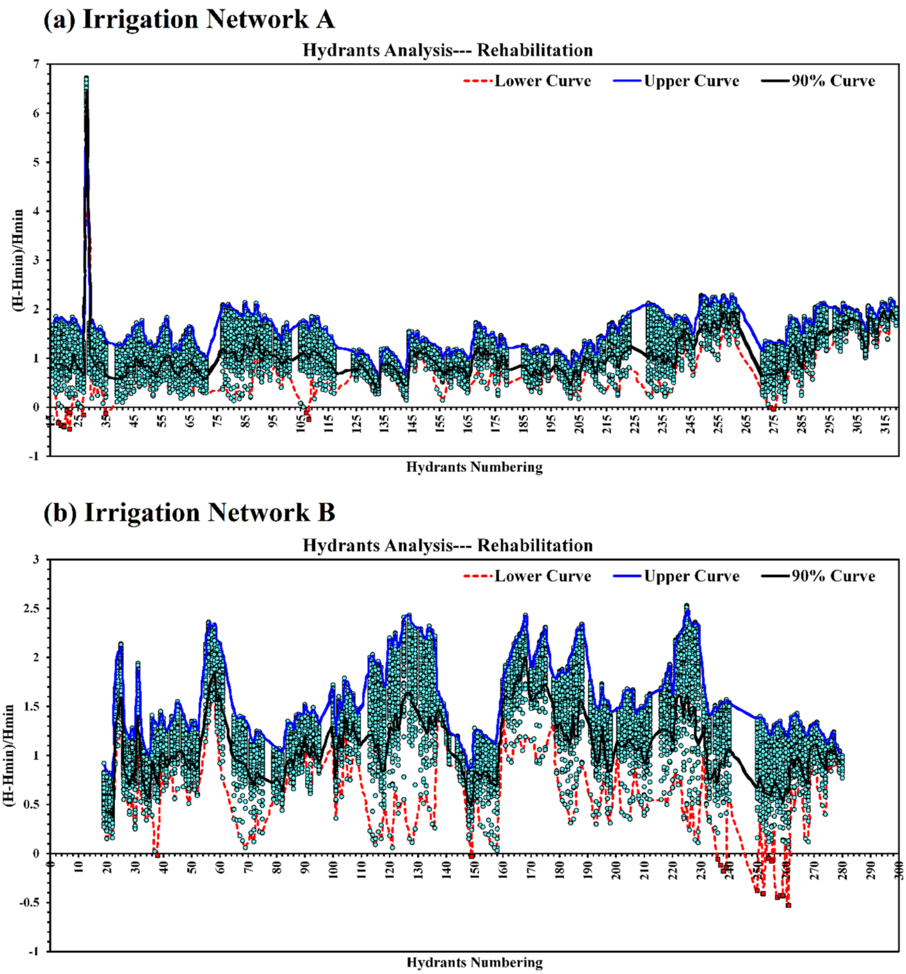

Fig. 12 Changes in the relative pressure deficit index in each hydrant obtained from 1000 discharge configurations, after optimizing the pipelines, **a** Irrigation network A and **b** Irrigation network B

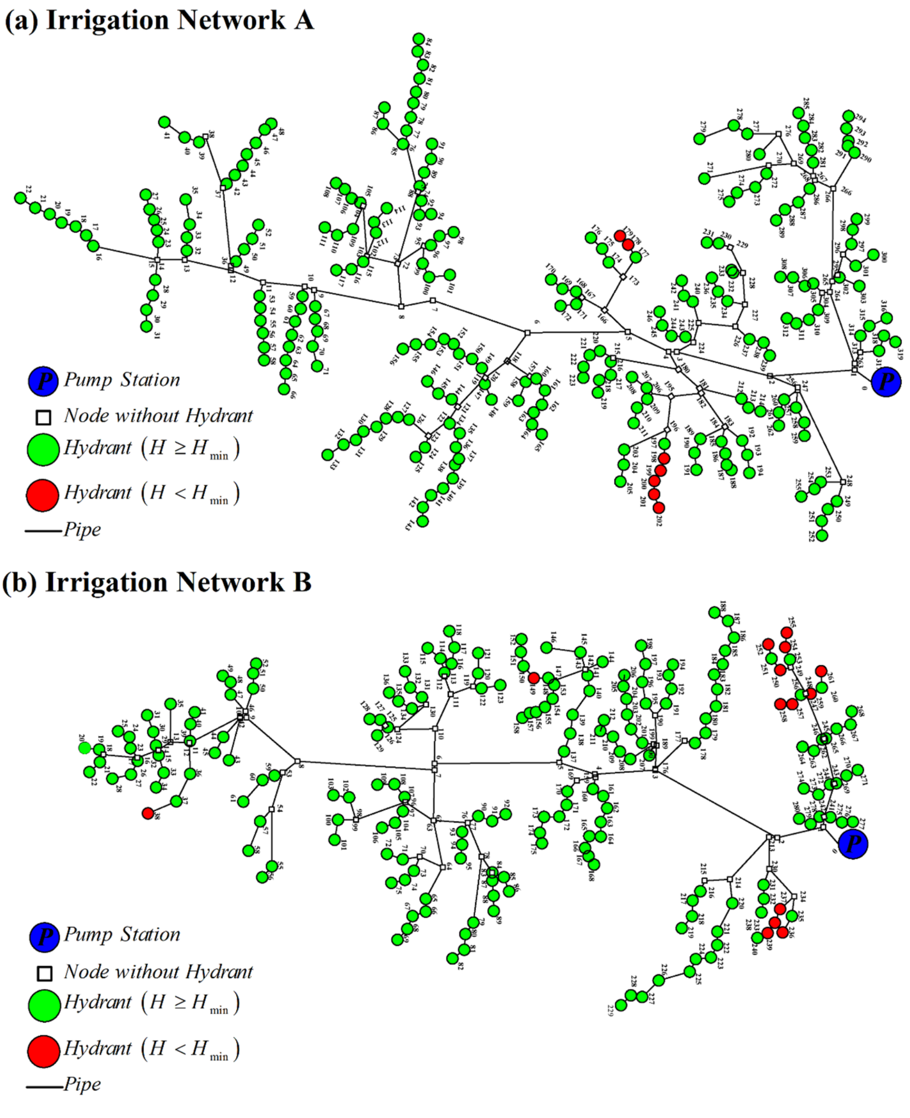

Fig. 13 Position of unsatisfied hydrants after optimization, based on relative pressure deficit index; **a** Pressurized irrigation network A and **b** Pressurized irrigation network B

4 Conclusions

In the present study, the feasibility of changing management options of two pressurized irrigation networks was investigated. The COPAM model was used to evaluate the performance and rehabilitate the networks. Results showed that it is possible to improve the network performance by analyzing the current situation and then by identifying different options. Currently, the analysis carried out showed that for the irrigation networks A and B, it is not possible to supply the minimum pressure head at 47% and 36.9% of hydrants.

Reducing the nominal discharge in unsatisfied hydrants improved the performance of the networks. In this case, the possible dissatisfaction of farmers should be further analyzed in detail. The Rehabilitation by optimization of pipe diameter was performed. The diameters of 72 and 65 pipes were modified in irrigation networks A and B, respectively. Using this approach, the number of failing hydrants in the two irrigation networks decreased from 118 and 79 hydrants to 2.8% (7 hydrants) and 6.5% (14 hydrants), respectively and the amount of energy required by the networks decreased. Also, the option to increase the upstream piezometric elevation was analyzed but this solution may cause excessive energy consumption, so it should be further analyzed. Therefore, it is possible to convert water delivery management in the pressurized irrigation network with a central pumping station from a traditional rotational into on-demand and it is recommended.

Authors' Contributions Conceptualization: [Younes Aminpour, Nicola Lamaddalena], Methodology: [Younes Aminpour], Formal analysis and investigation: [Younes Aminpour, Eisa Maroufpoor, Nicola Lamaddalena], Writing—original draft preparation: [Younes Aminpour]; Writing—review and editing: [Eisa Maroufpoor], Resources: [Nicola Lamaddalena], Supervision: [Eisa Maroufpoor, Nicola Lamaddalena].

Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests The authors declare that they have no competing interests.

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