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Notes

Hydraulic analysis of the pressurized network of section 01 of irrigation district 001 under different operating scenarios

Análisis hidráulico de la red presurizada de la sección 01 del Distrito de Riego 001 ante diferentes escenarios de operación

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Abstract

The modernization of irrigation district 001 began in 2004. Although the construction process is still underway, the fully completed irrigation sections are now in operation. The modernization project includes construction and operational changes with respect to the original design, so the objective of this study was to analyze the hydraulic behavior of the section 001 distribution network in seven operating scenarios in order to identify the most suitable one for irrigation management. The demand on the 126 hydrants of the study section was obtained by modular expenditure, randomly assigning one of the crops of the pattern. The current cropping pattern, irrigation interval and zero precipitation were considered in all scenarios. The first three scenarios considered a shift distribution, with differences in the irrigation requirements and emitter application rates. The fourth scenario considered a mixed shift and on-demand distribution. These four scenarios considered an irrigation interval of 48 hours, plus an irrigation time of 3.2 hours per shift and were simulated in EPANET software. The fifth, sixth and seventh scenarios considered an on-demand distribution, applying Clément's first generalized formula with a supply guarantee of 90, 95 and 99 %, respectively, with a daily irrigation interval, and were implemented in MATLAB. The results indicated that the network is not capable of operating with on-demand irrigation and that, given the current cropping pattern, a strict shift irrigation system is a better option.

Keywords: Irrigation networks, shift irrigation, on-demand irrigation, irrigation district 001, irrigation scenario, hydraulic simulation of networks.

Resumen

La modernización del Distrito de Riego 001 inició en 2004, actualmente sigue en proceso de construcción y operando las secciones de riego completamente terminadas. El proyecto presenta cambios constructivos y de operación respecto al original, por lo que se planteó como objetivo analizar el comportamiento hidráulico de la red de distribución de la sección 01 en siete escenarios de operación, para identificar el más idóneo para el manejo del riego. La demanda de los 126 hidrantes de la sección de estudio se obtuvo por gasto modular, asignando aleatoriamente uno de los cultivos del patrón. Se consideraron el patrón de cultivos e intervalo de riego actuales, y una precipitación nula en todos los escenarios. Los tres primeros escenarios consideran una distribución por turnos, con diferencias en las necesidades de riego y en las láminas horarias de los emisores. El cuarto escenario consideró una distribución mixta por turnos y a la demanda. Estos cuatro escenarios consideraron un intervalo de riego de 48 horas, tiempo de riego de 3.2 horas por turno y fueron simulados en el programa EPANET. El quinto, sexto y séptimo escenario consideraron una distribución a la demanda, aplicando la primera fórmula generalizada de Clément, con una garantía de suministro de 90, 95 y 99 %, respectivamente, con un intervalo de riego diario, y se implementaron en MATLAB. Los resultados indicaron que la red no está capacitada para operar con un riego a la demanda y que, ante el patrón actual de cultivos, un riego por turnos estrictos es una mejor opción.

Palabras clave: redes de riego, riego por turnos, riego a la demanda, Distrito de Riego 001, escenario de riego, simulación hidráulica de redes.

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Introduction

Water is used in various ways in all human activities, whether to subsist or to produce and exchange goods and services (Conagua, 2018). It is important to highlight that the agricultural sector is the one that consumes the most water in Mexico, approximately 76 % of the total used at the national level (Conagua, 2018), with high losses in conduction and distribution (30 %), and in the application at plot level (Altamirano *et al*., 2019). A strong competition for water between the different uses and its inefficient use causes a negative water balance in Mexico (Martínez, 2020). In order to make more efficient use of irrigation water in Mexico, strategic actions must be established such as irrigation technification, modernization of conduction and distribution networks, measurement of irrigation service delivery, and formulation of irrigation plans consistent with the availability of water (Conagua, 2017). A rethinking of the cropping pattern is required, as it has been found that crops with low productivity put the availability of aquifers, such as the Calera aquifer, at risk (Flores, Cristóbal, Pascual, De-León, & Prado, 2019). When designing an irrigation system, the most important challenge is the calculation of flow rates circulating in the network, which depends on climatic conditions, cropping pattern and farmer behavior (Daccache & Lamaddalena, 2010). Íñiguez, De-León, Prado and Rendón (2007) found that the on-demand delivery method, with Clément's probabilistic method, could be the most appropriate to redesign the main conduction system of the La Begoña, Guanajuato irrigation district (ID) to guarantee flexible irrigation to a cropping pattern different from the one originally projected. It is important to consider the possibility of climate change in the agricultural area to guarantee adequate irrigation in future years (Granados, Martín, García, & Iglesias, 2015).

The ID modernization project began in 2004 based on a proposed piped conduction and distribution system, fed by the Plutarco Elías Calles dam. The irrigation system was projected as a mixed system involving shift-based distribution and controlled demand for drip irrigation at plot level. There are several problems that affect the operation and performance of the pressurized network. There are users who irrigate by sprinkling, a water application technique that requires more pressure and water to operate than originally projected. There are users who do not respect the assigned irrigation shift and irrigate on an on-demand basis, resulting in lower pressures at certain delivery points than those required for the emitters to operate correctly. Another major problem is that there are users who irrigate for long periods of time so as not to irrigate daily, but the irrigation system is designed for continuous (daily) irrigation. In addition, there are some users who are assigned night irrigation shifts, but prefer to irrigate during the day. Another important aspect to consider is that the cropping pattern proposed in the original design differs from the one currently established within the ID. Although the original project was conceived as having a water delivery system with a certain degree of flexibility, the aforementioned problems and the construction and climate modifications, with respect to the original project plan, could generate supply problems in some plots once the infrastructure is fully completed and the operation of the entire district begins (Pérez, Smout, Rodríguez, & Carrillo, 2010; Planells, Tarjuelo, Ortega, & Casanova, 2001), since few sections are currently operating and section 01 is the most complete. Consequently, the aim of this work was to analyze the hydraulic behavior of the main conduction network and the distribution network of section 01, in different operating scenarios, and to identify the best water delivery alternative. The current characteristics of the cropping pattern, climate and operation were considered. The shift-based operating scenarios were implemented in EPANET software (EPA, 2020), and on-demand scenarios, based on Clément's (1966) first generalized formula, were executed in MATLAB (The Math Works, Inc., 2019).

Materials and methods

Pabellón de Arteaga ID 001 is located in the municipalities of Pabellón de Arteaga, Rincón de Romos and Tepezalá, and is supplied by the Presidente Plutarco Elías Calles dam. The hydraulic behavior of section 01 of the 19 sections that make up ID 001 was analyzed because it is the one with the most advanced construction and because it is totally supplied by the Calles dam, unlike other sections where some hydrants have been adapted to receive water from deep wells. Galván and Exebio (2020) note that the section's conduction network is closed, composed of 253 segments (97 % of the length) of class 5 pipe and eight segments (3 % of the length) of class 7 pipe; it currently operates with 126 hydrants with nominal flow rates of 10 and 20 l s^{-1} and four pressure regulating valves (PRV) calibrated at different operating pressures to irrigate 317.25 ha (Figure 1b).

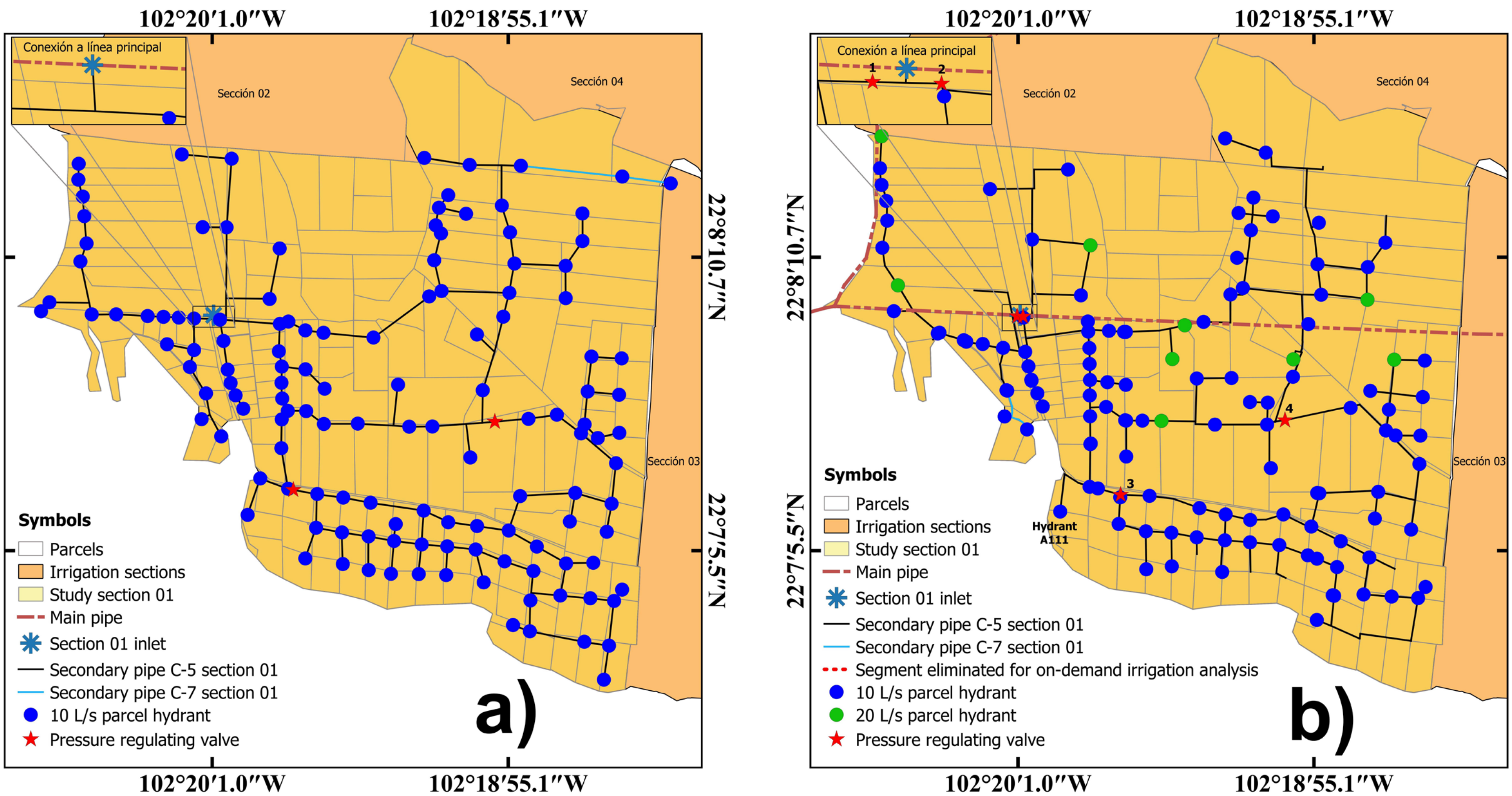

Figure 1. Topology of section 01: (a) original network; (b) installed network.

The section 01 conduction network had changes with respect to the initial project (Figures 1a and 1b), of which the following stand out: reduction of hydrants from 132 to 126, increase in PRVs from two to four and reduction of the domain area from 353.33 to 317.25 ha. Currently, the number of hydrants and irrigation area is constantly changing due to the sale of water rights, which is approved by the ID's Civil Association of Users (ACU). The sale of rights can take place within the same section in very distant places, even from one section to another, affecting the supply capacity at some points of the hydraulic network.

Estimation of gross irrigation requirements

Gross irrigation requirements (GI_R) (mm) were calculated to compensate for the deficit between crop evapotranspiration (ET_C) (mm) and effective rainfall (P_{ef}) (mm) during crop growth (FAO, 2021). P_{ef} was omitted because site precipitation is erratic (INIFAP, 2019). GI_R were obtained from net irrigation requirements (NI_R) (mm), the uniformity coefficient (*UC*) of the emitters, soil washing requirements (F_{SW}), and application efficiency (*AE*) (Equation (1)) (Tijerina, 1999):

$$GI_R = \frac{NI_R}{AE} = \frac{NI_R}{UC(1-F_{SW})} \quad (1)$$

A *UC* of 90 % was considered, with an *AE* of 95 % for micro irrigation and 85 % for spraying (De-León & Robles, 2007). The F_{SW} (dimensionless) was determined with the equations proposed in FAO paper 24 for low-frequency (sprinkler) and high-frequency (micro-sprinkler and drip) irrigation (Doorenbos & Pruitt, 1977). The maximum electrical conductivity values of the soil saturated paste extract (*EC*se, max) (dS m^{-1}) were taken from FAO paper 29 (Ayers & Westcot, 1976). The electrical conductivity in water (EC_w) (dS m^{-1}) of the Calles dam is 0.1368 dS m^{-1}. NI_R were calculated with a soil water balance (De-León & Robles, 2007), considering the adjusted crop evapotranspiration ($ET_{C\,Adj}$), disregarding P_{ef} and contributions from the water table.

The $ET_{C\,Adj}$ resulted from adjusting the ET_C by the factors of: location (F_L), climate (F_C) and advection (F_A) (Equation (2)) (Pizarro, 1996):

$$ET_{C\,Adj} = (F_L)(F_C)(F_A)(ET_C) \quad (2)$$

ET_C was calculated with crop coefficients (k_c) and reference evapotranspiration (ET_O) (mm). The K_c were taken from the FAO 56 manual and ETo was calculated with the Penman-Monteith equation (Allen, Pereira, Raes, & Smith, 2006). The daily average climatic information for the calculation of ET_O was obtained from the CEPAB automatic weather station (INIFAP, 2019) for the period from May 2003 to March 2019. The calculation of irrigation requirements was made based on the start-end dates and duration of the established cycles for each crop and considering that the agricultural cycle begins on October 1, according to information collected with the ACU.

Unit flow rate per crop

In section 01, a flow rate per unit area (unit) (q_u) per crop was calculated, based on the installation framework and flow rates of the emitters that most of the users employ in ID 001, according to information provided by

ACU operational staff. A single value (average value) was obtained in sections 02 to 19.

Current irrigated area

At the time of this study, the total irrigated area in the ID was 5,460 ha. This amount resulted from the sum of the domain area reported by the ACU in the sections that are already operating, and the initially projected area in the sections that are under construction and to be built. The areas for sections 01, 02, 03, 04, 05, 06, 07, 08, 09, 10, 11, 12, 13, 14, 15, 16, 17, 18 and 19 are 317.25, 78.63, 353.82, 235.05, 115.51, 91.73, 166.85, 316.71, 387.08, 144.66, 144.61, 478.63, 215.68, 132.38, 716.45, 574.90, 129.96, 456.05 and 404.06 ha, respectively.

Cropping pattern for section 01

A projection was made of the planting area per crop for the agricultural cycle in the entire ID, so that the total planting area would not exceed the 5,460 ha of the ID per month, and that the volume demanded would be equal to or less than the volume granted by CONAGUA for the agricultural cycle, whose value is 32.5 hm^3. The area considered for each crop in section 01 resulted from multiplying the planting area of the crop in the ID by the percentage of the area of section 01, with respect to the total area to be irrigated in the ID (5.81 %).

Irrigation times

The irrigation time (I_T) (h) required for each of the crops was calculated with the application rate (S_H) (mm h^{-1}) applied by the emitters (drippers, micro-sprinklers and sprinklers) and the GI_R of each crop to apply irrigation in 48-h intervals.

Operating scenarios

In order to analyze the operating scenarios, the current operation was taken as a reference, which consists of irrigating in two-day irrigation intervals (48 hours) organized into 15 irrigation position shifts of 3.2 hours each (Table 1), and considering that the main line of the irrigation system is completely finished and irrigating 100 % of the ID area. The areas per crop were randomly assigned in section 01 to obtain the irrigation demands per hydrant and per shift. The irrigation demands of sections 02 to 19 in the 15 irrigation shifts were calculated with the unit flow rate and with one-fifteenth of the irrigation area corresponding to each section.

Table 1. Schedules of irrigation operating shifts in ID 001.

Shift	Schedule
1	00:00 - 03:12
2	03:12 - 06:24
3	06:24 - 09:36
4	09:36 - 12:48
5	12:48 - 16:00
6	16:00 - 19:12
7	19:12 - 22:24
8	22:24 - 01:36
9	01:36 - 04:48
10	04:48 - 08:00
11	08:00 - 11:12
12	11:12 - 14:24
13	14:24 - 17:36
14	17:36 - 20:48
15	20:48 - 24:00

The hydrants irrigate the domain area (0.83 to 1.67 ha) in one to four blocks and can only irrigate one block at a time per shift, as is currently done and as originally planned.

Seven operating scenarios were proposed for section 01 based on changes made to the original modernization project, mainly in: operation of the pressurized network, cropping pattern and the sale of water rights.

The first three scenarios considered a shift-based irrigation delivery system, the fourth a hybrid delivery by irrigation shift and on demand, and the last three considered on-demand irrigation. The first scenario supplies the irrigation requirements of the projected agricultural cycle's critical month, considering the currently installed emitters, which emit a higher flow than originally projected, with an irrigation interval of 48 h, distributed in the 15 operating shifts (Table 1); it considers the premise that the user respects the irrigation shift assigned in the original project. The second scenario considers the same irrigation requirements and the same number of shifts and irrigation interval as the first one, but adjusting the irrigation application rate applied by the current emitters to guarantee 3.2 h per irrigation shift, due to a decrease in the flow emitted per emitter; the objective is to use irrigation application rates similar to those of the original project since their values are currently different and higher than those projected. The third scenario considers the supply of the maximum irrigation requirements that each crop would present in the projected agricultural cycle, adjusting the application rates of the emitters, as in the second scenario, to guarantee 3.2 h per irrigation shift in the 15 shifts; the objective is to take into account a possible increase in irrigation requirements due to a change in planting dates and in the climatic regime. In the fourth scenario, irrigation requirements are estimated as in scenario one and considers a hybrid delivery, which is the closest to the current operation, which is applied at certain points in the network; 86 hydrants with irrigation delivery by shifts and 40 randomly-distributed hydrants with on-demand irrigation delivery were considered in the daytime shifts, respecting in the 126 hydrants an irrigation time of 3.2 h per shift and a 48-h irrigation interval. The fifth, sixth and seventh scenarios considered the supply of the irrigation requirements of the projected agricultural cycle's critical month, with the opening of hydrants to on-demand distribution with a supply probability of 90, 95 and 99 %, respectively. In the three scenarios, a daily irrigation interval and an irrigation time of 12 h were considered. These three scenarios were considered because the original project generated in the ID users the idea that irrigation would be on demand.

Modeling of operating scenarios

The hydraulic simulation of the first to fourth operating scenarios was done with EPANET software (Rossman *et al.*, 2020; EPA, 2020). Although this software was created for drinking water networks, it can be used to analyze irrigation networks since the hydraulic principle is the same in both cases (Pérez-Sánchez, Sánchez, Ramos, & López, 2016). With the operating shifts, irrigation areas and unit flow rates, the demand curves were generated at the representative nodes of the inlets of sections 02 to 19 and the hydrants of section 01. The flow rates to be circulated for each segment of the network for the fifth, sixth and seventh scenarios were determined with the equation proposed by Clément (1966) for heterogeneous hydrants with different discharges and operating probabilities at a given instant, and these simulations were implemented with MATLAB® (The Math Works, Inc., 2019) software. Friction losses were calculated using the Hazen-Williams resistance equation.

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Hydraulic analysis considerations

The hydraulic load for all scenarios was 3.02 kg cm^{-2}, the result of the difference between the elevation of the intake point (1,963.00 masl) and the Extraordinary Minimum Water Level (1,993.25 masl) of the Calles dam, which is the minimum operating level of the irrigation system. The current operating pressure of the PRVs (2.80 kg cm^{-2}) in the dead-leg segment of the main line and 0.25 kg cm^{-2} of energy loss in the filtering platform were considered, according to values provided by the ACU. The ID is divided into 19 irrigation sections, each of which connects to the main conduction line at a single point and then branches into lower-ranking lines. Sections 02 to 19 were symbolically represented as a delivery node in the main network, with a flow rate assigned to cover the needs of the crops in each irrigation shift in order to simulate the complete operation of the main network. In section 01, the values to which PRV1, PRV2, PRV3 and PRV4 are calibrated were considered, which are 3.5 kg cm^{-2}, 4.5 kg cm^{-2}, 3.5 kg cm^{-2} and 3.8 kg cm^{-2}, respectively (Figure 1b), according to information provided by the ACU. In the fifth, sixth and seventh scenarios, the section network was considered open, suppressing four segments of the network (Figure 1b) since Clément's formula only applies to open networks, and a common and constant pressure was considered at the section 01 inlet in the 12 h of irrigation. The minimum operating pressure for the hydrants was 2.5 kg cm^{-2} to guarantee covering the energy loss generated by the hydrant components (1.3 kg cm^{-2}) and the losses due to conduction for each block (0.2 kg cm^{-2}), as well as to take into account the emitter operating pressure (1.0 kg cm^{-2}). Flow velocity values in a range of 0.5 to 2.5 m s^{-1} were considered acceptable, as suggested by Mexican standard NMX-O-177-SCFI-2011, which establishes the general guidelines for irrigation system projects (DOF, 2011). This avoids having to acquire large-diameter pipes that have a higher cost.

Results

The month with the highest demand (critical month) of the projected agricultural cycle was May with 6,274.8 dam^3. Identifying the critical month allowed determining the irrigation demands of scenarios one, two and four, and five to seven, corresponding to the pair of days (26 and 27) of maximum demand of that month and the day (27) of maximum demand of that month, respectively.

Irrigation time per crop

The I_T was lower than the time per shift established by the ACU (3.2 h) in the first and fourth operating scenarios, except for the grapevine crop where drippers with a lower application rate are used (Table 2). In the second scenario, the I_T is forced to be equal to the time per shift; the q_u demanded by each crop decreased between 17 and 83 % with respect to the first and fourth scenarios, which translates into lower conduction flow rates and lower energy losses due to friction in the section 01 network segments, reducing the risk of not supplying the required pressures in the hydrants.

Table 2. Irrigation characteristics in section 01 from the first to the fourth operating scenario.

Crop	**First, second and fourth scenario**			**Third scenario**		**I_T (h)**	
	[1]$GI_{R\ 26}$ (mm)	**[2]$GI_{R\ 27}$ (mm)**	**[3]$GI_{RB\ 48h}$ (mm)**	**[4]$GI_{R\ maximum}$ (mm)**	**[5]$GI_{R\ 48h}$ (mm)**	**First and fourth scenario**	**Second and third scenario**
Alfalfa	5.23	5.29	10.52	5.65	11.30	2.44	3.20
Cranberry	4.10	4.13	8.23	4.27	8.54	2.67	3.20
Asparagus	2.87	2.89	5.76	4.42	8.84	1.27	3.20
Strawberry	2.31	2.30	4.61	4.20	8.40	0.54	3.20
Walnut	1.73	1.69	3.42	4.36	8.72	0.95	3.20
Grapevine	2.22	2.21	4.43	3.58	7.16	3.32	3.20
Zucchini	3.39	3.43	6.82	4.11	8.22	2.41	3.20
Onion	4.82	4.86	9.68	5.08	10.16	1.71	3.20
Chili	4.82	4.87	9.69	5.33	10.66	1.71	3.20
Corn (Forage	3.03	3.02	6.05	4.84	9.68	1.34	3.20
Corn (Grain)	3.03	3.02	6.05	4.84	9.68	1.34	3.20
Cucumber	3.72	3.77	7.49	4.12	8.24	2.64	3.20

[1]GI_R 26 = gross irrigation requirement for day 26, corresponding to the critical month (May).

[2]GI_R 27 = gross irrigation requirement for day 27, corresponding to the critical month (May).

[3]GI_R 48h = maximum accumulated gross irrigation requirement for two days (26 and 27) of the month of maximum demand (May), to be applied in 48 h

[4]$GI_{R\ maximum}$ = maximum daily gross irrigation requirement of the crop cycle

[5]$GI_{R\ 48\ h}$ = twice the maximum daily gross irrigation requirement of the crop cycle, to be applied in 48 h.

In the third scenario, q_u values were notably lower than in the first and fourth scenarios and higher than in scenario two, because the maximum daily gross irrigation requirement ($GI_{R\ maximum}$) projected at 48 h was higher than the maximum accumulated in 48 h of the month of maximum demand; the greatest differences were observed in asparagus, strawberry, walnut, grapevine, and corn (forage and grain), in a range of 54 to 155 %.

Hydraulic behavior of shift-based distribution

In the first operating scenario, the flow rates delivered to the section 01 inlet were very diverse (Figure 2). Irrigation shifts one to five did not show large fluctuations, but from shift six onwards, there were several relative minimum and maximum values. This hydraulic response of scenario one is largely due to the fact that the emitters currently used in the ID have a higher flow rate than those considered in the original project; consequently, they apply the irrigation demand in less time at the cost of higher flow rates in the conduction, which were not contemplated in the currently installed pipes.

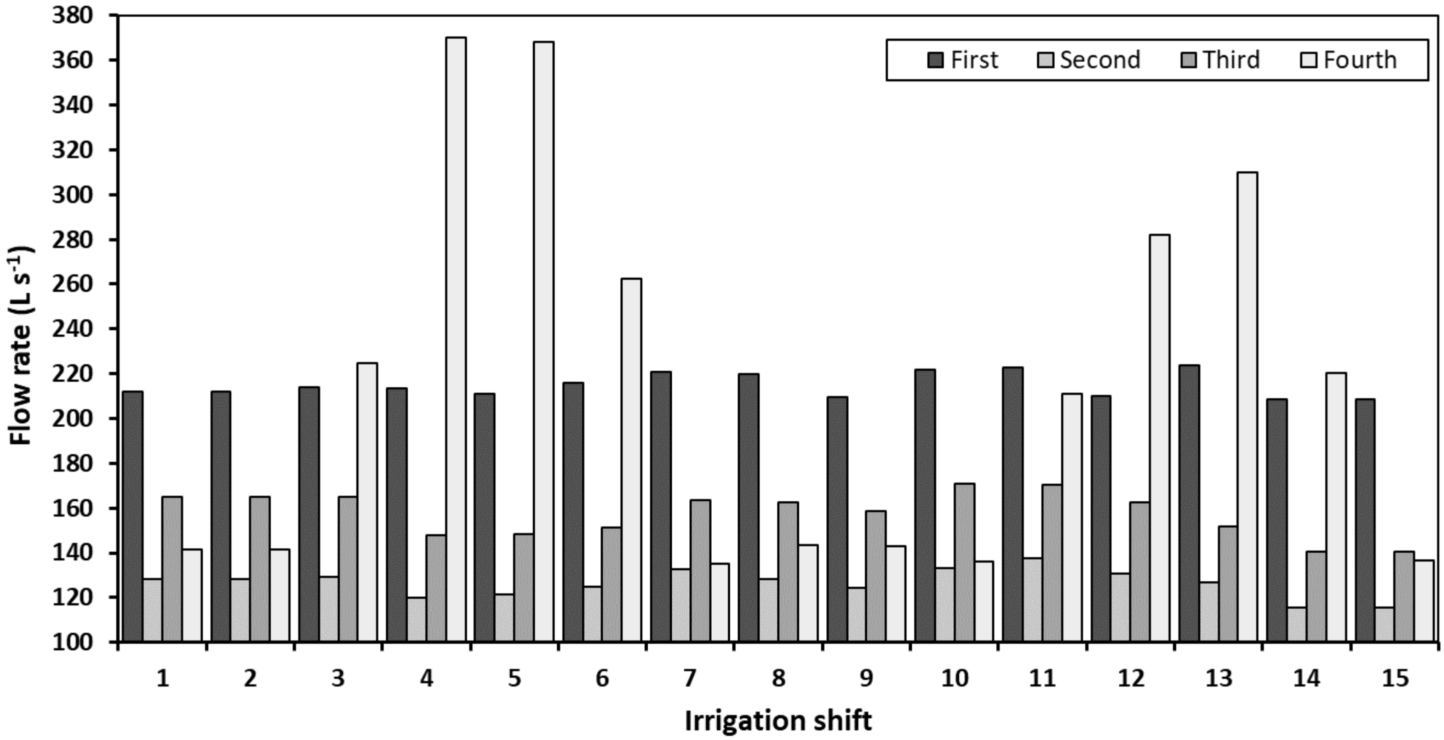

Figure 2. Flow rate behavior at the section 01 inlet, from the first to the fourth operating scenario.

In the second operating scenario, the flow rates at the section 01 inlet also fluctuated as in the first scenario, but with fewer minimum and maximum peaks (Figure 2). The adjustment of the emitter flow rates reduced those delivered at the section 01 network inlet by up to 45 % on average, compared to the first operating scenario; therefore, a better behavior was expected in scenario two than in scenario one, with lower velocities and energy losses due to friction in the conduction segments (Table 3).

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Table 3. Hydraulic behavior of section 01 in the shift-based operating scenarios.

Comparative variable	Scenario			
	1	**2**	**3**	**4**
Hydrants with pressure ≥2.5 (kg cm^{-2})	99	123	122	58
Hydrants with pressure ≥1.5 and < 2.5 (kg cm^{-2})	18	3	4	18
Hydrants with pressure < 1.5 and ≥ 0 (kg cm^{-2})	8	0	0	33
Hydrants with pressure < 0 (kg cm^{-2})	1	0	0	17
Maximum flow rate at section inlet (L s^{-1})	223.73	137.59	170.70	370.36
Minimum flow rate at section inlet (L s^{-1})	208.36	115.46	140.64	135.10
Flow rate fluctuation at section inlet (L s^{-1})	15.37	22.13	30.06	235.26
Minimum pressure at section inlet (kg cm^{-2})	5.17	5.19	5.20	5.19
Maximum pressure at section inlet (kg cm^{-2})	5.14	5.17	5.13	5.09
Maximum velocity (m s^{-1})	2.89	1.64	1.76	4.15
Maximum energy loss (kg cm^{-2})	2.22	0.69	0.77	2.22

In the third operating scenario, flow rates followed a similar trend as in the second scenario (Figure 2). Similarly to the second scenario, in this scenario the emitter flow rate had a positive influence, despite the fact that the crops demanded more water, increasing the flow rates in the network segments; only five hydrants did not receive the minimum operating pressure (Table 3).

In the fourth scenario, flow rates and pressures at the section 01 inlet varied, with a different behavior from scenarios one to three (Figure

2), due to the fact that users currently irrigate without prior notice, a situation that adversely affects the performance of the hydraulic network. The increase in the number of hydrants that do not receive the minimum operating pressure with respect to the first scenario is notable, which shows that not respecting the assigned irrigation shift has an unfavorable impact on the network's performance (Table 3).

Table 3 shows a summary of the hydraulic response of the Section 01 network to operating scenarios one to four. It highlights the importance of respecting the assigned irrigation shift and adjusting the flow rate of the emitters, where scenario two was the most favorable and scenario four the least favorable.

Hydraulic behavior of on-demand distribution

In scenarios five, six and seven, flow rates remained constant at the section 01 inlet during irrigation (Table 4), increasing from 40 to 100 %, compared to operating scenarios one to three. No appreciable differences were observed in the behavior of scenarios five and six with respect to those of the daytime shifts of scenario four. The water pressure was 5 kg cm^{-2} at the connection point of the section 01 network with the main line, during the 12 h.

Table 4. Hydraulic behavior of section 01 in the on-demand operating scenarios (supply guarantees).

Hydraulic characteristics	Scenario 5 (p = 90 %)	Scenario 6 (p = 95 %)	Scenario 7 (p = 99 %)
Hydrants with pressure ≥ 2.5 (kg cm^{-2})	31	27	23
Hydrants with pressure ≥ 1.5 and <2.5 (kg cm^{-2})	22	20	19
Hydrants with pressure < 1.5 and ≥ 0 (kg cm^{-2})	28	25	13
Hydrants with pressure < 0 (kg cm^{-2})	45	54	71
Flow rate at section inlet (L s^{-1})	355.48	371.94	402.82
Maximum velocity (m s^{-1})	4.08	4.37	4.92
Minimum velocity (m s^{-1})	0.26	0.30	0.38
Loss due to maximum friction (m)	16.97	19.28	26.75

Increases in flow rates resulted in higher energy losses in the conduction, substantially reducing the number of hydrants with the required operating pressure. These results contrast sharply with those obtained in the irrigation shift operating scenarios. Even scenario five, the one with the lowest probability of supply (90 %), significantly surpassed scenario four (hybrid operation) in the number of hydrants with negative pressures. Indeed, Fouial, Lamaddalena and Rodríguez (2020) found that when the simultaneity of hydrants' opening is high (62 %), there is a pressure deficit in some hydrants and a reduction in delivered volume of up to 19.0 % on the day of maximum demand. From the fifth to the seventh scenario, velocities that exceed the maximum allowable water velocity (2.5 m s^{-1}) were presented, which could favor pipe breakage due to the possible presence of water hammer, since its maximum allowable pressure is 5.0 kg cm^{-2}.

Discussion

Of the seven scenarios that were simulated with the current cropping pattern, the second scenario was the most favorable in the hydraulic performance of the section 01 network, with the third scenario being the second best. The on-demand scenarios presented more difficulties than the irrigation shift scenarios since there are few hydrants that satisfy the operating pressures. To operate in a mixed (shift and on-demand) or only on-demand manner, pressures greater than 5.0 kg cm^{-2} are required at the section 01 inlet. This requirement would require releasing pressure in the PRVs of the dead-leg segment of the main pipe and section 01, by adjusting their current calibration values. However, this would imply replacing some segments of the existing pipe with another pipe capable of working at higher pressures, since the transients caused by the random opening and closing of hydrants could generate excessive pressures in some segments and hydrants (Derardja, Lamaddalena, & Fratino, 2019).

For the implementation of the water rights transfer alternative, it is advisable to conduct an analysis of the hydraulic behavior of the network before approving the change, since its response depends on several aspects, in addition to those addressed here, such as water management and rehabilitation (Fouial & Rodríguez, 2021). Pressure exceedance generated by random hydrant openings and closings should be taken into account because it can cause damage to the infrastructure and interrupt irrigation service (Derardja *et al.*, 2019). In this study, it was observed that the transfer generated an increase in conduction velocities and energy losses due to friction. The unforeseen changes mentioned above and a change in the cropping pattern can generate a low irrigation application uniformity level (Khadra, Lamaddalena, & Inoubli, 2013). To irrigate with greater flexibility or on demand in section 01, without being affected by the transfer of water rights, the pipe diameters would have to be changed, which would be costly (Lapo, Pérez, Aliod, & Martínez, 2020; Calejo, Lamaddalena, Teixeira, & Pereira, 2008) and not very operationally sound because its implementation would interrupt irrigation. The best alternative would be to opt for an optimal shift-based arrangement with emitters that allow all hydrants to receive the minimum required pressure (Lapo *et al.*, 2020).

Another task that still needs to be undertaken is to analyze the joint hydraulic performance of the main piping network and the conduction networks of the ID 001 irrigation system's various sections, including a cost analysis since in on-demand irrigation it has been observed that despite the fact that there is greater variability of flow rates in the terminal segments of a network than in the main pipe, changing diameters in the latter is more expensive (Alduán & Monserrat, 2009). In this study and others (Monserrat, Poch, Colomer, & Mora, 2004; Íñiguez *et al.*, 2007), it was observed that Clément's method could be a good alternative to design irrigation systems because it adequately represents the statistical behavior of irrigation users, except in one or two months of the year where it can be better represented by another type of probabilistic distribution (Pérez-Sánchez, Carrero, Sánchez-Romero, & López-Jiménez, 2018), providing different degrees of flexibility in the irrigation service; however, this alternative requires systems with greater conduction capacity and a high initial investment, but, in the long term, operating costs can be significantly reduced (Espinosa, Flores, Ascencio, & Carrillo, 2016).

Conclusions

The current section 01 network does not have the hydraulic capacity to operate with an on-demand or mixed irrigation (shift and on demand) because the hydrants would not receive the irrigation service, due to increased flow rates and energy losses in the network segments. An on-demand operation would require a modification of the calibration pressures of the pressure regulating valves of the dead-leg segment of the main pipe and of section 01, connection of segments in closed circuits, and the replacement of pipes with higher working pressure in multiple segments, so a strict shift-based demand system is the best alternative. The current irrigation conditions, represented by the first shift-based operating scenario, are unfavorable since 21.4 % of the hydrants in the study section would not receive the required operating pressure. The most favorable irrigation shift operation would imply reducing the flow rates of the currently used emitters and that the duration of the irrigation applications be the same as the duration of the irrigation shifts currently established by the ACU (scenarios 2 and 3), thus reducing to less than 3.2 % the number of hydrants without the required operating pressure.

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