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Methodology for flushing pressurised irrigation networks for fertigation and operation maintenance purposes

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Abstract
Pressurised irrigation networks with a certain degree of automation allow centralized fertigation and maintenance operations such as cleaning subunits and preventing the proliferation of invasive species such as zebra mussels. Until now, there is no methodology that guarantees the total cleaning of the network of a substance in the shortest possible time. In the same way, it does not exist to guarantee reaching all consumption points with a certain concentration of a substance, injecting the minimum possible amount. For that purpose, a general novel methodology has been developed that makes use of the network's hydraulic model and parallel multi-objective genetic algorithms to flush the network of a certain substance or to get it to all consumption points in the shortest possible time and supplying a minimum volume. This method assumes that the available pressure at the source is always over a minimum value. The arrival times to the consumption points are minimized and the injected volume is reduced to the minimum of replacement, that is, the volume of the network pipes. The methodology applied to the study case allowed the entire network to be flushed in a minimum time of 2.46 h. On a normal irrigation day, without making any changes to the irrigation schedule the time to completely flush the network is 11.76 h. Furthermore, the injected volume differs greatly from the total volume of the pipes.

Introduction

Chemigation refers to the application of chemicals such as fertilizers, insecticides, pesticides, fumigants, nematicides, soil amendments, and other compounds through irrigation water (Burt 1998).

Particularly, of the various types of chemigation, the most widely used is fertigation (Fares et al. 2009). This is widely used in micro-irrigation techniques such as drip and sprinkler where fertilizer doses can be supplied accurately. Proper management of fertigation can improve nutrient uptake efficiency and minimize leaching below the root zone. Thus, it can contribute to an increase in crop yield as well as crop quality as compared to those with conventional dry fertilizer application (Alva et al. 2008).

Fertilizer distribution has been studied at subunit level due to uniformity which can be affected by injectors, (Bracy et al. 2003; Li et al. 2007; Fan et al. 2017), the emitter type (Li et al. 2007), and the lateral layout (Fan et al. 2017).

Moreover, some decision support systems (DSS) have been developed to design and optimize irrigation management and fertigation systems to improve nutrient uptakes, minimizing percolation and improving fertigation uniformity but all of them focused at irrigation subunit level not in collective pressurised irrigation networks (Moreira Barradas et al. 2012; Azad et al. 2018; González Perea et al. 2020).

Collective fertigation in pressurised irrigation networks was assessed by Jimenez-Bello et al. (2011a). Particularly, how fertilizer is distributed along with the network and how irrigation scheduling influences in effective fertilization time (EFT) was analysed. A methodology was proposed to homogenize the EFT in case of the existence of irrigations without fertilization and the presence of users who do not want to receive fertilizers. Similarly, in the case that the supply is energy-dependent, the organization of the most efficient irrigation scheduling from the energy point of view does not have to coincide with the distribution that guarantees a better EFT for each user. For this reason, a methodology was proposed that combines those groups of optimal intakes from the energy point of view with those that allow increasing EFT. The conclusions obtained were

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that the existence of intakes that do not wish to carry out fertilization decrease the uniformity of EFT and, therefore, do not assure any fertilizers reaching them.

Collective fertigation is widely used in Water Users Associations in the Mediterranean Region where the average plot size is small (0.4–1 ha) and monocrop is dominant (Ortega-Reig et al. 2017). However, the introduction of new crops in the irrigation districts poses new challenges when it comes to efficient management, since not all of the crops have the same fertilizer needs, nor do they apply the same treatments. Another important challenge to address is the possible presence of organic crops in the network. This involves flushing the network as quickly as possible of the remaining substances to adapt irrigation water chemical composition to the needs of the crops that are irrigated at a certain moment.

Similarly, carrying out maintenance operations, such as cleaning subunits to avoid emitter clogging (Keller and Bliesner 1990), involves injecting nitric, phosphoric, sulphuric or hydrochloric acid, whose pH must be 2–3 to achieve a good result. A reference is to inject 6 l m^{-3} of acid, so it is interesting to minimize the used amount to lower the cleaning cost (CAJAMAR 2014).

Another frequent operation in irrigation networks is the use of disinfectants for the removal of zebra mussels (*Dreissena polymorpha*). This aquatic invasive alien species has caused severe worldwide economic damage by blocking pipelines and other infrastructure, impacts on water quality, and eradication costs (Aldridge et al. 2004; Gallardo and Aldridge 2020). In the Ebro Valley Basin (Spain), Zebra Mussel has caused damages worth 1600 M€ in 10 years (Morales-Hernández et al. 2018).

Physical and chemical control methods are used to combat the zebra mussel (Ebro Hydrographic Confederation 2014). Chemical methods can be used preventively when the larvae enter the facilities, or reactive, in which case the chosen strategy will depend on the degree of colonization to determine the dosage of the product and the exposure time. Used substances are oxidants such as chlorides and ozone that react with the medium, the latter at a higher speed; and non-oxidants such as aluminum sulfate, ammonium nitrate, sodium metasulfite, copper sulfate and Potassium. These substances can be assumed not to react with the medium.

Morales-Hernández et al. (2018) developed a model to assess the presence of zebra mussels comparing the measured pressures with modelled pressures at the hydrant.

Nevertheless, so far no methodology has been created to assess how to perform the above-mentioned tasks of flushing the network to apply different fertigation treatments, irrigation subunits cleaning, or combating invasive alien species.

In this work, a novel methodology is presented that allows to minimize the network flushing time, or what is the same, to make a substance arrive as quickly as possible at all consumption points to allow the application of different chemigation treatments, at the same time that the minimum operating pressures are guaranteed at demand nodes. In the case a substance is requested for treatment, its amount can be minimized because of the pipe-volume replaced is the minimum required and no water is wasted. The methodology takes into account that the pressure at the head of the network is constant or does not decrease under a certain value.

Methodology

Case study

The case study chosen is Sector XI of the Acequia Real del Júcar (ARJ), a historic irrigation district where a modernization process is being taken (Ortega-Reig et al. 2017). Sector XI is located in the municipality of Algemesí (Valencia, Spain). It is a collective network of 88 multi-user hydrants, with 565 intakes with automated opening valves, 14.9 km of pipes, which total volume is 607 m^3, and 434 ha of irrigated farms where 60% are persimmons, 27% citrus and the remaining area is cropped with other types of fruit trees. Each fruit tree farm has assigned an average amount of 4050 m^3 ha^{-1}. The irrigation head is at a height of 28.14 m and the levels of the hydrants vary between 21.12 and 32.6 m.

Figure 1 shows the layout of the hydraulic network.

The supply is made through a general high-pressure network that delivers water to another 90 irrigation heads that compose ARJ. Of these, currently, only 36 have completed the modernization process under pressure irrigation, which represents 22% of the 15,000 ha of which the ARJ is composed of. The rest continue operating using surface irrigation (Ortega-Reig et al. 2017). The regulation of the general network guarantees that the head pressure does not exceed 43 m, while the minimum pressure is not guaranteed. In the period of greatest water requirements, the intakes operate three times a day, in periods of 1 h. Farmers make the water request for each season and the technicians arrange the opening sequence of the intakes that is empirically distributed throughout the day to reduce head losses in the distribution network and provide the service with the minimum pressures required in each hydrant, 20 m. So far, the injected fertilizer is the same for all the orchards. The concentration is 0.1% in volume from March to June and 0.04% in volume from July to October. Proportional flow pumps perform the fertilizer injection. As reference, 133 kg ha^{-1} of N are applied per ha.

The technicians want the possibility of establishing different fertilization programs flushing previously the network, having the possibility to alternate zebra mussel proliferation prevention treatments and carry out maintenance operations to avoid clogging emitters.

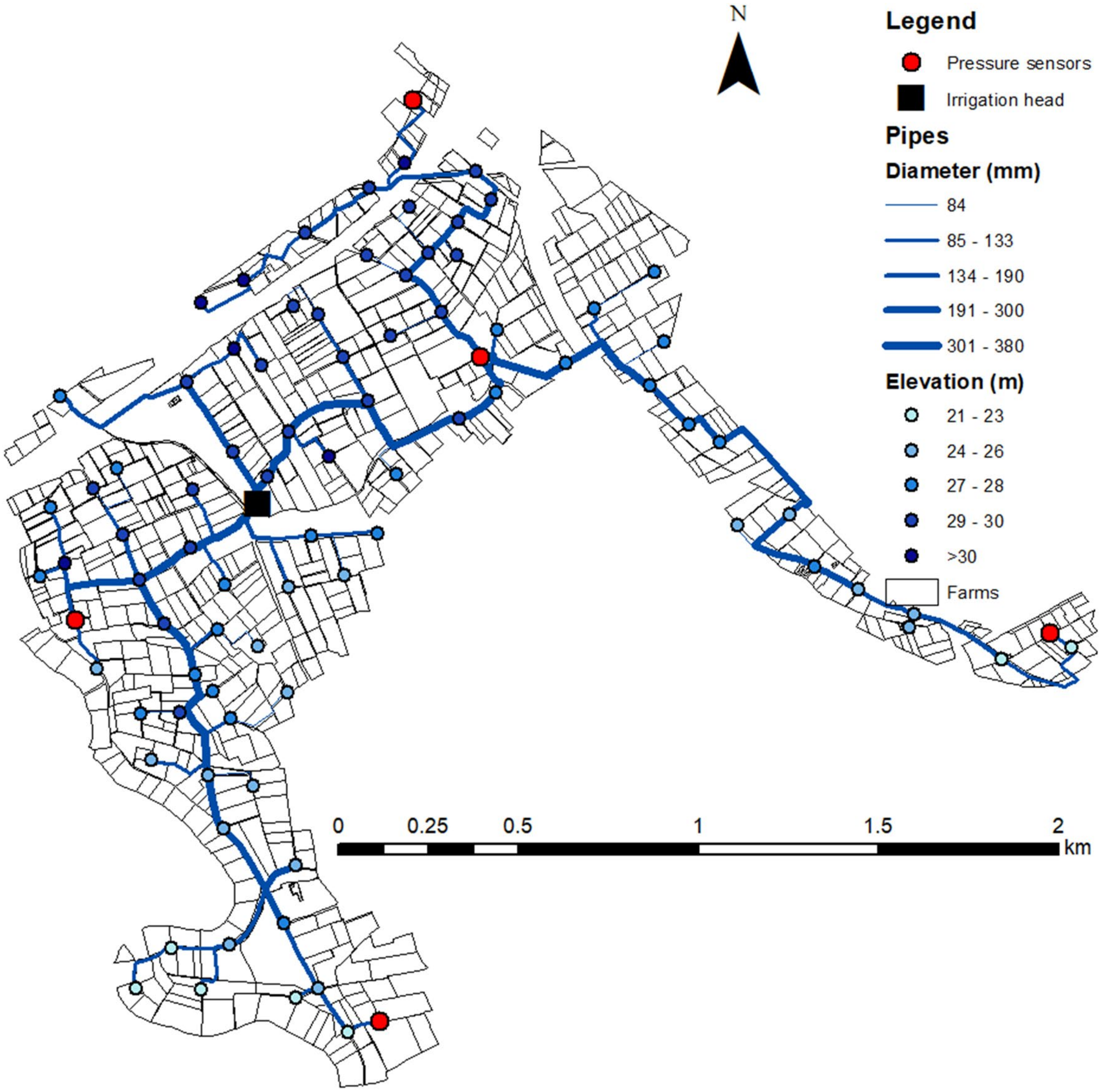

Fig. 1 Layout of the irrigation network of Sector XI of the Acequia Real del Júcar

Model calibration

Once the hydraulic network model was built for simulation in EPANET (Rossman 2000) it was calibrated. This software performs extended period simulations of hydraulic behavior and water quality in pressurized networks and today is the main reference in this field (Iglesias-Rey et al. 2017). To do this, five pressure sensors were installed (SSC2035 Sensortechnics, Puchheim, Germany) with a data collection frequency of 2 min. In the irrigation head, there was a sensor that measured pressure with a 1-min frequency. The location of the sensors is shown in Fig. 1.

Comparing the real pressure measurements with the simulated ones, after slightly correcting the sensor elevations, the mean square error was 0.711 m and 0.709 m for the two dates when the calibration was carried out (11/08/2019 and 08/12/2019). It was not necessary to modify any initial parameters such as roughness or pipe diameters.

Figure 2 shows the mean, maximum, minimum pressures and the 12-day standard deviation during the irrigation campaign (1/8/2019–12/8/2019) recorded at the head. The pressure variations in the main network are due to the opening of intakes in the different irrigation networks of which the ARJ is composed and the discharge into the canals at the atmospheric pressure of the infrastructures that continue to operate by gravity.

The EPANET quality model was not tested experimentally in this work. Good performance was assumed from the results obtained in previous work (Jimenez-Bello et al. 2011b) where the measured arrival times of phosphoric acid

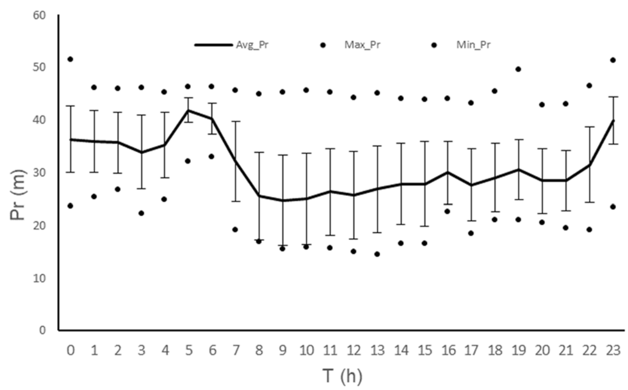

Fig. 2 Average pressures (Avg_Pr), standard deviation and maximum (Max_Pr) and minimum (Min_Pr) pressures for the period from 1/8/2019 to 8/12/2019

injected at the head to the consumption nodes had an error lower than 1 min, less than hydraulic time step set to 60 s. Mass imbalances have been detected in EPANET water-quality simulations due to discretization problems when the distance travelled by the water in a quality time step is greater than the total length of the pipe (Davis et al. 2018). These authors recommend to diminish the water-quality time step to reduce the inaccuracies from the current default value of 300 s. In this work, a water-quality time step of 12 s was set.

Methodology assuming that pressure at the irrigation head is constant

Assuming that head pressure is constant, or that it will not decrease below a reference value, a methodology has been proposed that uses the hydraulic model with Non-dominated Sorting Genetic Algorithm II (NSGA-II), a parallel multi-objective genetic algorithm (Deb et al. 2002) that has demonstrated faster convergence in comparison to similar algorithms.

Genetic algorithms have been widely used for irrigation network design (Reca and Martínez 2006; Fernández García et al. 2017) and energy optimization (Fernández García et al., 2013; Jiménez-Bello et al., 2015; Jiménez-Bello et al. 2010, 2011b).

Particularly Alonso Campos et al. (2020) used NSGA-II for minimizing the cost of energy while minimizing pressure deficit at the critical hydrants obtaining greater computational efficiency by posing the problem from a multi-objective approach and by establishing the parallel evaluation of the objective function.

To perform a renewal of the network water, the hydrant valves must be gradually opened to allow the water to advance towards them. It is admitted that the network is branched, and all branches and final branches end in a hydrant, otherwise, the water in that branch could not be renewed. When the new water reaches a certain hydrant, we will assume that it closes immediately to avoid waste of water with a certain substance, since the objective is to retain the water with that substance for a time so that it exerts its action.

On the other hand, if we were to open all the hydrants at the same time, we would collapse the network, which is not prepared to assume that flow, and the pressures would be below the minimum value required by the hydrants for the flow rates discharged, which are supposed to be fixed and known. Therefore, the hydrants must be opened gradually, and closed as before, when the substances reach them.

The problem that arises is at what time each hydrant has to open and at what time has to close, to carry out the renewal of all the water in the network in a minimum time, with the restriction of complying with certain pressures minimum, and limit the maximum flow velocity through any pipe. If everything is carried out correctly, and the hydrants close when the new water arrives, it is obvious that the entire volume of the network will have been renewed, so that the volume of water injected at the head will be equal to the volume of the pipes.

The hypothesis on which it is based the methodology is that the more intakes which operate, the higher the velocity in pipes, and the sooner the consumption nodes will be reached. The minimum required injected volume (V_{Tot}) to completely flush the network is the total pipe volume. It is assumed that all or part of the intakes from the same hydrant work at the same time and minimum pressure operation at the head is guaranteed.

The methodology consists of n steps until the substance achieves all the consumption nodes. Basically, a front of the water with substance is advancing through the network from head step by step. Each time the front reaches an open hydrant, the current step is ended, and the next step starts. Each step involves the following phases:

1. Maximizing the flow at the irrigation head, while minimizing the average pressure deficit at hydrant (APD) for an optimization process step:

$$\mathrm{Max}\left(Q_t\right) = \sum_{i=1}^{N_{\mathrm{H},n}} q_{i,n} \tag{1}$$

$$\mathrm{Min(APD)} = \frac{1}{N_{\mathrm{H},n}} \sum_{i=1}^{i=N_{\mathrm{H},n}} \mathrm{Max}\left\{\left(p_{\mathrm{min\_req},n} - p_{\mathrm{min\_calc},n}\right)\right\}, \tag{2}$$

where Q_t is the flow sum, $N_{\mathrm{H},n}$ are the total number of hydrants that operates at process step n, $q_{i,n}$ is hydrant flow determined by the intakes number that operate at n, $p_{\mathrm{min\_req},n}$ is the minimum required pressure at hydrant and $p_{\mathrm{min\_calc},n}$

is the minimum computed pressured, but only regarding if hydrant flow is higher than 0.

At first step $n=0$ and all hydrants are able to be selected, but at step n only a reduced set of hydrants can be operated, those that remains to be opened. For this purpose, a genetic algorithm is built in which the number of variables is equal to the number of hydrants in the network. These are coded as integer variables and the value ranges are 0 or 1.

$$H_{i,n} = \{0, 1\}, \tag{3}$$

where $H_{i,n}$ are the values of the variable i for n. The value 0 means that the hydrant intakes are opened and value 1 that they are closed. An INP file, the native standard format for EPANET (Rossman 2000), is used as a template. The performed hydraulic simulation is static and pipe flows and node pressures are determined for each scenario.

The justification for maintaining the minimum required pressures in the flushing operation is to guarantee the perfect operation of the irrigation subunits and to keep their flows constant and predictable.

The parameters regarding the GA, initial population, termination condition, selection type, crossover type and mutation probability are set.

2. Once the solution is selected, for which Q_t maximizes and APD minimizes, the arrival time (TH_n) of the injected substance at the first hydrant or hydrants where intakes operate is determined.

For this purpose, an INP template is used where a quality dynamic analysis is performed starting from the beginning. When the substance reaches the first hydrants the simulation stops. Sometimes more than one hydrant can be reached simultaneously. Then those hydrants where $H_{i,n}=0$ changes to $H_{i,n+1}=1$, that is to say, that when the substance reaches the first operating hydrants, they are shut and TH_n becomes the arrival time to them. $n+1$ is the next quality simulation where TH_{n+1} will be calculated. For $n+1$, time patterns for these hydrants will be built where operating time will be set from the step time n when they were opened to TH_{n+1}.

Those operating hydrants where substance have not reached yet, continue working ($H_{i,n+1}=0$).

3. To determine the new operating hydrants, the GA is used again to maximize Q_t and minimize APD. GA is restarted incorporating the solution from the previous stage into the initial population, to speed up the process for the best solution. In short, those hydrants to which the substance reached, the variable value is 1, those that were operating and substance did not reach them, the value remains 0 and those that were not operating can take the value 0 or 1 according to the GA procedure. The process is repeated until the substance reaches all hydrants. At the end of the process, the GA and the quality simulation model will be run as many times as the substance reaches operating hydrants. The theoretical maximum number of steps (n) will be the NH, although some of them can be reached at the same time.

Figure 3 summarizes the process method to reach at all operating nodes guaranteeing the minimum injected volume, the total pipe volume.

Studied scenarios

First, the operation of the irrigation network has been evaluated in one of the representative days in the periods of highest demand, such as the first week of August. For this and for the rest of the studied scenarios, the total volume (V_T), the APD, the average arrival time of substance per hydrant ($T_{\mathrm{H\ M}}$), the minimum arrival time ($T_{\mathrm{H\ Min}}$), the maximum arrival time ($T_{\mathrm{H\ Max}}$) and the minimum operation time an intake remains open ($T_{\mathrm{Irrig\ Min}}$) were assessed. The minimum required pressure set at hydrant (P_{Min}), was 20 m.

The purpose of the scenarios was to study the flushing time and the flow velocity in the pipes to avoid unwanted transient phenomena. In these scenarios, the fixed pressure established in the network head has been the daily hourly average, 31 m.

Injection of substances into the network was simulated using the option *Source Quality* of the node that represents the irrigation head. Since the injection device is a pump that keeps a constant concentration of fertilizer, the option *Flow Paced Booster* was used as it is recommended to model direct injection of a substance into the network (Rossman 2000). A pattern curve simulating the beginning and ending of substance injection formed and assigned to the irrigation head.

Prior to simulation, quality (Q_{TS}) and hydraulic time step (H_{TS}) were set up (Rossman 2000). The accuracy of the results depends on these parameters. The former has to be much smaller than the latter, at least a fifth (Davis et al. 2018). For most of the scenarios, Q_{TS} has been set to 12 s and H_{TS} to 60 s. Then, to assess the sensitivity of these parameters scenarios with other Q_{TS} and H_{TS} have been run.

Scenarios were defined according to the intake number of each hydrant that works at the same time, adjusting the flow rate as close as possible to 75, 50, 25, and 15% of the total flow rate of each hydrant (q%). For all scenarios, the initial population is 100 chromosomes. The population size has to be kept as low as possible, provided that it allows to effectively explore the search space. It could be considered a rule of thumb to choose a number of chromosomes of the same magnitude order as the number of variables.

In both methodologies, the intakes of the same hydrant have been assumed to operate at the same time. The probability of mutation has been established at 10%, the selected crossing method has been the "SinglePointCrossover" and the selection method has been "BinaryTourment2" (Durillo and Nebro 2011).

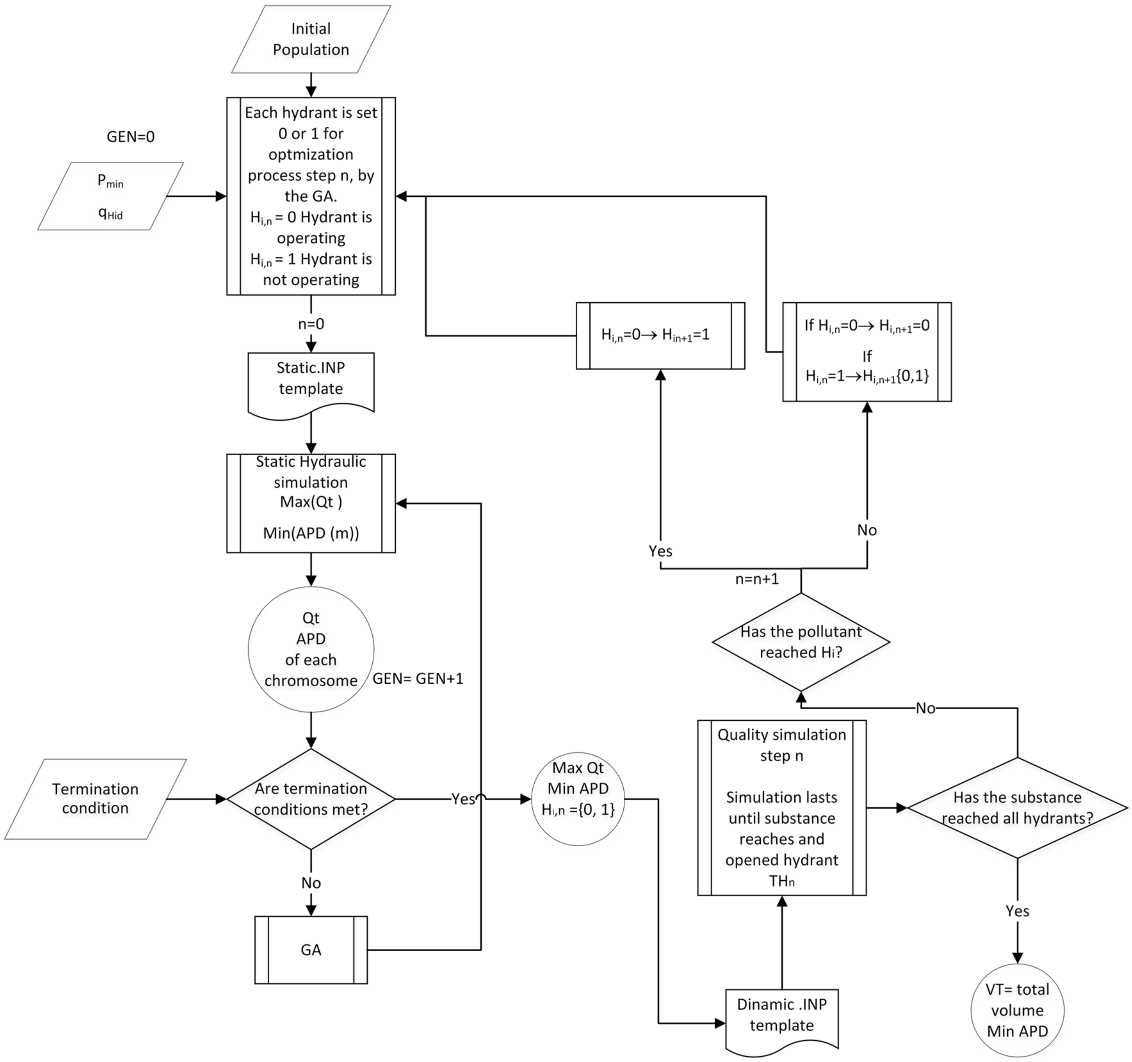

Fig. 3 Flow process to determine the hydrant operating scheduling to minimize the arrival times of a substance

Results and discussion

Analysis of the network operation on an irrigation day

The evolution of the injected flow and the pressure at the head for an irrigation day is showed in Fig. 4. The average operating time of each intake is 3.1 h. The total volume provided is 7803 m^3, and the observed times are $T_{\mathrm{H\,M}}=3.15$ h, $T_{\mathrm{H\,MIN}}=0.33$ h and $T_{\mathrm{H\,MAX}}=11.76$ h. Two of the hydrants in an extreme branch do not receive any amount of substance within 24 h. A total of 317 intakes operate below $P_{\mathrm{Min.}}$ APD is 2.45 m. This is due to the difficulty of arranging irrigation scheduling to minimize head losses without a network model, especially when the pressure at the head is variable. This could be solved by applying methodologies such as those developed in Jiménez-Bello et al. (2010) and Alonso

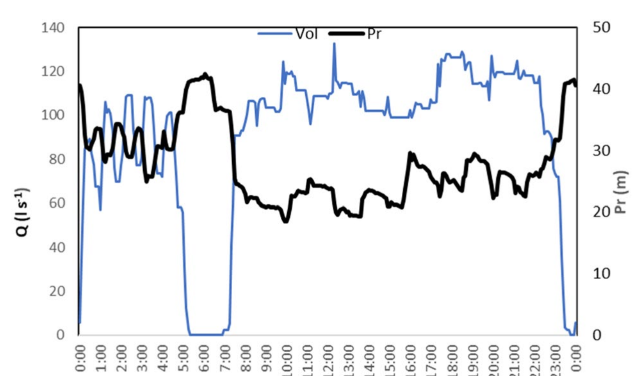

Fig. 4 Head flow (Q, l s^{-1}) and pressure (Pr, m) for an irrigation day of maximum water requirements

Campos et al. (2020) where scheduling is arranged in such a way that the total energy consumption is minimized by means of heuristic methods and the mathematic network model, while a minimum required pressure is guaranteed at each node.

Scenario analysis

The scenario results are shown in Table 1. For all scenarios, the substance reaches all network hydrants. The injected volume for all scenarios coincides with the total volume of the network pipes, 607 m^3. Comparing this volume to the injected on a normal day, 7803 m^3, a reduction of 92.2% is achieved, in the event that the technicians would inject a substance or wanted to flush the network without modifying the irrigation scheduling.

Nevertheless, in case H_{TS} is set to 300 s, the injected volume is 693 m^3. This is because H_{TS} is not small enough to close intakes, at the real time the substance reaches them.

When $Q\% = 100$, as N_{Ev} increases, APD decreases, while $T_{H\,M}$ and $T_{H\,Max}$ remain almost unchanged. In addition, the time it takes to flush the network is reduced by 0.02 h, comparing SC2 to 7 (from 2.48 h 2.46 h). This is due to the nature of the genetic algorithm, which by performing more evaluations finds a greater number of hydrant intakes that can operate simultaneously. The higher the evaluated solutions, the better the results, but in this case, it only affects a small amount of APD. This is mainly due to a 320 m branch where head losses of 40 m km^{-1} occur when hydrants operate at $Q\% = 100$.

For scenario 5, the network flushing time is completed in 2.46 h, although $T_{H\,M}$ is 0.27 h. Compared to scenario 1, the length process is reduced by 79%. The presence of ending branches with low flows produces an increase in the flushing length process. Figure 5 shows the evolution of the network head flows for SC5, and SC8-11. As observed, the methodology concentrates the operation of the hydrant intakes at the beginning and then decreases as the substance reaches the hydrants and the intakes shut.

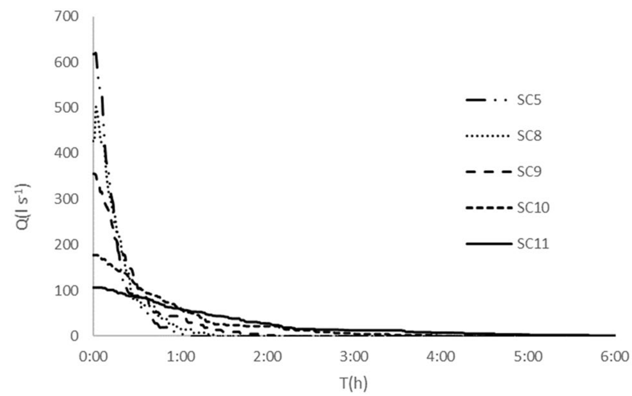

Fig. 5 Evolution of the injected flow at the irrigation head for the scenarios 5 and 8–11

This produces high velocities at the network main of 5.6 m s^{-1}, where the initial flow is 643.84 l s^{-1} (see Fig. 5) and the pipe diameter is 380.4 mm, which can cause excessive pressure variations when changing the network operation regime, especially at the beginning of the flushing maneuver. Furthermore, it involves opening a large number of intakes in a very small time, 1 min, an unadvisable maneuver in opening valves due to the short duration. For example, the technicians of the case study recommend a minimum operation of 5 min for avoiding unexpected transient phenomena.

Figure 6 shows the evolution of the water injected with a certain substance from the source, in this case for scenario 5. The red pipes indicate that the water with substance (or with clean water) has not yet been reached. Once the

Table 1 Optimal scenarios based on the number of evaluations (N_{EV}) and the percentage of the operating intakes

SC	N_{Ev}	Q (%)	$T_{H\,M\,(h)}$	$T_{H\,Min\,(h)}$	$T_{H\,Max(h)}$	APD (m)	$T_{Irrig\,Min(h)}$
1	–	100	3.15	0.5	11.76	2.45	1
2	500	100	0.28	0.016	2.48	1	0.033
3	1000	100	0.28	0.016	2.48	0.79	0.0166
4	5000	100	0.27	0.016	2.46	0.73	0.033
5	10,000	100	0.27	0.016	2.46	0.89	0.033
6	20,000	100	0.27	0.016	2.46	0.64	0.033
7	50,000	100	0.27	0.016	2.46	0.32	0.033
8	10,000	75	0.36	0.016	3.25	0.05	0.033
9	10,000	50	0.52	0.016	4.92	0	0.066
10	10,000	25	0.52	0.016	9.83	0	0.083
11	10,000	15	1.72	0.016	16.4	0	0.083

For each one, the average arrival time in the network hydrants ($T_{H\,M}$), the minimum time ($T_{H\,Min}$), the maximum time ($T_{H\,Max}$), the deficit in hydrant pressure (APD) and the minimum operation time an intake remains open ($T_{H\,Min}$)

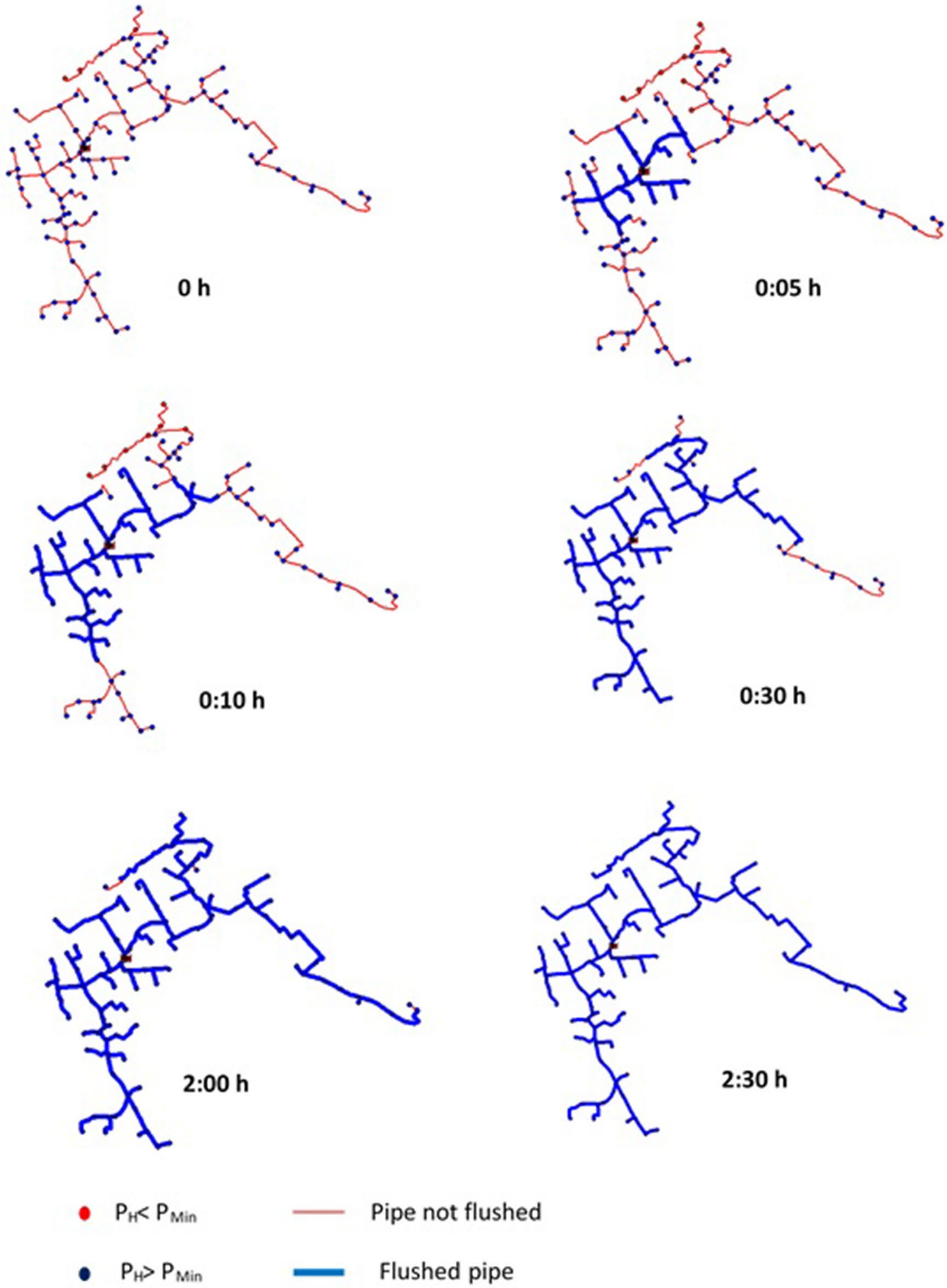

Fig. 6 Evolution of the injected substance front from the network head to the consumption points. The red color of the pipes indicates that the substance has not yet arrived and the red color that it has. Hydrants in red indicate that the pressure is less than required and in blue greater than required (Color figure online)

water reaches the pipes, they turn blue. The dots represent the hydrants. The red color indicates that the hydrant operates below the established minimum pressure. The black color indicates that the hydrant operates above the minimum operating pressure. It is observed that when the substances reaches most of the hydrants pressure is higher than required due to APD is very low, 0.89 m.

The substance front advances rapidly, mainly through the higher flow pipes. The extreme branches and with low flows are those that slow down the process of flushing the network, conditioned by the distance from the injection source.

In SC 8-11, in which the number of intakes operating at the same time in each hydrant has been reduced to avoid high velocities in main pipes, the arrival times increase is observed. These scenarios are more convenient to reach all the hydrants with lower pipe velocities, but taking longer. For SC 11 the maximum flow velocity reached is 0.96 m s^{-1}. In the case of applying treatments with a reactive substance with an average reaction time superior to the arrival time, to guarantee the initial concentration at the head reaches the consumption points, these solutions would be more convenient to reduce the transient effects than with Q (%) = 100. In addition, $T_{\mathrm{Irrig\ Min}}$ increases up to 5 min.

Nevertheless, the model can be applied to reactive substances. To know the final substance concentration achieving a node, the reactions model quality options should be implemented (Rossman 2000).

The method can be applied to any kind pressurised branched irrigation network keeping a minimum pressure at the head. In the study case, the network is fed from a general main pipe with a pressure variable supply in time. If the supply were carried out with pumps, these could maintain a certain set pressure in the case of having frequency speed drivers, but this would not be compatible with minimum energy consumption. An economic study of the convenience of this methodology would be necessary, depending on the times in which these network cleaning operations are carried out, the cost of the products, and the energy cost. Nevertheless, further research will be developed to apply similar methodologies to meet the energy consumption and the minimum flushing times.

Conclusions

In automated pressure irrigation networks, certain operations require flushing or injecting a substance through the network, either for fertilizing, cleaning or disinfecting. In any case, it is important that this is carried out in the shortest time possible and using the least amount of injected volume. So far, there is no methodology that guarantees the minimum flushing time of a network, maintaining the operating pressure at the demand nodes.

For this purpose, a methodology was developed that uses the mathematical models of the network together with parallel multi-objective genetic algorithms. The methodology can be used in any system independently of its operation, provided that a minimum pressure is guaranteed. It has been tested in a system fed by one source, but it may be applied to systems with different sources.

The methodology applied to the study case allowed the entire flushing of the network in a minimum time of 2.46 h and just injecting the pipe volumes. This means a 92.2% less injected volume compared to a normal irrigation day (Esc 1) and flushing time reduction of 79% in addition to guaranteeing that the injected substance reaches all consumption points.

Next research will be developed to meet the energy consumption along with flushing goals. The same methodology can be applied as well to determine the best irrigation schedules in order to guide the distribution of fertilizers through the network to avoid it reaches ecological crops while the appropriate doses to the non-ecological crops are provided, in centralized irrigation networks where both types of crops coexist. Finally, as an alternative to genetic algorithms, other deterministic methods based on tracking by events the progress of the substance transported by water will be studied.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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