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Abstract: With the aim of reducing energy consumption and improve water use in pressurised irrigation systems, the methodology for grouping intakes of pressurised irrigation networks into sectors to minimize energy consumption developed by Jimenez Bello et al.(2010a) was modified to allow irrigation intakes to operate the scheduled time according to crop water needs instead of operating in restricted irrigation periods of the same length. Moreover a method was developed to detect the maximum number of intakes that can operate without extra energy in the case the source has enough head to at least feed some of them.
These methods were applied to a Mediterranean irrigation system, where the total cropped area was orchards, mainly citrus. In this case study, water was allocated to two different groups of intakes, one fed by gravity and the other one by pumps. A saving of 36.3 % was achieved, by increasing the total volume supplied by gravity, by decreasing the injection pump head and by improving the pump performance. Therefore all intakes operate just the strict irrigation time at the minimum required pressure.

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Dear Editor:

The work we submit for reviewing to Agricultural Water Management is the fourth manuscript of a serial that deals about energy, water and fertilizer management in pressurized irrigation networks. In the previous ones, a methodology to schedule irrigation intakes in pressurized networks minimizing energy consumption was introduced and validated.

In the present work, this methodology has been extended to apply just the crop water requirements by allowing to operate irrigation intakes the proper irrigation time. Moreover a new method has been deployed to increase the volume applied by gravity.

The methodology has been applied to a real study case that represents a characteristic Mediterranean modernized irrigation district.

The authors belong to several research institutes from the Universitat Politècnica de València (UPV), Spain

Thank you for receiving our work.

Best regards.

Miguel Angel Jimémez Bello

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Cover Letter

We have improved a methodology for energy saving in irrigation networks. Intakes are scheduled just the required irrigation time. We have developed a methodology to increase the volume delivered by gravity. Energy consumption decreased after methodology was applied.

Methodology to improve water and energy use by proper irrigation scheduling in pressurized networks

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Abstract

With the aim of reducing energy consumption and improve water use in pressurised irrigation systems, the methodology for grouping intakes of pressurised irrigation networks into sectors to minimize energy consumption developed by Jimenez Bello et al.(2010a) was modified to allow irrigation intakes to operate the scheduled time according to crop water needs instead of operating in restricted irrigation periods of the same length. Moreover a method was developed to detect the maximum number of intakes that can operate without extra energy in the case the source has enough head to at least feed some of them.

These methods were applied to a Mediterranean irrigation system, where the total cropped area was orchards, mainly citrus. In this case study, water was allocated to two different groups of intakes, one fed by gravity and the other one by pumps. A saving of 36.3 % was achieved, by increasing the total volume supplied by gravity, by decreasing the injection pump head and by improving the pump performance. Therefore all intakes operate just the strict irrigation time at the minimum required pressure.

Keywords: Energy saving, Irrigation network; Irrigation scheduling; Water use.

List of abbreviations

$CEVT_p$: Energy consumption per m^3 of pumped water (kWh m^{-3}).

$CEVT_t$: Energy consumption per m^3 of total delivered water (kWh m^{-3}).

CoEVT: Energy cost per m^3 of total delivered water (c€ m^{-3}).

$CoEVT_t$: Energy and power cost per m^3 of total delivered water (c€ m^{-3}).

EDI: energy dependence index. Relation between the pumped volume and the total volume delivered, when some intakes can be supplied by gravity (dimensionless).

FSP: Fixed speed pump.

GA: genetic algorithms.

I_{NOC}: Number of intakes with not enough pressure.

I_{OC}: Number of intakes that operate correctly.

ND: Nominal diameter (mm).

N_{int}: Number of intakes.

PHI: pumping head injected by a pumping station (MPa).

P_{min_Hid}: Minimum required pressure at hydrant (MPa).

T_{Grav}: Time period when water is delivered by gravity (h).

T_{Pump}: Time period when water is delivered by pumps (h).

V_{Grav}: Water volume supplied by gravity (m^3).

$V_{MaxGrav}$: Maximum potential water volume supplied by gravity for a given scenario (m^3).

V_{Pump}: Water volume delivered by pumps (m^3).

VSD: Variable speed driver.

VSP: Variable speed pump.

WHI: Water head at the intake point (m).

WUA: Water users association.

V_{NOC} : Volume supplied by intakes with not enough pressure (m^3).

V_{OC}: Volume supplied by the intakes that operate correctly (m^3).

1 Introduction

The modernization of the irrigation systems in semi-arid regions has increased the water use efficiency, but at the same time there has been a large increase in energy consumption (Jackson et al., 2010; Corominas, 2010) reducing the economic profitability of irrigated agriculture, especially for low price crops. Due to the continuous energy price rising, more attention has been paid to reduce its use. The first group of actions are those carried out during the irrigation system design process. The network layout and pipe size diameter are determined having into account economic criteria (Labye *et al.*, 1988; Lansey and Mays, 1989; Planells et al., 2007 and Theocharis et al., 2006). Previously, base demand for each consumption node is determined according to the crop water requirements for the most demanding water period (Clément and Galand, 1979; Planes et al., 2001; Pulido-Calvo et al., 2003). Since the crop water requirement changes along the irrigation season, the required pumping head and flow discharges change over the season, especially in systems operating on demand (Lamaddalena and Sagardoy, 2000). For this reason the pump set selection and its operation mode by the use of variable speed driver technology (VSD) is a key aspect not only to guarantee the water delivery, but to be efficient in the use of energy. With this aim Planells et al. (2005) developed an algorithm for minimizing the investment and operation costs of pumping stations. They determined the maximum and minimum system head curves and the evolution of demand curves to obtain the maximum discharge needed. Then the number of required pumps and its operation mode, fixed or variable speed, were determined. Moreno et al. (2009) studied how to get the optimal characteristic and efficiency curves at pumping stations and concluded that if the selected pumps fit those curves, the number of variable sped pumps (VSP) did not need to be increased. Lamaddalena and Khila (2013) studied the use of

VSP in on demand pressurised systems. Energy efficiency was achieved matching the discharge and the system curve by regulating the operation of the pumping station on the basis of maximum efficiency.

All these actions were developed for on demand irrigation networks. However, from the operational point of view, when the user's operation is restricted to a given period of time, the required head can be reduced, as well as the energy consumption. To assess how this operating way would improve the energy efficiency, Rodríguez et al. (2009a) studied the potential savings in a case study by simulating the change of the operation system from on-demand to operate by sectors. The irrigation network was divided in two sectors according to a homogeneous elevation criterion. Each of the hydrants from the two performed sector could work freely on the assigned period (12 hours). It was concluded that energy savings could be as high as 27%. Carrillo Cobo et al. (2010) proposed a methodology for sectoring the irrigation network using a topological criteria. Irrigation hydrants were grouped according to their distance and height to the injection point of the network by means of clustering techniques where the number of sectors was fixed beforehand. Each hydrant could operate freely in the period scheduled for its sector. The disadvantage of this sectoring network approach is that it does not ensure optimum performance from the energy point of view. In fact, this approach tends to group nearby hydrants into sectors, thus increasing the head loses in the pipes, making it not suitable for use in undersized or overloaded networks.

Fernandez-Garcia et al. (2013) modified the previous methodology to be used with different water sources. Once sectors were performed, the pumping calendar was established by means of genetic algorithms (GA) with the aim of minimizing a multi-objective function: the energy consumption and the systems failures (the number of hydrants without enough pressure). The decision variables were the number of operating sectors, the pump heads and the number of operational months.

The three last approaches assumed a high constant efficiency of pumping groups (0.75-0.8), but actually efficiency is variable depending on the demand scenario. This approach could lead to choose a solution associated with low pump efficiencies, being not a good solution (Moreno et al., 2010, Jimenez-Bello et al. 2011).

For irrigation networks operating on-turns where users have strictly restricted when to operate, Jimenez Bello et al. (2010a) developed a methodology based on GA and hydraulic models where hydrants or irrigation intakes were grouped in efficient sectors in terms of energy. The goal was to optimise the energy consumption per irrigation event, i.e. reducing the amount of energy used per m^3 of pumped water. As a result, irrigation sectors to minimize energy consumption could be established and, in addition, the minimum head pressure required for proper operation of each irrigation sector was known in advance. The potential saving of the energy consumption per m^3 of water delivered (CEVT, kWh m^{-3}) for the scenario that simulated the actual performing of a study case was 22.3%. Then this methodology was successfully applied in this study case for several campaigns achieving an actual energy saving of 16% (Jimenez Bello et al, 2011). Reasons why not the potential saving was achieved were restrictions in the real operation of the network. Besides central fertigation was performed but not for all users, then the non fertigating-intakes had to operate in the same sector (Jimenez Bello et al, 2010b). Moreover users had the option to shut off their manual valves, making the total demanded flow different to that assumed in the simulations, and then the pumps did not operate with the highest predicted performance.

García- Prats et al. (2012) used another heuristic optimization method, Simulated Annealing, to make sectors with minimum energy consumption. It was coupled with hydraulic models as well. As in the previous study, it was applied to a case study where irrigation was scheduled on strict irrigation turns. Potential savings for this case study were 11.8% and 15.5% compared to the network operating on demand and sectorized using the criterion of hydrant elevation with respect to the pumping station.

Despite these last two approaches reduce energy consumption, it is not ensured that water use is optimal, as occurred in the two aforementioned case studies. Since not all plots have the same crops, they are not in the same phenological stage, and the characteristics of the subunits are different, the theoretical irrigation times will be different. If the same irrigation time was scheduled for all of them, some plots will receive more water than required and other less, resulting in an inefficient water management.

To solve this problem, the methodology developed by Jimenez Bello et al. (2010a) for grouping intakes of pressurised irrigation networks into sectors to minimize energy consumption has been improved to allow operating intakes at different scheduled times without affecting pump performance.

In addition, one way to save energy in pressurized irrigation networks is to maximize the number of intakes that can operate without pumping, in other words, maximizing the water volume supplied by gravity. Thus the energy dependence of the system decreases. This strategy can be applied in irrigation districts where there is enough elevation head between some demand nodes and the water sources.

These methodologies have been applied in an irrigation district where currently users make their water petitions ordering an irrigation time. Then, technicians arrange the irrigation scheduling by their own criteria trying to minimize the energy consumption while meeting user requirements.

The results of the simulated scenarios were compared with the irrigation system management carried out on 2012 by means of some energy indicators proposed for energy audits in Water Users Associations (WUAs; IDAE, 2008; Abadia et al., 2008).

2 Methodology

2.1 Case study

The WUA of Realon is located in the municipality of Picassent in Valencia (Spain; 39º 22' 43'' N, 0º 28' 20'' W). The total irrigated area was 180 ha composed of 500 plots. The average plot area is 3.598 m^2. The irrigation network is branched and has 62 multioutlet hydrants and a total of 342 intakes. A multioutlet hydrant has several intakes, a common solution adopted for network design when plot size is small. In this way, network pipe lengths are shorter and more economic. As a result, users connect their drip irrigation subunits to the water supply system through water intakes. The average hydrant elevation is 90.8 m, ranging from 111.5 m to 79 m, and total network length is 14426 m. Pipes are made of polyvinyl chloride and according to standard UNE EN ISO 1452-2:2010, internal nominal diameter (ND) ranges from 500 to 125 mm. Nominal pressure ratings are 1.0 and 0.6 MPa. Fig. 1 shows the network layout and the hydrant location.

Water is stored in a pond feed by a canal. Its elevation is 114.4 m and it is 3 m above the pumping station. The system regulation is carried out by three equal vertical multistage pumps each powered by an engine of 45 kW. Fig. 2 shows the characteristic curves, head-flow and performance-flow obtained after being tested. Two of them are Fixed Speed Pump (FSP) and the other one is a Variable Speed Pump (VSP). All users are charged according to their water consumption with a fixed price per m^3. Collective fertigation is performed for all users. The total cropped area is orchards and the predominant crop is citrus (95 %). All of them are drip irrigated.

The system is operated by a Supervisory Control and Data Acquisition System (SCADA), which reports on real time flow-meter readings and informs on system failures.

Users make requests on how long they want to irrigate. The WUA's technicians arrange irrigation scheduling dividing intakes in two groups: those that can be feed by gravity and those that need extra head by pumps. The criteria to select the intakes that will operate by gravity is based on the difference between the water elevation head and the hydrant elevations. This difference should be at least higher than the target pressure at hydrants, which is set to 0.25 MPa.

Table 1 shows the structure of the contracted tariff by the WUA where energy is charged according to the energy consumption (€ kWh^{-1}) and the contracted rate power (€ kW^{-1} $Month^{-1}$), which has a fixed price. WUA has contracted 198, 120 and 35 kW for the off-peak, regular and peak periods respectively. The off -peak power is contracted to guarantee the operation for three pumps, the regular period for two pumps and the peak period to perform maintenance. In the event the power exceed the maximum contracted, pumps are turned off.

The irrigation intakes that need extra energy are scheduled in the off-peak period, from 00:00h to 8:00 h. and from 8:00 h to 10:00 h (regular period). The WUA's technicians try to make homogenous the pumped flow, avoiding exceeding the maximum power contracted to not be penalized by the energy supplier. The outlet pump pressure is fixed to 0.32 MPa by the system control for all pumping periods.

In order to avoid pumping out of off-peak periods, the irrigation time for users was limited to a maximum of 4 h. The average scheduled irrigation time per intake was 1.85 h.

Gravity intakes are scheduled from 10:00 to 24:00 in one irrigation day, when the energy is more expensive. This daily schedule is maintained during the irrigation season only with small changes suggested by the users. As crop water requirements increase along the season, the number of irrigation days per week was increased. The total number of irrigation days in 2012 was 132 and the average supplied volume applied per day 5977 m^3.

2.2 Methodology for irrigation scheduling with minimum energy consumption and optimum water use.

The sectoring model developed by Jimenez-Bello et al. (2010a) was applied to the Realon Irrigation district. Briefly, the model allows to group irrigation intakes in such a way that the sum of the intake flows drops in the regions where the pump efficiency is higher and the pressure head is lower fulfilling the minimum required pressure at the demand node (see Fig. 4 in Jimenez-Bello et al., 2010a). The required data comes from a calibrated mathematical model of the irrigation network. Calibration is feasible nowadays because modern irrigation systems are equipped with pressure sensors placed in hydrants and flow meters at each intake. The required input parameters for grouping intakes are 1) the minimum pressure head required at hydrants, 2) the desired number of sectors and 3) those parameters related with GA. The decision variables are the sectors to which each hydrant or intake can belong to. Once the GA model is run, the best solution to the grouping problem is achieved after some termination conditions are reached, as a maximum generation number. Indeed, this procedure guarantees that irrigation can be carried out at the lowest energy consumption per total volume of water delivered.

However, in the above method the operation time is the same for all intakes grouped in a sector. For example, in the case study depicted in Jimenez-Bello *et al.* (2010a, 2011a) intakes were grouped into 6 consecutive sectors of two hours. All intakes irrigate the same time with the minimum energy consumption but the method did not guarantee the optimal water use.

For this reason the method has been modified in such a way that each intake could operate just the required time, according to the crop type, the phenological stage, the irrigation subunit features or the farmer criteria.

With this aim, the irrigation day now is divided into time slots, where intakes can operate. Then the decision variables are the time slot at each intake starts to operate. For example if the irrigation day lasts ten hours, this period can be divided into intervals of 15 minutes. In that case, the domain of the decision variables will be integers ranged 1-40. If it is divided into intervals of 5 minutes the domain will range 1-120. Once a slot is assigned by the GA to an intake, it operates the scheduled time (rounded to an integer number of time slots)**.**

Fig. 3 shows the time pattern of a multi-outlet hydrant with two intakes which operation does not overlap and another hydrant with 5 intakes where some intakes operate overlapped. Hydrant base demand is the sum of intake flows. Each intake has a demand factor. Then the hydrant demand is simulated multiplying the base demand by the intake factor when it operates.

The optimisation process gives as result for each intake the slots in which has to operate to minimise the energy consumption, satisfying at the same time the crop water requirements.

The highest the number of slots, the more accurate the method will optimize the water use, because scheduled irrigation times will fit better the theoretical ones. Nevertheless the optimization process will take longer, due to the increased number of time slots require more computations.

2.3 Methodology for setting the intakes to be fed by gravity

When water head at source point (WHI, m) is enough to deliver water at the required pressure for some irrigation intakes, a way of reducing the energy consumption is to avoid pumping when these intakes operate. This strategy can be used particularly in hours when energy is more expensive.

For that purpose, a new methodology was developed based on the previous one. Again the available period is divided into time slots, being the decision variable the slot when each hydrant or irrigation intake starts to operate. Now, the objective function is either to maximize the number of intakes or the water volume delivered during this period without using pumps, fulfilling the minimum pressure required. In addition, the final network scheduling must not have intakes without enough pressure, which can be formulated in a single goal function:

$$Max(I_{OC} - I_{NOC}) \tag{1}$$

$$Max(V_{OC} - V_{NOC}) \tag{2}$$

where I_{OC} are the number of intakes that operate correctly, I_{NOC} the number of intakes with not enough pressure. Alternatively, V_{OC} is the delivered volume for the intakes that operate correctly and V_{NOC} is the delivered volume for intakes with not enough pressure.

A new integer decision variable is added to each intake that indicates whether it operates or does not, resulting in a chromosome that has twice number of genes than intakes (N_{int}). The first N_{int} gen values ranges between 1 and the number of slots, determining when the intake starts to operate. The second N_{int} gen values range between 0 and 1, meaning 1 the intake operates and 0 does not.

Previously, to get a faster solution those intakes that cannot work with the minimum required pressure because the difference in elevation between the source and the hydrant is not enough, are discarded. The options selected for the GA process were an initial population of 100, roulette rank selection, uniform crossover, 10 % mutation probability and the process stops when 1500 generations were processed (Jimenez- Bello at al., 2010a). No meaningful improvements were found in the fitness solution when the number of generations was increased.

The result is an irrigation scheduling with the maximum number of intakes operating without pumping and fulfilling the minimum pressure required. Intakes not operating in the final solution will need extra energy.

2.4 Application to the case study

The mathematical model of the network represented the elements at the level of multioutlet hydrants where each hydrant is assigned to a demand node in the EPANET scenario. The network was built in 2009 and the characteristics of the layout are perfectly defined. The model was calibrated by means of five pressure sensors (SSC2035 Sensortechnics, Puchheim, Germany) placed at five hydrants and the network head before the filtering system there was an additional one. The scale of pressure transducers was from 0 to 1.0 MPa which maximum non linearity was ± 0.20 % of FS. Data was stored in data loggers (Model CDL-2U Meinecke, Hanover, Germany). The flow meters of each intake were used to measure the water flows. At pump station there was and electromagnetic flow meter model (Model HMS 2500, Liquid Controls Illinois, USA) with accuracy ± 0.8 % for velocity greater than 1 m s^{-1}. The difference between the total sum of water flow meters and the water flow meter measured at the pump units was meaningless. For this reason network water losses were not considered. Since intake flows and pipe diameters were perfectly known, pipe roughness of each diameter size was chosen as calibration variable. Due to the restricted number of pressure sensors, criterion used to choose hydrants was to maximize the number of equations that will include the 16 diameter sizes existing in the network. Selected hydrants were located at the end of network branches. The total number of equations was 29, due to intakes located in the same hydrants operated at different times adding extra equations. The goal function was to minimize the quadratic error of estimated pressure versus measured pressure. This approach is known as Simple Least Squares (Moreno et al 2008).Pipe head losses were calculated using Darcy-Weisbach formula. Minor head losses were assigned to pipe roughness. A value of 0.007 mm was set to pipe roughness. The average relative pressure error in the model was 3.84%.

In order to assess the error model, CEVT was calculated for an actual scenario and compared to that obtained from the energy billing data. Pump behaviour of VSP was simulated by using affinity laws (Planells et al. 2005). To assess this assumption, a power and energy analyser (Model C.A 8334B, Chauvin Arnoux, Paris, France) was installed from 10th to 15th May 2012.

Next, new scenarios where defined according to the minimum required service pressure at hydrant (P_{min_Hid}) and the pumping operating time per day (T_{Pump}). The rest of the day was assumed to be used for gravity delivery. For each scenario, first the maximum number of intakes that could operate by gravity fulfilling the minimum pressure requirements was identified by applying the methodology depicted above. Then, for the rest of the day those intakes that require extra energy were processed with the AG method to search for the proper time scheduling with the minimum energy consumption. Finally the different scenarios were compared to decide what irrigation strategy should be more convenient.

3 Analysis of the results

3.1 Scenarios tested

To assess the application of the aforementioned methodologies, seven scenarios were studied.

The first scenario (Sce1) simulates the irrigation scheduling performed along the season 2012, decided by the WUA managers. The rest of scenarios were simulated modifying the P_{min_Hid} (0.2, 0.22 and 0.25 MPa) and the T_{Pump} (6, 8 and 10 h). Main scenario features and analysis results are showed in Table 3.

3.2 Model assessment

Once the network hydraulic model was built, its accuracy was assessed for the period 10th to 15th May of 2012. The actual irrigation scheduling was run by the model (T_{Pump} = 10 h) providing a CEVT value of 0.147 kWh m^{-3} while the actual value for the tested period was

0.151 kWh m^{-3}, which means a relative error of -2.98 %. The VPS behaviour was assessed by comparing its simulated energy consumption with that empirically registered using an energy analyser. For an irrigation day the average simulated consumption was 216.5 kWh. Compared to the actual one the relative error was 3.9 %, making the model enough reliable.

From the analysis of Scenario 1 came out that 77 intakes had a pressure lower than 0.25 MPa, 25 while pumps worked (from 00:00h to 10:00h) and 52 while fed by gravity (from 10:00h to 00:00h). Table 2 shows the actual operating pressure of the irrigation intakes.

3.3 Optimization of volumes delivered by gravity

Once the model reliability was assessed, the GA algorithm to maximize the volume supplied by gravity was applied. The pumped volume (V_{Pump}) for the actual scenario (Sce 1) was 4381 m^3 and the volume supplied by gravity (V_{grav}) was 1596 m^3, then the energy dependence index (EDI) was 73.3 % (Table 3). However the potential volume to be delivered by gravity ($V_{Maxgrav}$) was 2594 m^3.

Scenario 4 was run to study if the system had the possibility to supply more water without pumping, being P_{min_Hid} and T_{Grav} the same as for scenario 1. The EDI was reduced by 12.3 %. The number of operating intakes was 3 less than in Scenario 1, however the selected intakes supplied larger volume. Moreover all operating intakes would operate having pressure higher than 0.25 MPa, not like Scenario 1 where 52 intakes had lower pressure than the required minimum.

To test whether increasing T_{Grav} then also V_{grav} increases, T_{Grav} was extended to 24 hours (Scenario 7). This scenario would be convenient for those periods where water demand is not high and irrigation take place only some days per week. Thus, when a high irrigation frequency was not necessary, pumps could operate some days and irrigate by gravity the remaining days. Results showed that EDI would be 59.7%, a 13.6 % lower than scenario 1 and 1.3 % lower than scenario 4. The potential volume supplied by gravity for P_{MinHid} = 0.25 MPa was not achieved due to the diameters of the final network branches were small (ND 125). The total length of these pipes was 2995 m, being the head losses quite high in those segments. For example if these segments would be replaced for pipe diameters of ND 160 EDI would be 56.6%, achieving $V_{Maxgrav}$. This shows that topological criteria to group intakes, as shown in Carrillo Cobo et al. (2010), are not convenient to reach the optimum solution.

Scenarios 2 and 3 simulated the actual schedule T_{grav} = 14 h, but P_{MinHid} was set to 0.20 MPa and 0.22 MPa, decreasing EDI by 27.1 % and by 21.8 % respectively. Fig 5. shows the plots irrigated by gravity in scenarios 1, 2 and 4. Graduated colours are assigned according to the irrigation starting time. This method spreads the intakes in such a way that reduces the head losses along the network.

Since in scenario 1 T_{Pump} used two hours of regular tariff, T_{grav} was extended 2 hours to use pumps only during peak-off periods, from 0 to 8:00 h (scenario 5). Even though intakes had two additional hours to be scheduled, EDI was 60.6 %, that is just 0.4% more volume would be supplied by gravity than in scenario 4, due to the aforementioned restriction of the pipe size diameter. Even for T_{grav}= 18 h the EDI was 60.5 %, a slight decrease compared to scenario 4.

3.4 Optimization of volumes delivered by pumps

Once V_{grav} was maximized for each scenario, irrigation scheduling for V_{pump} was arranged by the GA that minimizes the energy consumption. Scenario 4, the optimized counterpart of scenario 1, had a consumption per m^3 water pumped ($CEVT_p$) of 0.126 kWh m^{-3}, which means a reduction of 23.5 % compared to scenario 1 (0.164 kWh m^{-3}). $CEVT_p$ for scenario 1 was the average of the irrigation season as the daily irrigation scheduling was the same. This saving was mainly due to two reasons. The first one is the pumping head injection (WHI) was lower because operating intakes are distributed along the T_{Pump} in such a way the flow is more homogenous, head losses are minimized, and PHI was adjusted to guarantee P_{MinHid}. Fig. 6 shows the water head injection (WHI, MPa), the pumping head injection (PHI, MPa) and the pumped flow (Q, l s^{-1}) for scenarios 1, 4, 5 and 6. WHI was set by WUA technicians to 0.32 MPa for scenario 1. As the water level storage pond is 3 m above, PHI was 0.29 MPa. WHI was 0.273 MPa for scenario 4, lower than in scenario 1.

The second reason is that the final scheduling guarantees the best pump performances. In Fig. 6, efficiencies of the VSP (η_{1VSP}) and the two FSP (η_{2FSP}, η_{3FSP}) can be observed. As the WHI remains constant along the pumping period then η_{2FSP} is 0.58, not far from the optimal (0.68, see Fig. 2). When there are peak or low demands, the VSP operate to adjust the flow rates. The flow fluctuations make the VPS performance being low in some periods, with a mean value of 0.52 and maximums for the $CEVT_p$ up to 0.24 kWh m^{-3}. Moreover because water pumping has to finish before 10:00 h to avoid peak tariff periods, performances in the two previous hours are unstable for all pumps.

Fig. 6 shows that FSP_1 performance for scenario 4 is lower than for scenario 1. As the PHI decreases then η_{2FSP} decreases for flows higher than optimal (see Fig. 2). However η_{1VSP} remains almost constant along the pumping period, close to the optimum. The adapted GA methodology allows the progressive incorporation of the intakes in such a way that the demanded flow guarantees the minimum $CEVT_p$. As it can be observed FSP_2 was not necessary for this scenario, which permits a reduction of the maximum power contracted. The PHI ranges from 0.221 MPa to 0.243 MPa, but as the control system does not allow to set pressures dynamically, the maximum value was kept fixed. This fact avoids a lower $CEVT_p$ (Jimenez-Bello et al 2010a).

Considering both the pumped and the gravity volume, the comparison of the consumed energy per m^3 for the total delivered volume ($CEVT_t$, kWh m^{-3}) between scenario 4 and scenario 1 gives a saving of 36.4%, higher than $CEVT_p$ saving because of the lower EDI for scenario 4.

Since energy is charged according the daily period when it is consumed, the scenarios were compared by means of the economic cost instead of the energy cost. The total energy cost of total water delivered (pumped and gravity), by disregarding the power cost (CoEVT, c€ m^{-3}) and taking it into consideration ($CoEVT_t$, c€ m^{-3}), were calculated. For the sake of simplicity, the power cost was charged by dividing the annual power cost by the total annual supplied volume, giving an average unit cost of 0.532 c€ m^{-3}.

In spite of energy was 5.2 c€ kWh^{-1} cheaper in the peak-off period than in the regular period, the extra power to pump more volume in less time did not compensate this fact. Then scenarios 5 and 6 had higher $CoEVT_t$ than scenario 4, but all of them had lower $CoEVT_t$ than scenario 1. In particular, scenario 4 had a total cost 26.5 % lower than scenario 1. However comparing to CoEVT (36.4 %) the saving is lower because power is a fixed cost.

Another cost saving strategy is to reduce the contracted power, especially in the most expensive periods. As Fig. 6 shows, scenario 4 does not use the three pumps, therefore the contracted power could be reduced from 198 kW to 120 kW for the peak-off period. That would mean a total energy cost of total water delivered modifying the power contracted ($CoEVT_b$) of 1.406 c€/m^3 and a saving of 28.7 %.

For scenarios 5 and 6 the power contracted could be reduced in the ordinary period from 120 kW to 60 Kw (for maintenance purposes). In this case, comparing scenario 5 to scenario 1 the $CoEVT_b$ would be 31.5% lower.

4 CONCLUSIONS

The methodology developed by Jimenez-Bello et al (2010a), where intake operation is scheduled in such a way that energy use is minimized, has been improved allowing each intake operate just the scheduled time according to crop needs. In this way, crop water requirements can be satisfied more efficiently and intakes are not restricted to operate in fixed time periods.

Moreover, a new method based on the previous one can be used to maximize the number of intakes fed by gravity, in those irrigation systems where the sources has enough head to supply water to some demand nodes without using pumps.

Both methods were applied to a case study where a realistic energy saving of 36.4 % was achieved, in terms of energy consumption (kWh m^{-3}). This was mainly due to increasing the intakes fed by gravity, decreasing the pump head injection and increasing the pump performances. In addition the contracted maximum power could be reduced as well, which leads to a potential saving for the total energy costs of up to 31.5 % (c€ m^{-3}). These are the potential savings. To achieve them, continuous monitoring of the system should be carried out to fit the model to the events along the irrigation season (Jimenez-Bello, 2011).

Nevertheless if the minimum required pressured at hydrant would be 20 m, i.e. 20 % lower, savings up to 65.6 % in energy consumption could be achieved for the studied irrigation system. More attention should be paid in head losses from the hydrant to the irrigation subunit.

In conclusion, the modern irrigation districts with SCADA systems allow to collect data to feed hydraulic network models. By means of the aforementioned methodologies energy performance can be improved by proper scheduling. Users only suffer the restriction of when they can irrigate along the day, but crop water requirements are fulfilled and big energy savings are achieved.

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Table 1 Rates for energy consumption (€ kWh^{-1}) and maximum power (€ kW^{-1} $Month^{-1}$) for the tariff periods on 2012 in the study case.

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Fig. 4 Chromosome structure of the optimization process where it is showed the chromosome length (twice the number of intakes) and the range of integer values for each gen. The gens of first half range between 1 and the number of slots while the gens of second half indicates if the intake operates or does not.

Fig. 5 Plots irrigated by gravity for scenarios 1, 4 and 2.

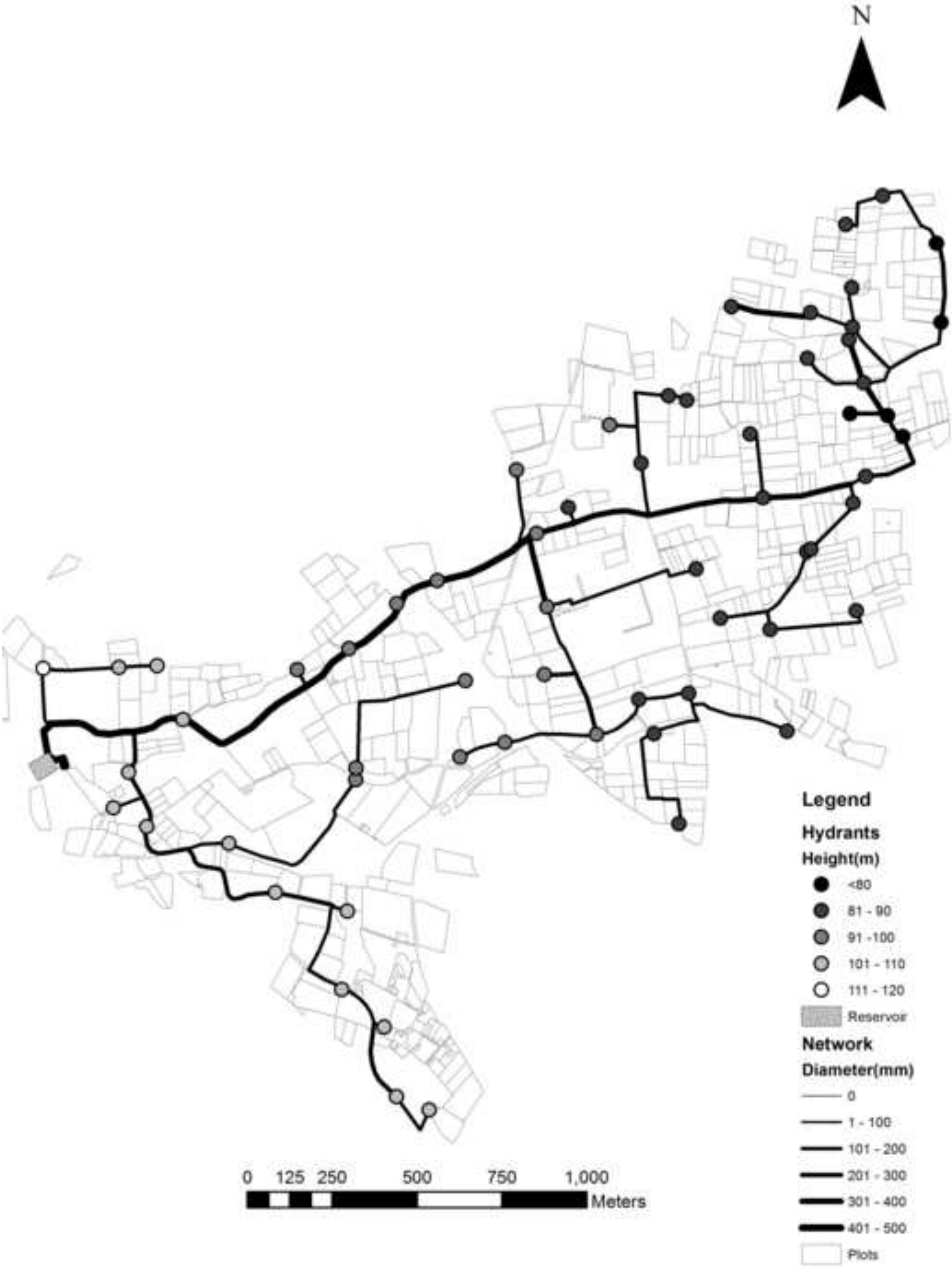
Fig. 6 Total demanded flow (Q, ls-1), water head intake (WHI, MPa), pumped head injection (PHI, MPa),consumed energy per m3 of pumped water (CEVTp, kWh m-3) and pump efficiencies of the Variable Speed Pump (η1VSP) and the two Fixed Speed Pumps (η2FSP and η3FSP) for scenario 1 (the actual scenario performed on 2012 season),s cenario 4 (Pmin_Hid =0.25 MPa; TPump= 10 h), scenario 5 (Pmin_Hid = 0.25 MPa; TPump= 8 h) and scenario 6 (Pmin_Hid = 0.25 MPa; TPump= 6 h). Parameters were computed for each 5 minutes.

Tables

	Peak off	Regular	Peak
Time (hh:mm)	00:00 -8:00	8:00-10:00; 16:00-00:00	10:00-16:00
Energy € kWh^{-1}	0.109	0.161	0.185
Power € kW^{-1} Month^{-1}	0.362	1.577	2.557

P_{hid} (MPa)	N_{int}
>0.25	245
0.20-0.25	56
0.15-0.20	19
0.10-0.15	2
<0.10	0

Sce	**P_{min_Hid} (MPa)**	**T_{Pump} (h)**	**T_{Grav} (h)**	**WHI (MPa)**	**I_{NOC}**	**V_{pump} (m^3)**	**V_{grav} (m^3)**	**EDI (%)**	**$V_{MaxGrav}$ (m^3)**	**$I_{MaxGrav}$**	**I_{Grav}**	**$CEVT_p$ (kWh m^{-3})**	**$CEVT_t$ (kWh m^{-3})**	**CoEVT (c€ m^{-3})**	**$CoEVT_t$ (c€m^{-3})**	**$CoEVT_b$ (c€ m^{-3})**
1	0.25	10	14	0.320	77	4381	1596	73.3	2594	179	152	0.164	0.120	1.440	1.972	1.972
2	0.2	10	14	0.218	-	2761	3216	46.2	3793	228	175	0.090	0.042	0.496	1.029	0.986
3	0.22	10	14	0.244	-	3081	2896	51.5	3529	219	172	0.119	0.061	0.731	1.264	1.221
4	0.25	10	14	0.273	-	3644	2333	61.0	2594	179	149	0.126	0.077	0.916	1.449	1.406
5	0.25	8	16	0.289	-	3622	2355	60.6	2594	179	145	0.146	0.088	0.963	1.495	1.351
6	0.25	6	18	0.307	-	3617	2360	60.5	2594	179	149	0.173	0.105	1.146	1.678	1.534
7	0.25	0	24	0.141	-	3567	2410	59.7	2594	179	156	-	-	-	-	-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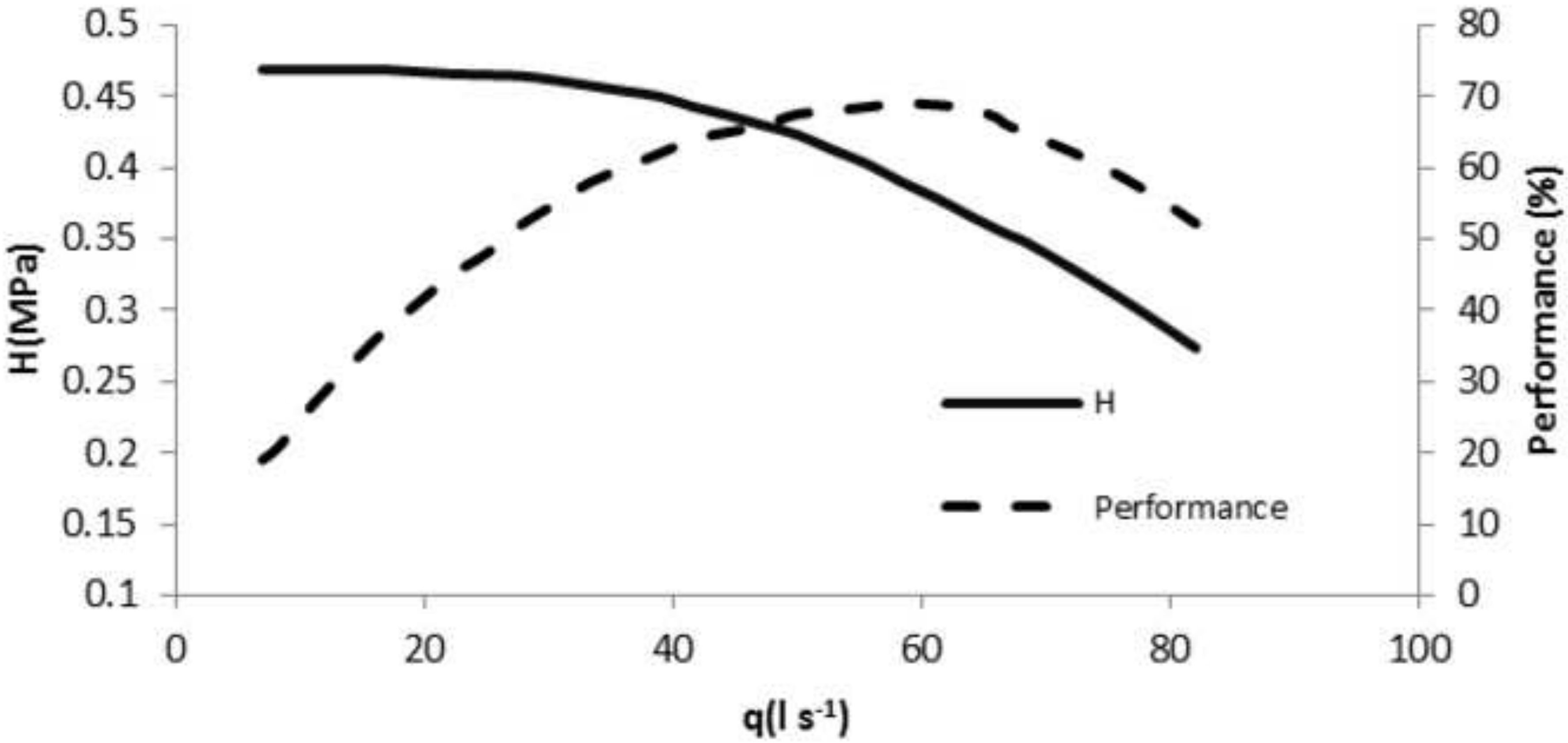
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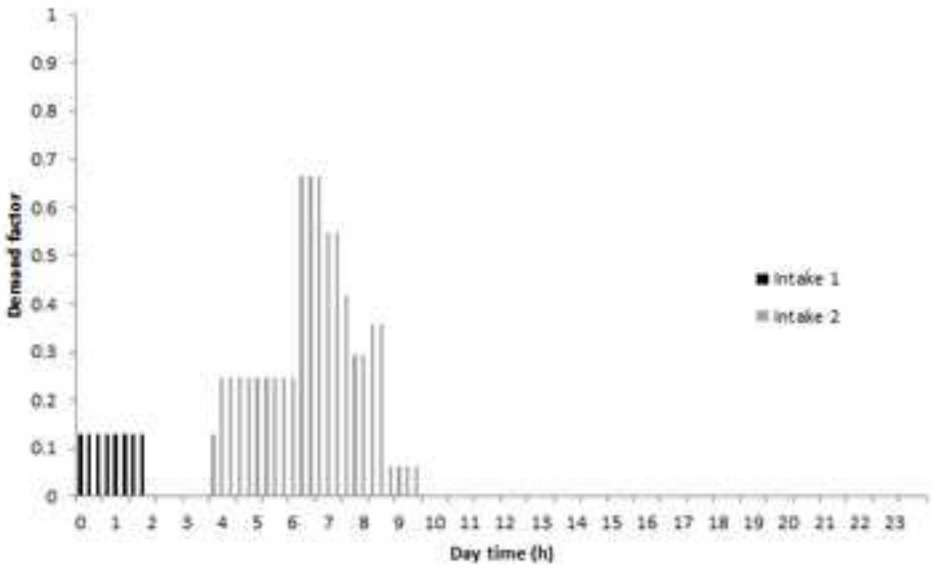
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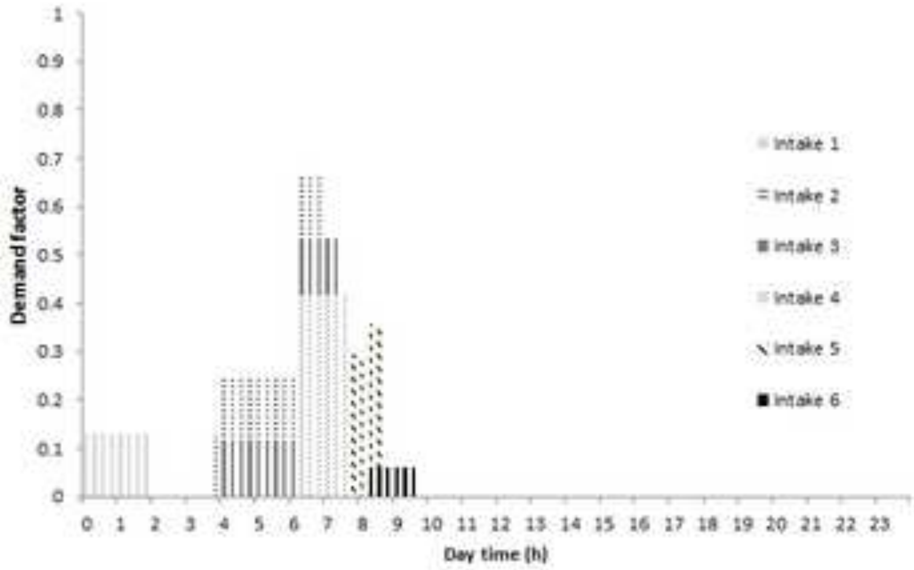
▥ Intake 2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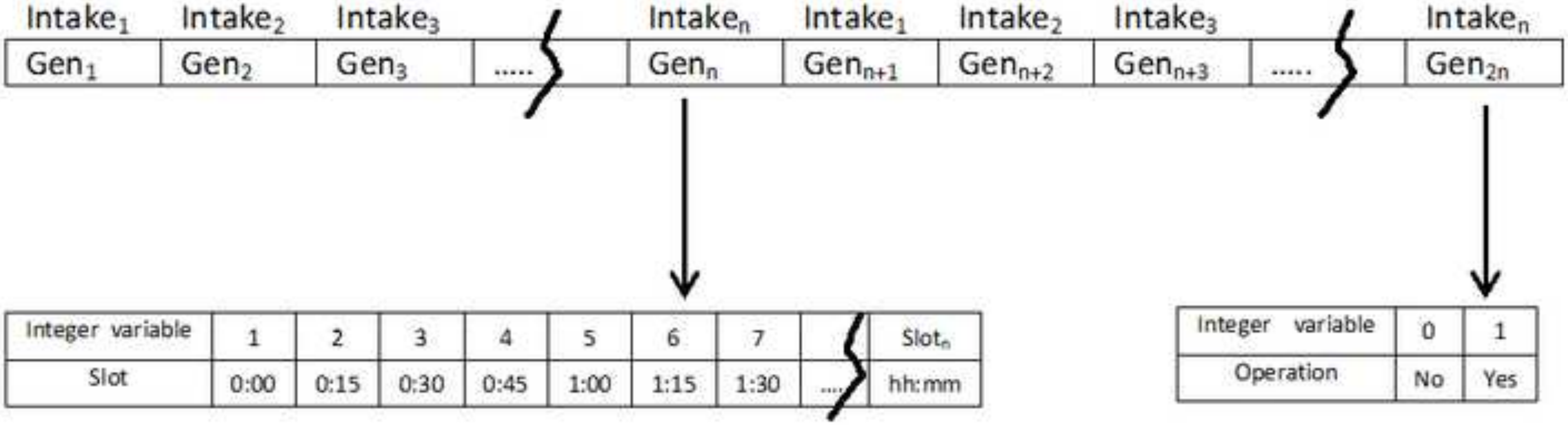
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Genn+2
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.....
Gen2n
Integer variable
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2
3
4
5
6
7
Slotn
Slot
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0:30
0:45
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1:15
1:30
....
hh:mm
Integer variable
0
1
Operation
No
Yes


Sce 1
Sce 4
Sce 2
Irrigation starting time

Figure

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