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

M.A. Jiménez-Bello[a,*], A. Royuela[b], J. Manzano[b], A. García Prats[c], F. Martínez-Alzamora[a]

[a] Instituto de Ingeniería del Agua y del Medio Ambiente (IIAMA), Universitat Politècnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain
[b] Centro Valenciano de Estudios del Riego (CVER), Universitat Politècnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain
[c] Departamento de Ingeniería Hidráulica y Medio Ambiente (DIHMA), Universitat Politècnica de Valencia, Camino de Vera s/n, 46022 Valencia, Spain

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ABSTRACT

With the aim of reducing energy consumption and improving water use in pressurised irrigation systems, the methodology to minimise energy consumption by grouping intakes of pressurised irrigation networks into sectors, as developed by Jimenez-Bello et al. (2010b), was modified to enable irrigation intakes to operate during the scheduled period for each intake instead of operating during 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 if the source has sufficient head to feed at least some of the intakes.

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

1. Introduction

The modernisation of irrigation systems in semi-arid regions has increased water use efficiency, but at the same time there has been a large increase in energy consumption (Jackson et al., 2010; Corominas, 2010) and together with low crop prices this has reduced the profitability of irrigated agriculture in these areas. Due to continuously rising energy prices, more attention is being paid to reducing energy 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 taking into account economic criteria (Labye et al., 1988; Lansey and Mays, 1989; Planells et al., 2007; Theocharis et al., 2006). Previously, the average demand for each consumption node was determined according to the crop water requirements for the most demanding water period (Clément and Galand, 1979; Pulido-Calvo et al., 2003). Since the crop water requirement changes with 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, pump set selection and its operation using variable speed driver technology (VSD) is a key aspect for guaranteeing water delivery and the efficient use of energy. With this aim Planells et al. (2005) developed an algorithm for minimising the investment and operational costs of pumping stations. Planells et al. determined the maximum and minimum system head curves and the evolution of demand curves to obtain the maximum discharge needed. The number of required pumps and the operation mode, fixed or variable speed, were then determined. Moreno et al. (2009) studied how to obtain the optimal characteristic and efficiency curves at pumping stations and concluded that if the

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Abbreviations: $CEVT_p$, energy consumption per m^3 of pumped water ($kW\,h\,m^{-3}$); $CEVT_t$, energy consumption per m^3 of total delivered water ($kW\,h\,m^{-3}$); 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 pumped volume and 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 insufficient 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_{Intake}, time period when an intake is operating; 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 insufficient pressure (m^3); V_{OC}, volume supplied by the intakes that operate correctly (m^3).

* Corresponding author. Tel.: +34 96 3710768.
E-mail address: mijibar@dihma.upv.es (M.A. Jiménez-Bello).

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selected pumps fitted those curves, then the number of variable speed 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 system curve by regulating the operation of the pumping station on the basis of maximum efficiency.

All of 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 approach would improve energy efficiency, Rodríguez et al. (2009) studied the potential savings in a case study by simulating the change of the operation system from on-demand to operation by sectors. The irrigation network was divided into two sectors according to a homogeneous elevation criterion. Each of the hydrants from the two sectors could work freely on the assigned period (12 h). 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 relative to the network injection point) 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 network sectoring 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 loss in the pipes and making the approach unsuitable for use in undersized or overloaded networks.

Fernández García et al. (2013) modified the previous methodology so that it could be used with different water sources. Once sectors were created, the pumping calendar was established by means of genetic algorithms (GA) with the aim of minimising a multi-objective function: energy consumption, system failures (the number of hydrants with insufficient pressure), and irrigation deficits simultaneously. The decision variables were the number of operating sectors, pump heads, and the number of months the system was operational.

The last three approaches assumed a high constant efficiency of pumping groups (0.75–0.8); but efficiency was variable depending on the demand scenario. This approach could lead to choosing a solution associated with low pump efficiencies–which would be a poor choice (Moreno et al., 2010; Jiménez-Bello et al., 2011). To overcome the above limitation, Fernández García et al. (2014) coupled the methods developed in these three approaches with a simulation of the pumping station.

For irrigation networks operating turns where user operation times are strictly restricted, 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. reduce the amount of energy used per m^3 of pumped water. Unlike Fernández García et al. (2014), no topological criteria was used to initially determine the sectors, so intakes were grouped in such a way that the pumping head guaranteed that service pressure was minimum and the highest pump performances were achieved. As a result, irrigation sectors to minimise 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, $\mathrm{kW\,h\,m^{-3}}$) for the scenario that simulated the study case was 22.3%. This methodology was then successfully applied in the study case for several campaigns and achieved an estimated energy saving of 16% (Jiménez-Bello et al., 2011). The potential saving was not achieved because of restrictions in the real operation of the network. Central fertigation was not carried out for all users and so non-fertigating intakes had to operate in the same sectors (Jimenez-Bello et al., 2010a) and this restricted the possibilities of making those sectors with the best performance. 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.

Garcia-Prats et al. (2012) used another heuristic optimisation method, simulated annealing, to create sectors with minimum energy consumption. This approach was coupled with hydraulic models. As in the previous study, it was applied to a case study where irrigation was scheduled with strict turns. Potential savings for this case study were 11.8% and 15.5% compared to a sectorised network operating on-demand and using the criterion of hydrant elevation with respect to the pumping station.

Although these last two approaches reduced energy consumption, water use was not necessarily optimal, as occurred in the two aforementioned case studies. As plots have differing crops and are not at the same phenological stage, and the characteristics of the subunits differ, the theoretical irrigation times will vary. If the same irrigation time was scheduled for all the plots then some will receive more water than required and others less, resulting in 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 minimise energy consumption has been improved to enable intakes at different scheduled times without affecting pump performance. How irrigation periods are scheduled will depend on the irrigation district and how it is managed. Periods can be determined in several ways according to: user's criteria; the FAO methodology (Allen et al., 1998); or following advice from irrigation advisory services (Ortega et al., 2005).

In addition, another method to save energy in pressurised irrigation networks is to maximise the number of intakes that can operate without pumping, in other words, maximise 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 demand nodes and water sources. This approach avoids the construction of new facilities in cases where necessary pipes were not included during the design phase, or energy prices and the tariff structure were modified after the project was developed and so existing facilities prevent efficient energy use.

These methodologies have been applied in an irrigation district where users make their water requests by ordering an irrigation time. Technicians arrange irrigation scheduling using their own criteria and try to minimise the energy consumption while meeting user requirements.

The results of the simulated scenarios were compared with the irrigation system management carried out in 2012 using several energy indicators proposed for energy audits by water user 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; 39°22′43″N, 0°28′20″W). The total irrigated area is 180 ha and it contains some 500 plots. The average plot area is 3.598 m^2. The irrigation network is branched and has 62 multi-outlet hydrants and a total of 342 intakes. It was modernised in 2009. A multi-outlet hydrant has several intakes, a common solution adopted for network design when plot sizes are small. Every intake has an electric valve and can operate independently of the other hydrant intakes. In this way, network pipe lengths are shorter