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Energy audit of irrigation networks

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ABSTRACT

The relationship between water and energy in water distribution systems (WDS) has been a growing concern among energy and water experts. Among the different strategies to improve water-energy efficiency in water distribution networks, energy audits are of paramount importance as they quantify water flow requirements, the amount of energy consumed to meet demand and leakage and friction losses. Previous work has presented the energy audit process for urban WDS and this energy audit is extended to irrigation networks here. This work analyses the most common types of irrigation emitters (sprinklers and pressure compensating and non-pressure compensating drippers), hydrant specifications, irrigation management systems (on-demand or rigid scheduled), and energy losses due to friction in pipes, control valves and irrigation hydrants. The energy audit does not assess whether management of the network is optimal, but analyses the energy consumption. Some of the performance indicators have already been defined for agricultural water networks, some are identical to those of urban WDS, but in addition, a new one is presented that disaggregates the energy dissipated into three terms, energy losses in pipelines, in hydraulic valves and in irrigation hydrants. These indicators show information necessary to better understand the performance of the irrigation network under study, to carry out a deep analysis of energy consumption and to allow for comparison with similar systems. The paper presents the analysis of a real case study conducted on the irrigation network of the garden of the Universidad Politécnica de Valencia.

Keywords: pressurised irrigation, water, energy, audit, leakage, urban irrigation

1. INTRODUCTION

The headline "more crop per drop" perfectly reflects the need for more efficient irrigation, a direct consequence of the substantial increase in irrigated areas in recent decades. To achieve this goal, the strategy has been largely based on converting traditional gravity-fed irrigation into pressurised irrigation systems. And indeed, this has resulted in larger areas being irrigated with the same amount of water. But these water savings have entailed much greater energy consumption, energy itself being a scarce and valuable resource. Table 1 (Corominas, 2010) details water and energy consumption in Spain in the last century and clearly reflects how the situation has changed in a country with a long agricultural tradition.

Table 1 shows that energy consumption becomes relevant from 1950. The initial increase in energy use cannot be attributed to drip irrigation but the silent revolution (Llamas and Martinez

Santos, 2005) which supported the intensive use of groundwater. A couple of decades later, in the 70s, a progressive transformation of irrigation took place from gravity-fed to pressurised irrigation. Table 1 shows that between 1950 and 2007 the irrigated area grew by a factor of 2.5, while water consumption doubled and energy expenditure became 19 times greater.

The energy price has been increasing slowly but progressively. This has resulted in a reduction of benefits for farmers. However now prices have risen so much that farmers can no longer sustain this situation and the relationship between water and energy has become a key point on the agenda of developed countries (Department of Energy, 2006). Moreover, the first detailed analysis that quantifies this link between water and energy (CEC, 2005) showed that 19% of the electricity consumption of the State of California was related to water use, a significant amount.

On the other hand, although most of this energy consumption occurs in urban and industrial areas, agriculture is also energy hungry. The electricity consumed by agriculture reached more than 4% of the total energy consumed in the state of California (while the water use in agriculture represents 22% of the water consumption of the State). This energy use was divided between water supply (groundwater pumping consumption represented 30% of the total energy consumption in irrigation) and distribution (the remaining 70% was related to water distribution in pressurised irrigation networks).

The interest in reducing the energy bill can be addressed using two different and complementary policies. The first (and most natural) strategy deals with the reduction of water consumption, as water savings result in energy savings. This strategy involves a set of actions covered by the term "water demand management". The first step is not to use more water than necessary (in short, to optimise the water delivered to the crop). These needs are directly linked to climatology and to soil moisture. Traditionally, great efforts to quantify the proper amount of water required in scheduled irrigation have been made. Studies in this area include those related to climate prediction (WMO, 2010), the use of soil moisture sensors (Greenwood et al., 2010), deficit irrigation strategies (Geerts and Raes, 2009) and remote sensing and agro-climatic water balance models (Bastiaanssen et al., 2007; Droogers et al., 2010).

The second is linked to the optimisation of the design and operation of irrigation networks from an energy-related point of view. This has been an active research area since pressure irrigation began (Allen and Brockway, 1984), and in recent years, for the aforementioned reasons, it has been attracting increased attention. Irrigation networks have to be dimensioned (Farmani et al., 2007; Daccache et al., 2009, González -Cebollada et al., 2011) taking into account energetic implications. Furthermore they require pumping stations (Moradi-Jalal et al., 2004; Moradi-Jalal and Karney, 2008; Moreno et al., 2010a) and complementary elements (Kale et al., 2008; Armindo al., 2011) to be implemented to minimise energy expenditure. And once the system is working, its management should also be optimised from the energy perspective (Jimenez-Bello, 2010; Lamaddalena and Khila, 2012).

It should be highlighted that the delivery scheduling method in an irrigation system demonstrates different levels of energy consumption. These schedule types may be classified (Replogle and Gordon, 2007), in order of increasing flexibility, as rigid (rotation, predetermined), central control, intermediate control (arranged) or flexible (on-demand, modifiable). Several studies have shown that between these two extremes, the more flexible the schedule is, the more energy hungry the system becomes (Rodriguez et al., 2009; Moreno et al., 2010b). Moreover, other approaches have been carried out to show the influence of management systems on energy consumption in farm systems, considering the life cycle assessment of a crop (Rodrigues et al.,2010), and the energy gain of crops and water productivity (Chen and Baile, 2009; Guzman et al., 2008). The use of pressurised (or not) irrigation networks is shown to be a key factor in these analyses.

Apart from the initial concern over irrigating during the hours at which the electricity tariffs are cheapest (Pulido-Calvo et al., 2003), the requirement of energy optimisation is also considered regarding the design and operation processes of irrigation networks. Moreover, performance indicators of irrigation systems have been defined (Luc et al., 2006; Calejo et al., 2008, Pérez et al., 2009: Moreno et al., 2010c; Rodriguez et al., 2011). And even, in a clear attempt to consider all the possibilities for improvement, the comparison of different systems using benchmarking strategies (Malano and Burton, 2001; Makin et al., 2004; Córcoles et al., 2012) allows the regulator to identify the networks whose practices should be followed.

When a decision maker deals with the reduction of energy consumption in irrigation networks, the first step is to properly calculate the amount of water required by crops. The second stage is to quantify the water and energy losses through the network in order to have all relevant information. The two last stages are closely linked as they include showing actions to reduce energy consumption and performing a cost benefit analysis to select the most convenient option.

This work deals with the second stage of this process, the quantification of the water and energy consumption in irrigation networks. It includes the use of the energy audit (Cabrera et al., 2010) in agricultural water networks (new terms such as the energy lost in hydraulic valves and hydrants have been added) and the definition of new performance indicators (necessary information to carry out an analysis of energy consumption throughout the system) that consider the key features of irrigation networks.

This energy audit is more comprehensive than those that have gone before, including the identification and quantification of all elements that either supply energy to (which can be of two kinds, potential energy supplied by reservoirs, which depends on the height of the header tank or reservoir, and shaft work supplied by the pumps or draw energy from the irrigation network (the energy output is broken down into energy delivered to users (in irrigation networks, this term refers to energy delivered to crops), energy dissipated due to friction and energy losses through leaks (energy lost when water is depressurised and is lost). This last term is not negligible in irrigation networks and its calculation is one of the key objectives of this work. Water losses have always existed in irrigation ditches, although in pressurised water networks they involve energy losses as well.

In order to complete the energy audit, two premises should be met. The first is to have calculated the water audit, an easy task if the network has proper metering devices (a flow meter at the head of the network and water meters installed in every irrigated area); while the second is to obtain a calibrated hydraulic model that adheres as closely as possible to reality (unfortunately, all WDS are leaky and the model should consider leaks as pressure-dependent demand when the hydraulic calculations are first done). Once these stages are completed, the energy balance quantifies the amount of energy used for the delivery of water in any network.

As commented before, some performance indicators have been defined for agricultural water networks (while those used in urban networks also apply here). These indicators show the information necessary to carry out an analysis of energy consumption throughout the system. The current energy analyses (Moreno et al., 2010c; Rodriguez et al., 2011) are summarised in just one indicator, shaft energy per volume (injected or consumed, kWh m^{-3}).The fact that these studies do not disaggregate energy expenditure means that they do not effectively identify or diagnose the weaknesses of the systems they consider. The results obtained with the new performance indicators show where the head losses are produced.

In conclusion, this work applies the energy audit to a real landscape irrigation network (real case study). And according to the values of the indicators, actions to improve water and energy management are proposed, the energy benefits are quantified and a cost analysis is performed.

Nomenclature

$C_{e,i}$ Emitter coefficient at node i (m$^{(3-\alpha)}$ s^{-1})

C_{sj} Emitter discharge coefficient of every sprinkler (m$^{(3-\alpha)}$ s^{-1})

C_1 Context Information – Energy nature (dimensionless)

C_2 Context Information – Network energy requirement (dimensionless)

$E_{dissipated}(t_p)$ Energy losses due to friction for the simulation period (MJ)

$E_f(t_p)$ Friction energy in pipes for the simulation period (MJ)

$E_h(t_p)$ Friction energy in hydrants for the simulation period (MJ)

$E_{input}(t_p)$ Input energy for the simulation period (MJ)

$E_l(t_p)$ Energy through leaks for the simulation period (MJ)

$E_{\min,useful}$ Minimum useful energy needed in a frictionless, leak-free network served with the minimum required pressure (MJ)

$E_{\min,flat}$ Minimum theoretical energy needed in an ideal network, frictionless, leak-free and flat (MJ)

$E_n(t_p)$ Energy supplied by the reservoirs for the simulation period (MJ)

$E_{output}(t_p)$ Output energy for the simulation period (MJ)

$E_p(t_p)$ Energy supplied by pumping stations for the simulation period (MJ)

$E_u(t_p)$ Energy supplied to users for the simulation period (MJ)

$E_v(t_p)$ Friction energy in valves for the simulation period (MJ)

$E_{wasted}(t_p)$ Energy wasted in leakage and dissipation for the simulation period (MJ)

h_{mi} Minimum required piezometric head at node i (m water column, m.w.c.)

h_h Head at the sprinklers (m.w.c.)

$h_i(t_k)$ Piezometric head at node i at time t_k (m.w.c.)

$h_{ni}(t_k)$ Piezometric head at the reservoir i at time t_k (m.w.c.)

$h_{pi}(t_k)$ Piezometric head of the i pump at time t_k (m.w.c.)

h_{sj} Piezometric head at the sprinkler j (m.w.c.)

I_1 Performance indicator – excess of supplied energy (dimensionless)

I_2 Performance indicator – network energy efficiency (dimensionless)

I_3 Performance indicator – energy dissipation (dimensionless)

I_4 Performance indicator - leakage energy (dimensionless)

I_5 Performance indicator – standards compliance (dimensionless)

I_6 Performance indicator – characterisation of energy losses (dimensionless)

I_{61} Performance indicator – energy losses in pipes (dimensionless)

I_{62} Performance indicator – energy losses in valves (dimensionless)

I_{63} Performance indicator – energy losses in hydrants (dimensionless)

n Number of demand nodes of the network (dimensionless)

n_i Number of time intervals ($t_p = n_i \cdot \Delta t$) (dimensionless)

n_h Number of hydrants of the network (dimensionless)

n_l Number of pipes of the network (dimensionless)

n_n Number of reservoirs (dimensionless)

n_p Number of pumps (dimensionless)

n_v Number of valves (dimensionless)

m Number of sprinklers (dimensionless)

N Rotation speed of the pumping unit using one variable frequency drive (r.p.m.)

N_0 Nominal rotation speed of the pumping unit (r.p.m.)

$\left(\frac{P_m}{\gamma}\right)_i$ Minimum required pressure at node i (m.w.c.)

$q_{hj}(t_k)$ Flow rate at hydrant j at time t_k (m^3 s^{-1})

$q_j(t_k)$ Flow rate at line j at time t_k (m^3 s^{-1}). This term is divided into flow rate that it is consumed and lost through leaks $q_j(t_k) = q_{lj}(t_k) + q_{uj}(t_k)$

$q_{li}(t_k)$ Leakage flow rate at node i at time t_k (m^3 s^{-1})

$q_{lj}(t_k)$ Flow rate at line j at time t_k (m^3 s^{-1}) that finally is lost through leaks

$q_{ni}(t_k)$ Flow rate supplied by reservoir i at time t_k (m^3 s^{-1})

$q_{pi}(t_k)$ Flow rate supplied by pumping station i at time t_k (m^3 s^{-1})

$q_{ui}(t_k)$ Consumed flow rate at node i at time t_k (m^3 s^{-1})

$q_{uj}(t_k)$ flow rate necessary to satisfy the users demand that circulates at line j at time t_k (m^3 s^{-1})

$q_{vj}(t_k)$ Flow rate at valve j at time t_k (m^3 s^{-1})

t_k Time in the steady state simulation (s)

t_p Total time of simulation (s)

X Energy lost by friction of the leaking water flow (dimensionless)

z_i Elevation of node i (m)

$\forall_L(t_p)$ Total leakage volume for the simulation period (m^3)

$\forall_N(t_p)$ Total volume injected for the simulation period (m^3)

$\forall_U(t_p)$ Total volume consumed by users for the simulation period (m^3)

$\upsilon_{u,i}(t_p)$ Total demand of node i during the simulation period t_p (m^3)

α Emitter exponent (dimensionless)

γ Specific weight of water (N m^{-3})

$\Delta h_j(t_k)$ Friction losses in line j at time t_k (m.w.c.)

$\Delta h_{hj}(t_k)$ Friction losses in hydrant j at time t_k (m.w.c.)

$\Delta h_{vj}(t_k)$ Friction losses in valve j at time t_k (m.w.c.)

Δt Time interval of integration ($\Delta t = t_{k+1} - t_k$) (s)

2 METHODOLOGY

2.1 Case study

To illustrate the audit procedure, the programmed sprinkling system used for watering the garden of the Universidad Politécnica of Valencia is analysed (figure 1). The irrigation area of this garden has grown through time and new species have been added to the grass meadow (*Festuca arundinacea, Pennisetum clandestinum* and *Poa annua*). There are over 50 deciduous, 31 evergreen, 16 coniferous, and 13 palm (or similar) tree species and over 20 different shrub species. Nowadays, the plot is divided into hydro-zones which are grouped according to the landscape coefficient method (Costello and Jones, 1999) depending on water needs and crop evapotranspiration values. The reference crop evapotranspiration has been calculated from local weather data using the Penman-Monteith method (Allen et. al., 1998). For the months of greatest water need, and depending on the hydrozone, overall water needs are 1.7 and 3.9 l m^{-2} day, corresponding respectively to the water demand of the least and most exposed areas of the garden.

Since the irrigation network has been periodically modified, an inventory to characterise the components of the irrigation network has been created. The network irrigates an area of 10.63 ha and consists of 326 nodes, 186 pipes, a water well, two impeller pumps running in parallel and 141 electrovalves upstream of the water discharge outlets, which are the hydrants. The total length of the network is 4.8 km.

The hydrants supply the irrigation subunits, which have been designed under the criteria of uniformity of pressure (and consequently flow) at each subunit. This has been reached using a looped network to maintain the same pressure at every subunit. All the subunits are equipped with pop-up emitters (mainly rotating sprinklers and spray sprinklers). Each subunit sprinkler has been identified (according to their brand, model and installation characteristics) in order to obtain the characteristic curve of each from their technical specifications.

Groundwater is fed to the system by two identical pumping units (with a characteristic curve described by the equation $h_{pi}(t_k) = -0.155 \cdot \left(q_{pi}(t_k)\right)^2 - 0.794 \cdot \left(q_{pi}(t_k)\right) + 93.55$, where $q_{pi}(t_k)$ and $h_{pi}(t_k)$ are, respectively, the flow rate (m^3 s^{-1}) and the head (in metres of water column, m.w.c.; a unit defined as the pressure exerted by a column of water of 1 m in height at 4 °C at the standard acceleration of gravity) at time t_k supplied by the pump i. The flow and pressure downstream of the pumping station is measured with a Woltmann meter (class B) equipped with a pulse emitter (1 pulse = 100 litres) and a pressure transducer respectively (full scale 1 MPa, accuracy ± 1%).

The irrigation management system is based on central system scheduled delivery. This schedule is not as rigid as rotation scheduled delivery (where the irrigation time allocated to each hydrant is not flexible), and it is not nearly as flexible as on-demand delivery scheduling methods (where the flow into the network is random, as is the number of hydrants open at a given time).

Some electrovalves are grouped and defined as an irrigation sector. All of them work simultaneously and their operation is remote controlled. The network sectoring has been performed by technicians and gardeners who consider the different hydrozones, the required irrigation time for each subunit and the hours when electricity rates are lower (night). Their key goal is to distribute the flow supplied by the pumps uniformly, considering some other requirements such as the use of the different irrigation areas or the works to maintain the vegetation.

2.2 Energy audit of irrigation networks

This section briefly describes how to estimate the amount of energy used in irrigation networks. The terms used in the energy audit for urban water systems (Cabrera et al., 2010) have been adapted to irrigation networks and the energy dissipated by friction has been divided into energy dissipation in pipes, control valves and irrigation hydrants.

In order to perform the analysis in an extended period (t_p, which can take values such as 1 year, 1 month, 1 day, etc.), it is necessary to divide duration time into n_i intervals of time (Δt_k; 300, 600, 900, 3600 seconds, etc.). Thus, the total energy consumed in the extended period ($t_p = n_i \cdot \Delta t_k$) is obtained from the sum of the energies consumed in each time interval of the steady state simulation.

2.2.1 Energy supplied by the reservoir

The external energy supplied by reservoirs is:

$$E_n(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{i=1}^{n_n} q_{ni}(t_k) \cdot h_{ni}(t_k) \right) \cdot \Delta t_k \qquad (1)$$

where γ is the specific weight of water, n_n is the number of reservoirs, $q_{ni}(t_k)$ and $h_{ni}(t_k)$ are, respectively, the flow rate (m^3 s^{-1}) and piezometric head (m.w.c.) supplied from each of the water tanks at time t_k, where Δt_k is the time interval (s).

2.2.2. Energy supplied by pumping stations

The shaft work supplied by the pumps is:

$$E_p(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{i=1}^{n_p} q_{pi}(t_k) \cdot h_{pi}(t_k) \right) \cdot \Delta t_k \qquad (2)$$

where $q_{pi}(t_k)$ and $h_{pi}(t_k)$ are respectively the flow rate pumped by the station (m^3 s^{-1}) and the pump head (m.w.c.) at time t_k. This calculation needs to be done for the n_p pumping stations that supply shaft work to the system at each discrete time t_k. This energy is water energy and by considering the performance of each pumping unit (an essential parameter for energy optimisation) the electrical equivalent can be calculated. In this paper, and since the focus is on new concepts, these energy losses have not been included in the analysis.

2.2.3 Energy delivered to users at consumption nodes

The energy delivered to users is:

$$E_u(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{i=1}^{n} q_{ui}(t_k) \cdot h_i(t_k) \right) \cdot \Delta t_k \tag{3}$$

where n is the number of demand nodes of the network, $q_{ui}(t_k)$ and $h_i(t_k)$ are respectively the flow rate delivered to users (m^3 s^{-1}) and the piezometric head (m.w.c.) at node i and time t_k.

2.2.4 Energy through leaks

Leaks represent energy leaving the system, formally analogous to the energy delivered to users although from the point of view of the audit it is lost energy. This term is:

$$E_l(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{i=1}^{n} q_{li}(t_k) \cdot h_i(t_k) \right) \cdot \Delta t_k \tag{4}$$

with n being the number of nodes in the network, $q_{li}(t_k)$ the leaked flow rate (m^3 s^{-1}) in the pipes adjacent to node i (and therefore associated with this node) at time t_k, and $h_i(t_k)$ is the piezometric head (m.w.c.) at time t_k in the node where the leak $q_{li}(t_k)$ has been concentrated.

2.2.5 Friction energy dissipation

The energy dissipated by friction is divided into energy dissipated in pipes, in control valves and in hydrants. As previously mentioned, the latter two of these parameters are specifically introduced to take into account the singularities of the irrigation networks. These elements can be present in urban water networks, but their influence is much lower (from an energetic point of view) than in irrigation networks. For instance, pressure control valves are common in irrigation networks and their energy dissipation becomes an important factor. Similarly, the particular configuration of an irrigation system may also indicate poor energy management, and therefore local hydrant losses can affect overall network performance.

2.2.6 Energy dissipation in pipes

The energy dissipated due to friction in pipes is:

$$E_f(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{j=1}^{n_l} q_j(t_k) \cdot \Delta h_j(t_k) \right) \cdot \Delta t_k \tag{5}$$

where n_l is the number of lines of the network, $\Delta h_j(t_k)$ are friction losses (m.w.c.) in line j at time t_k (this term is the difference in piezometric heads between the initial and final nodes), $q_{uj}(t_k)$ and $q_{lj}(t_k)$ are, in line j, the flow rate necessary to satisfy the users demand and the flow rate that finally is lost through leaks, respectively. Therefore, the total flow rate in line j, $q_j(t_k)$, is the sum of the two previous values.

2.2.7 Energy dissipation in hydraulic valves

The energy dissipated in hydraulic valves is:

$$E_v(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{j=1}^{n_v} q_{vj}(t_k) \cdot \Delta h_{vj}(t_k) \right) \cdot \Delta t_k \tag{6}$$

where $q_v(t_k)$ is the flow rate (m^3 s^{-1}) flowing through the hydraulic valve j at time t_k, n_v is the number of valves and $\Delta h_{vj}(t_k)$ is the piezometric head (m.w.c.) lost in the hydraulic valve j (calculated as the difference between the upstream and downstream nodes of the valve).

2.2.8 Energy dissipation in hydrants

The energy dissipated in hydrants is:

$$E_h(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{j=1}^{n_h} q_{hj}(t_k) \cdot \Delta h_{hj}(t_k) \right) \cdot \Delta t_k \tag{7}$$

where $q_h(t_k)$ is the flow rate (m^3 s^{-1}) flowing through the hydrant j at time t_k, n_h is the number of hydrants and $\Delta h_{hj}(t_k)$ is the piezometric head (m.w.c.) lost in the hydrant j (individual elements, water meters, filters, valves, etc.).

2.3 Final balance

From the preceding terms, where t_p is the period of calculation of the expressions (commonly one year), the following final balance results:

$$E_{input}(t_p) = E_n(t_p) + E_p(t_p) = E_u(t_p) + E_l(t_p) + E_f(t_p) + E_v(t_p) + E_h(t_p) =$$

$$= E_{output}(t_p) + E_{dissipated}(t_p) = E_u(t_p) + E_{wasted}(t_p) \tag{8}$$

Equation (8) states that the energy supplied by reservoirs and pumps to the water coming into the network is equal to the energy delivered to the users (throughout the water supplied) plus the losses (leakage and friction) $E_{wasted}(t_p) = E_l(t_p) + E_f(t_p) + E_v(t_p) + E_h(t_p)$. From this balance, energy losses can be evaluated and efficient actions aimed to improve system's efficiency can be planned.

These equations might be solved using water network modelling software to calculate all the values required (flow rates, piezometric head, friction losses, etc. in any element and at any time). The energy audit requires a calibrated model and the water balance, which needs to be calculated in advance. The key to performing the energy audit might be to get all the information from a single network, and this can readily be achieved using data loggers, remote sensors, monitoring devices and information systems such as GIS (Pereira et. al., 2002; Playan and Mateos, 2006; MARM, 2006; Avellá and García-Mollá, 2009). In fact, this situation is increasingly common, and even more so in areas where water is scarce. Once these requirements are met, all these values can be calculated using the water network modelling software, and the equations can be solved. The software selected here has been EPAnet (Rossman 2000), maybe the most widely used around the world. This software is used to calculate the flows, heads, head losses, etc. in all the pipes and at all the nodes in the model. EPAnet is demand-driven modelling software that uses temporal demand pattern multipliers to represent a diurnal demand curve, and a 168 h (1 week) extended period simulation may be performed.

2.4 Tools to assess performance system

2.4.1 Context information and Performance Indicators in irrigation networks

Context information and Performance Indicators defined elsewhere for water supply systems (Cabrera et al., 2010) are also valid for irrigation networks. In the following paragraphs, their mathematical expressions and a new performance indicator for irrigation networks are presented (table 2). For a better understanding of these indicators, two terms are explained here. The first is the minimum useful energy ($E_{\min,useful}$), the energy when delivering the flow at each node from the minimum required head ($h_{mi} = z_i + \left(\frac{P_m}{\gamma}\right)_i$). The second deals with the theoretical minimum required energy for a flat, leak-free and frictionless network ($E_{\min,flat}$).

Although all context information and Performance Indicators presented reveal new information, some of them are of paramount importance. The context information will help to identify easily whether these energy analyses are necessary or not; it shows the energy obtained without pumping (C_1), and if the network is flat or hilly (C_2). The energy audit will be performed if context information (which can be obtained in the absence of a hydraulic model) recommends it. The most relevant performance indicator is network energy efficiency (I_2) as it represents the portion of energy delivered to crops; this indicates whether the irrigation network is properly managed. Next come energy dissipation (I_3), characterisation of energy losses (I_6) (both of which refer to design and network sectoring processes) and leakage energy (I_4) (related to operation and management issues). Finally, excess of supplied energy (I_1) and standard compliance (I_5) reveal if regrouping of the numerous hydrants can reduce energy expenditure.

As irrigation networks generally have higher amounts of dissipated energy than urban water systems, an indicator for the determination of energy losses, I_6, is defined that estimates the importance of dissipated energy divided by the energy expended in the network. This indicator ranges from 0 to 1, where values close to zero indicate that the network is oversized (low friction losses), while values close to 1 indicate leak-free networks. This indicator complements indicators I_3 and I_4, providing a more detailed analysis of the network. Furthermore, as energy dissipation occurs in pipes, hydraulic valves and hydrants, the indicators I_{61}, I_{62} and I_{63} define their relative importance, where $I_6 = I_{61} + I_{62} + I_{63}$.

For any water network, the sum of energy efficiency, dissipated energy and leakage energy takes a value close to and above 1 ($I_2 + I_3 + I_4$=1+X). This excess (X) represents the energy lost by friction of the leaking water flow, with values that ranges from 0 (in leak-free networks) to 1 (an ideal and maximum value that would mean that all the input energy is lost by friction of the leaking water flow).

2.5 Simulation stage

The main features of the network are:

1. The irrigation subunits (manifolds, lateral and sprinklers) are installed at the water use nodes and, although considered in the characterisation of water consumption, for simplicity they have not been included in the hydraulic simulation model. The flow rate of the sprinklers depends on the water pressure through the discharge equation.

$$q_{hi}(t_k) = \sum_{j=1}^{j=m} C_{sj} \cdot h_{sj}{}^{\alpha} = \left(\sum_{j=1}^{j=m} C_{sj} \right) \cdot h_h^{\alpha} \tag{9}$$

   where C_{sj} (m$^{(3-\alpha)}$ s^{-1}) is the emitter discharge coefficient assigned to each node of the system to calculate the flow rates of every sprinkler, m is the number of sprinklers installed at the garden, α is the exponent of the emitter (α=0.5) and h_{sj} (m.w.c.) represents the piezometric head at the sprinkler j. As the pressure at every subunit is constant (as a consequence of the hydraulic design of the subunit, which leads to a suitable diameter of the pipe and a looped network that ensures a constant pressure), the piezometric head at every sprinkler can be expressed as h_h (in m.w.c.).

   In the simulation model, nodes were grouped into a single characteristic equation that represents all emitters of each subunit. Thus, the head losses at each subunit are assumed to be negligible, which means that the inlet pressure at each rotating or spray sprinkler is equal to that existing downstream of the electrovalve.

2. The behaviour of each hydrant is simulated by setting a variable pressure drop to each electrovalve. Three diameters (32, 50 and 63 mm) and six different brands are used in the garden (resulting in 15 different types of hydrant). The relationship between pressure drop and flow through the hydrant has been characterised in the laboratory (figure 2 shows an example) and these results have been compared with the information provided by the manufacturer. This requires each hydraulic element and its behaviour to be identified once again in the simulation model. The minimum required pressure at the nodes for the correct operation of the sprinklers takes a value of $\left(\frac{P_m}{\gamma}\right)_i$=15 m.w.c. This value has been adopted with regard to technical recommendations and the practical experience of the technicians and gardeners. At lower values of pressure, the pop-up and proper functioning are not guaranteed.

3. The model also considers leakage. The leaks have been measured using the night-flow method (UKWIR, 1994). This method requires the level of leakage to be measured when the delivered water is a minimum (and consequently the pressure is a maximum). Therefore, all the hydrants were closed to measure water consumption (using the Woltmann meter downstream of the pumping station), which in this scenario coincides with leakage. The leaks are assumed to be uniformly distributed (a simplification that comes from the fact that pipes are made of the same material and of the same age in the case study and from the difficulty in finding leaks throughout the system) and are grouped at the nodes in proportion to the length of the converging pipes (Almandoz et al., 2005). The four basic approaches to leakage management are pressure management, active leakage control, speed and quality of repairs and pipes renewal (Lambert and McKenzie, 2002), but leakage management practitioners are well aware that real losses cannot be totally eliminated (OFWAT, 2007) and the volume of

unavoidable annual real losses (UARL) represents the lowest technically achievable annual real losses for a well-maintained system. As a consequence of that, small leaks with flow rates for sonic detection if non-visible (background leakage) are not economically viable to repair. Leaks are represented as atmospheric relief valves (emitter coefficient), at each node of the network (like the water flow consumed). The design of each emitter has been made according to expression (Rossman, 2000)

$$q_{li}(t_k) = C_{e,i} \cdot h_i(t_k)^{\alpha} \tag{10}$$

where $C_{e,i}$ ($m^{(3-\alpha)}$ s^{-1}) is the emitter coefficient assigned to each node of the system, $h_i(t_k)$ (m.w.c.) represents pressure drops experienced by the water when passing through the hole and α is the exponent of the emitter. A value of α =0.5 is adopted herein. With the above expression, the leaks in the model are pressure driven demand. Leaks are not typically represented in this way because most hydraulic simulation software, including EPAnet2.0, represents water consumption as independent of pressure (demand driven).

4. As commented before, the irrigation management system is based on central system scheduled delivery. This type of operation is similar to the operation of many agricultural farms (and many networks of water user associations), where the modern technologies related to the operation and management of reservoirs, supply systems and hydraulic valves provide the effective use of automation and remote control for systems managers. This feature is considered in the hydraulic simulation model as a control valve (opened when an area has to be watered according to scheduled irrigation). Although the audit is calculated for a period of one year (used as a reference for comparison of results and indicators), irrigation is scheduled weekly. All these features were incorporated in the hydraulic model.

The energy use of on-demand delivery scheduling networks can be calculated using the EPAnet software and running a high number of simulations using the EPAnet toolkit. In each simulation, the total amount of water delivered has to be the same (as the energy consumption is linked to water consumed) and as the irrigation time of the hydrants is a fixed value (i.e. 3.5 hours per day), the opening time of each hydrant would be the parameter that would be modified randomly at each simulation.

It should also be highlighted that the energy audit performed here (based on the energy equation applied to incompressible fluids) only handles hydraulic equations that do not depend either on final water use or flow regulation. From the energy standpoint, the difference between the delivery scheduling methods is only a matter of boundary and temporal conditions, which are easy to consider using the hydraulic simulation software (with simple or rule-based controls). In the current case study, as the schedule is more rigid, the opening time of every hydrant is determined using control rules in EPAnet (e.g. valve 1.1-A open at time 15:30) and it is only necessary to run one simulation.

In the model, the water consumed at the end nodes is water used for irrigation while the water consumed at intermediate nodes is leaking water (water losses that do not meet their goal). All the information recovered in the garden is added to the model in the hydraulic simulation software (EPAnet or any other) and the calibration process starts. The objective of the calibration is to observe a good response between the simulated (model predicted) and the observed values (pressures and flows at several points of the network) over the entire simulation period (1 week). The calibration parameters considered here have been the unknown roughness coefficients (the simulations have been carried out using the Darcy-Weisbach equation to calculate the head losses) and the emitter coefficients to achieve better agreement between the observed and modelled pressures and flows respectively (using 5 transducers and one datalogger). A heuristic process in order to select the location of pressure transducers has been carried out. This process was used to obtain a representative sample of the pressure levels throughout the network for three days in July (when the water demand reaches its maximum).

2.6 Scenarios tested

The case study presents the energy analysis of an irrigation system with different leakage rates and with different type of pressure regulation. Case I and Case III represent the current irrigation network, with a volumetric efficiency slightly higher than 75% and a leakage flow rate of $2.166*10^{-7}$ m^3 (s^{-1} m^{-1}) or the equivalent (and more usual 0.78 m^3 (km h)$^{-1}$, which expresses that that every hour, 0.78 m^3 are lost in every kilometre of pipe) typical values oscillate between 0.2-2 m^3 (km h)$^{-1}$ in water networks; OFWAT, 2010). Case II and IV represent the initial state of the network (or the leak-free situation) with small leakage rates (96% volumetric efficiency and leak rates of $1.66*10^{-8}$ m^3 (s^{-1} m^{-1}), equivalent to 0.06 m^3 (km h)$^{-1}$).

In Case I and II, pressure regulation is performed using a pressure reducing valve (PRV) (after pumping, the network pressure drops throughout the simulation period to a given value) while in Case III and IV pressure regulation is performed using pumps equipped with variable frequency drive (VFD; figure 3). For hydraulic purposes, the values obtained at the pressure transducer (P1, figure 3) located downstream of the pumps (Case III and IV) or downstream of the pressure reducing valve (Case I and II) are the same (55 m.w.c.) in the four cases analysed here. Due to this fact, Cases III and IV show similar hydraulic results to Cases I and II (only the pressure control system has changed).

This paper does not intend to demonstrate whether the proposed control system, with two variable speed pumps, is more suitable than other configurations (the regulation problem can be solved with one VFD); the aim of the paper is to show that the pressure regulation systems shown at Cases III and IV are more efficient than the current regulation system.

3. RESULTS AND DISCUSSION

3.1 Results of the water audit

The results of the water audit for the Cases are:

- Input water flow: $\forall_N(t_p)$= 4.18 10^{-3} m^3 s^{-1} (equivalent to 0.132 hm^3 $year^{-1}$) (Cases I and III) and 3.26 10^{-3} m^3 s^{-1} (0.103 hm^3 $year^{-1}$) (Cases II and IV).
- Delivered water: $\forall_U(t_p)$= 3.14 10^{-3} m^3 s^{-1} (0.099 hm^3 $year^{-1}$) (for all the Cases).
- Real losses: $\forall_L(t_p)$= 3.14 10^{-3} m^3 s^{-1} (0.033 hm^3 $year^{-1}$) (Cases I and III) and 0.13 10^{-3} m^3 s^{-1} (0.004 hm^3 $year^{-1}$) (Cases II and IV).

3.2 Results of the energy audit

The results of the energy audit (MJ consumed per year) are given in table 3. Values in parentheses indicate the percentage that each term represents of the input energy. These values can be converted into MWh (a well known unit for practitioners) dividing them by 3600.

The most relevant results in table 3 are the decrease of the energy supplied by pumps in case II (leak-free scenario) in comparison with Case I (real scenario). Energy savings are obtained due to the lower values of energy dissipated (as a consequence of less flow circulating through the network) and due to the decrease in the energy losses through leaks.

Another approach to better energy efficiency in irrigation networks deals with the pressure regulation problem. The head loss at the pressure reducing valve (PRV) in Case I and II is 79-55=24 m.w.c., and the annual energy loss of the valve is 23832MJ (equivalent to 6.62 MWh) (98% of the energy dissipated in the hydraulic valves, table 3). Therefore, the elimination of the control valve and the use of variable speed pumps (Cases III and IV) will improve the energy efficiency of the system as the energy dissipated in hydraulic valves decreases.

There are some constraints (VFD price and reliability) that affect the worldwide implementation of this control technique (Pemberton, 2005). The new control system meets the water flow (1-18.5 l s^{-1}) and pressure (55 m.w.c.) requirements of the network through the day. The maximum flow rates (18.5 l s^{-1}) are delivered at a rotation speed equal to $N = 0.9 \cdot N_0$ (where N is the new rotation speed and N_0 is the nominal rotation speed of the pumping unit) while the minimum water flow (1 l s^{-1}) is achieved at a rotation speed equal to $N = 0.77 \cdot N_0$. The energy values for these new cases are given in table 3.

The comparison of the real scenario data with those after removal of the hydraulic valve (Case I and III, table 3) shows annual energy savings of 111143.9-85212.1=25931.8 MJ (equivalent to 30.87-23.67 = 7.20 MWh $year^{-1}$). It may seem small, but it represents 23% of the energy spent in the process and it also represents 198MJ (0.055 kWh) for each m^3 supplied to the system. Considering that the maximum power of the pumps is 12 kW (16.4 HP) and pump speed device (PSD) is supplied with 3-phase 440V, it results in a 3000 € per PSD (maximum power equal to 20 HP). In short, the investment is 6000 € (as there are two pumps operating in parallel and consequently 2 PSDs are required). Moreover, if considering that the energy costs are 0.15 € kWh^{-1}, the payback period of this alternative is 5.55 years and the annual energy savings are 1080 €. This payback period has been obtained only considering the pressure reduction and it will be shortened if other factors are taken into account since the delivery scheduling methods of irrigation also show themselves to be of key importance when obtaining the energy consumption in irrigation networks.

3.3 Indicator determination and discussion

The proposed context information and Performance Indicators provide better insight into the characteristics of the network under study. Their numerical values are depicted at table 4.

The context-related information has the same values in all the cases (independent of irrigation management mode and leaks in irrigation networks). Energy nature (C_1) ranges from 0 (if all the energy is provided by pumps) to 1 (if energy is supplied by the reservoir). This shows that the network is energy hungry and also that further studies on energy reduction are appropriate. Network energy requirements (C_2) range from 1 to infinity, and show whether the network is flat (values close to 1) or hilly (values far from 1). In this case, a value of 1.76, indicating that the network is fairly flat, as there is a 13.7 m difference in height between the highest and lowest nodes of the network.

By contrast, the Performance Indicators, shown in the remaining columns, depend on the state of the system. In order to clarify the information obtained from the Performance Indicators, the discussion has been disaggregated into the following two sections. The first with regard to Cases I and II (regulation performed with PRV) and the second, Cases III and IV (regulation performed with two variable speed pumps).

3.3.1 Performance Indicators at Cases I and II

The first indicator (I_1) shows the system's incoming energy with respect to the minimum useful energy, i.e. the outgoing energy at the nodes in the event that all nodes maintain the minimum pressure flow throughout the day. This energy is 4.33 times higher than the minimum useful energy, and if leaks are eliminated, there will be a small improvement of the system, to 3.36 (Case II).

About half of the input energy becomes energy delivered to crops (I_2=0.47), an acceptable value. The elimination of leaks in the irrigation network (Case II) significantly increases this value (I_2= 0.61). One third of the total network energy is dissipated by friction (I_3= 0.33), a typical value in irrigation networks and in Case II, although the value of the annual dissipated energy decreases (31092 compared to 37107.2 MJ; table 3), it is a greater proportion of the input energy, and this indicator slightly increases (Case II, I_3= 0.36).

Indicator I_4 quantifies the amount of input energy that is lost due to leakage. In this case study, the total energy lost through leakage is 20% of the overall input energy, a low value. In an ideal leak-free system, its value is 0. The expected values should be between 0.2 and 0.4.

The indicator I_5 shows the ratio between the energy delivered to users and the energy when delivering the flow at the minimum required head, and thus it quantifies the additional energy delivered to users (as a consequence of the additional head). The values of this indicator are good and typical of pressurised networks (I_5= 2.04 -2.05; Cases I and II). The closer to one, the better. Therefore, its higher value and better management (Case II) compared to the original network (Case I) reveal that the heads at all the nodes of the network are higher and as a consequence, more energy savings can be obtained following future energy policies. The value obtained here indicates that the network is energetically well-managed (although this is easy as it is a flat network, as indicated by C_2). However, it is always possible to improve energy efficiency, and irrigation indicators serve to identify the major energy losses and potential improvements of the system.

The new indicator, I_6, highlights the amount of energy lost by friction in comparison to the total energy lost in the system. In Case I (I_6 = 0.63), the result is typical of networks with leaks, while in Case II the value of this indicator is close to one as the network has small leakage rates. Indicators I_{61}, I_{62} and I_{63} reveal that the main energy losses occur in hydraulic valves (I_{62}= 0.41 and 0.56) and that energy losses in hydrants are meaningless (I_{63}= 0, energy dissipated in hydrants is low compared to energy wasted). In this particular case study, the energy lost due to friction in hydrants is not relevant, but this indicator can be of paramount importance in other networks.

In Case I the energy dissipated by leakage is 0.4% of the input energy ($I_2 + I_3 + I_4$= 1.004; X = 0.004). In Case II, leak-free, X is 0.

The data from the water and energy audits can be used to calculate the energy indicator expressed as kWh m^3, which is highly dependent on the topography of the terrain. It has the following values:

- Energy consumed per unit volume injected into the network: 841.62 KJ m^{-3} (0.23 kWh m^{-3}) in both cases (which means that 0.23 kWh are consumed to inject one cubic meter of water into the system), a figure that coincides with the estimate made by Corominas (2010).

- Energy consumed per unit volume consumed by the network: 1121.3 and 859.68 KJ m^{-3} (0.31 and 0.24 kWh m^{-3}) Case I and II, respectively (values that express that in order to irrigate one cubic meter of water, 0.31 kWh in Case I and 0.24 kWh are consumed). These values are greater than the previous one as they consider energy that is lost due to leaks.

The results outlined here show that active leakage control in irrigation networks results in energy savings because of the leakage reduction. Beyond these results, cost benefit analysis will describe the economic viability of future actions.

3.3.2 Performance Indicators at Cases III and IV

Cases III and IV show improvements with respect to Cases I and II. The new configuration presents lower energy values (I_1 = 3.32 Case III; I_1 =4.33, Case I) (table 4), a greater amount of input energy becomes energy delivered to crops (I_2 = 0.62 Case III) and friction losses decrease to very low rates (I_3 = 0.14 Case III compared to I_3 = 0.33, Case I).

The annual energy dissipated in hydraulic valves is now very low in Case III (473 MJ) and although the proportion of energy lost through leakage (I_4 = 0.20, Case I; I_4 = 0.25, Case III) is larger, this is because the energy input in Case III is much lower than in Case I. To highlight this fact, the annual energy associated with leakage in Case III (20607MJ) is lower than the same term in Case I (21534.2 MJ). The value of standards compliance (I_5 = 2.04 -2.05) is the same as before, because the amount of energy supplied does not change.

The dissipated energy in comparison to the total energy lost is much lower in Case III than in Case I where most of the dissipated energy is lost in the valve (I_6 = 0.37, Case III; I_6 = 0.63, Case I). However, in Case III most of the dissipated energy is lost in the pipes (I_{61} = 0.35) whereas energy dissipation in hydraulic valves and hydrants is insignificant (table 3).

The energy dissipated by leakage is 0.2% of the total input energy ($I_2 + I_3 + I_4$ = 1.002; X=0.02) in Case III, and 0 in Case IV (leak-free system). The energy consumed per unit volume injected to the network is 0.18 kWh m^{-3} in both cases (a low value, typical of an energetically well-managed network), while the energy consumed per unit volume used is 0.24 and 0.18 kWh m^{-3} (Case III and IV, respectively).

4 CONCLUSIONS

This work has adapted the energy audit, a tool that identifies the end uses of input energy in urban water supply networks, to irrigation networks. The main adjustment has been the decomposition of the energy dissipated by friction into three independent terms: the energy dissipated in pipelines, control valves, and hydrants. This separation allows the decision maker to have more detailed information about the characteristics of the network, and to better identify the primary source of friction losses. A new performance indicator is also proposed for highlighting the relevance of energy losses due to dissipation (friction in pipes, valves and hydrants). With this methodology, future actions can be adopted quantitatively (supported by the audit results) and not qualitatively.

The key output is a case study to show how the methodology can quantify the energy consumed in irrigation networks and to calculate the energy benefits derived from an efficient management of the irrigation network of the Universidad Politécnica de Valencia. The annual energy savings resulting from the use of a new control system as compared to current operations are (25931.8 MJ, equivalent to 7.20 MWh year^{-1}), a substantial value for a small irrigation system. Two case studies (Cases II and IV) have also shown significant annual energy savings in leak-free systems (24995 and 18435 MJ), respectively. Therefore, two ways of reducing energy losses in the network under study ($E_{wasted}(t_p)$) have been addressed, namely by reducing friction losses and leakage. The adaptation of the energy audit to irrigation systems has proved to be a powerful tool for the development of energy efficient strategies.

The types of irrigation (on-demand and rigid scheduled), hydrants and emitters (pressure-compensating, sprinklers, etc.) have been included (directly or indirectly) in the hydraulic model for the energy analysis of the system. The analysis of their effects is beyond the scope of this study, but they may be relevant when energy losses in irrigation hydrants are substantial. The proper design of the hydrant and irrigation subunit can improve energy efficiency. Additionally, a new indicator (I_{63}) that estimates the energy dissipated in irrigation facilities has been defined. The audit also considers leakage in irrigation networks. Water shortage, operational problems, the growing environmental concern and, ultimately, the economic cost of both water and energy losses justify the efforts to prevent leaks in the system.

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Figure

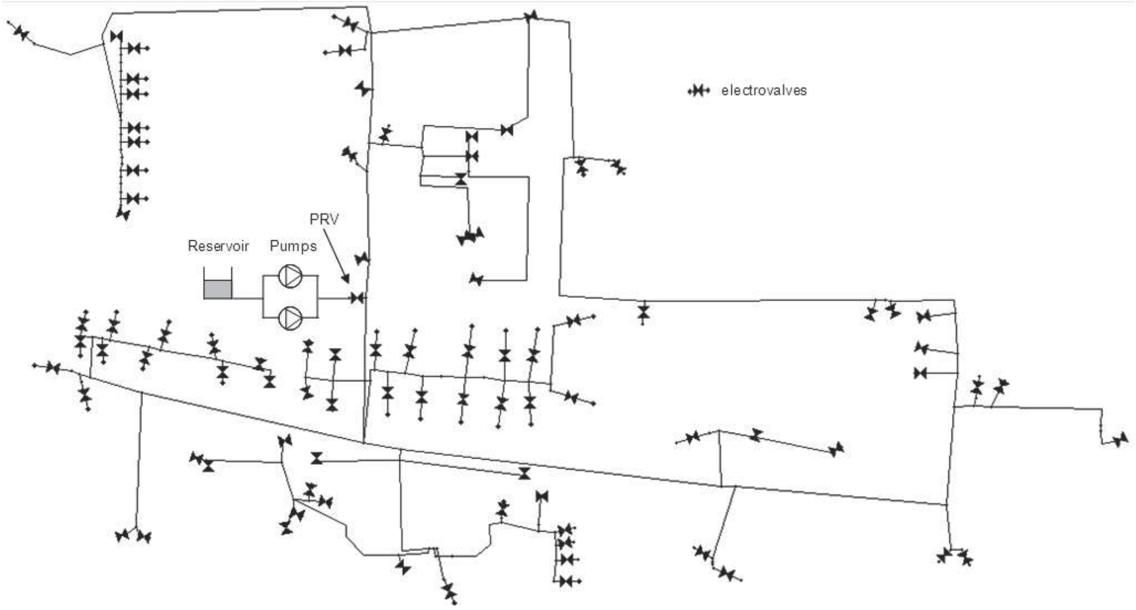


FIGURE 1. SIMPLIFIED LAYOUT OF THE NETWORK

Figure

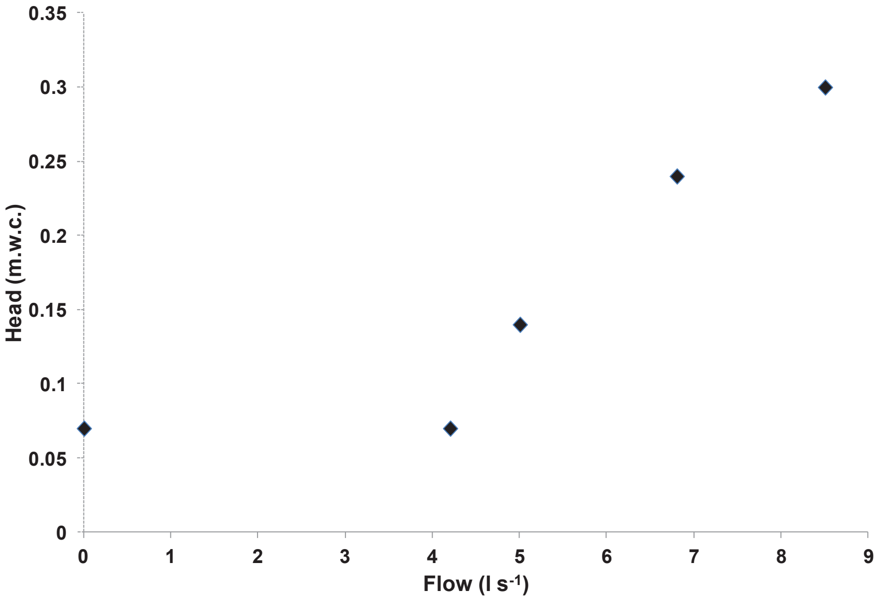
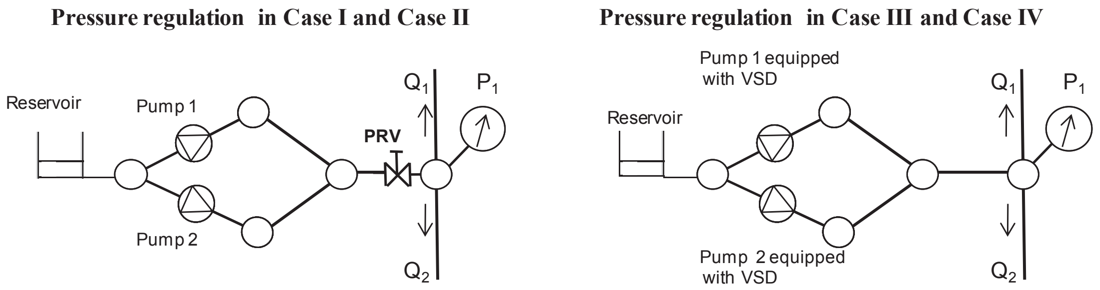


FIGURE 2. EXAMPLE OF WATER LOSS IN A HYDRANT OF THE NETWORK

Figure



Pressure regulation in Case I and Case II

Pressure regulation in Case III and Case IV

Figure 3. Types of pressure regulation

Table

TABLE 1. EVOLUTION OF WATER AND ENERGY CONSUMPTION IN IRRIGATION SYSTEMS IN SPAIN (COROMINAS, 2010)

Year	**Area** (Thousand ha)	**Water use** (hm^{-3})	**Energy consumption** (GWh)
1900	1000	5400	0
1930	1350	7594	182
1940	1500	8288	191
1950	1500	8353	309
1970	2200	12320	1056
1980	2700	14648	2093
1990	3200	17400	3480
2000	3410	18499	4893
2007	3760	20163	5866
Ratios of values in 2007 to the values in 1950	2.5	2.4	19.0

Table

TABLE 2. CONTEXT INFORMATION AND ENERGY EFFICIENCY INDICATORS

<table>
<tr><td colspan="2">C_1
Energy nature</td><td colspan="2">C_2
Network energy requirement</td><td colspan="2">I_1
Excess of supplied energy</td></tr>
<tr><td colspan="2">$C_1 = \frac{E_n(t_p)}{E_{input}(t_p)}$</td><td colspan="2">$C_2 = \frac{E_{\min,useful}}{E_{\min,flat}}$</td><td colspan="2">$I_1 = \frac{E_{input}(t_p)}{E_{\min,useful}}$</td></tr>
<tr><td colspan="2">I_2
Network energy efficiency</td><td colspan="2">I_3
Energy dissipation</td><td colspan="2">I_4
Leakage energy</td></tr>
<tr><td colspan="2">$I_2 = \frac{E_u(t_p)}{E_{input}(t_p)}$</td><td colspan="2">$I_3 = \frac{E_{dissipated}(t_p)}{E_{input}(t_p)}$</td><td colspan="2">$I_4 = \frac{E_l(t_p) + E_f(t_p) - E_f'(t_p)}{E_{input}(t_p)}$</td></tr>
<tr><td colspan="2">I_5
Standards compliance</td><td colspan="2">I_6
Characterization energy losses</td><td colspan="2">I_{61}
Energy losses in pipes</td></tr>
<tr><td colspan="2">$I_5 = \frac{E_u(t_p)}{E_{\min,useful}}$</td><td colspan="2">$I_6 = \frac{E_{dissipated}(t_p)}{E_{wasted}(t_p)}$</td><td colspan="2">$I_{61} = \frac{E_f(t_p)}{E_{wasted}(t_p)}$</td></tr>
<tr><td colspan="3">I_{62}
Energy losses in valves</td><td colspan="3">I_{63}
Energy losses in hydrants</td></tr>
<tr><td colspan="3">$I_{62} = \frac{E_v(t_p)}{E_{wasted}(t_p)}$</td><td colspan="3">$I_{63} = \frac{E_h(t_p)}{E_{wasted}(t_p)}$</td></tr>
</table>

Table

TABLE 3. ANNUAL ENERGY AUDIT (MJ)

		Case I	Case II	Case III	Case IV
$E_{input}(t_p)$	$E_n(t_p)$	0	0	0	0
	$E_p(t_p)$	111143.9	86148.9	85212.1	66777.0
$E_{input}(t_p)$		111143.9	86148.9	85212.1	66777.0
$E_{output}(t_p)$	$E_u(t_p)$	52414.1 (47.2%)	52526.6 (61.0%)	52414.1 (61.6%)	52526.8 (78.8%)
	$E_l(t_p)$	21534.2 (19.4%)	2442.2 (2.8%)	20607.6 (24.2%)	2336.9 (3.5%)
$E_{output}(t_p)$		73948.4 (66.6%)	54968.8 (63.9%)	73021.8 (85.8%)	54863.7 (82.3%)
$E_{dissipated}(t_p)$	$E_f(t_p)$	12712.3 (11.4%)	12198.1 (14.2%)	11547.4 (13.6%)	11270.8 (16.9%)
	$E_v(t_p)$	24312.8 (21.9%)	18811.7 (21.9%)	473.0 (0.6%)	472.9 (0.7%)
	$E_h(t_p)$	82.2 (0.1%)	82.2 (0.1%)	82.2 (0.1%)	82.2 (0.1%)
$E_{dissipated}(t_p)$		37107.2 (33.4%)	31092.0 (36.1%)	12102.6 (14.2%)	11825.9 (17.7%)