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Energy audit of irrigation networks

2

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15

16 ABSTRACT

17

18 The relationship between water and energy in water distribution systems (WDS) has been a
19 growing concern among energy and water experts. Among the different strategies to improve
20 water-energy efficiency in water distribution networks, energy audits are of paramount
21 importance as they quantify water flow requirements, the amount of energy consumed to meet
22 demand and leakage and friction losses. Previous work has presented the energy audit process
23 for urban WDS and this energy audit is extended to irrigation networks here. This work
24 analyses the most common types of irrigation emitters (sprinklers and pressure compensating
25 and non-pressure compensating drippers), hydrant specifications, irrigation management

26 systems (on-demand or rigid scheduled), and energy losses due to friction in pipes, control
27 valves and irrigation hydrants. The energy audit does not assess whether management of the
28 network is optimal, but analyses the energy consumption. Some of the performance indicators
29 have already been defined for agricultural water networks, some are identical to those of urban
30 WDS, but in addition, a new one is presented that disaggregates the energy dissipated into three
31 terms, energy losses in pipelines, in hydraulic valves and in irrigation hydrants. These indicators
32 show information necessary to better understand the performance of the irrigation network
33 under study, to carry out a deep analysis of energy consumption and to allow for comparison
34 with similar systems. The paper presents the analysis of a real case study conducted on the
35 irrigation network of the garden of the Universidad Politécnica de Valencia.

36

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

38

39 **1. INTRODUCTION**

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

48

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

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

55

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

62

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

70

71 The interest in reducing the energy bill can be addressed using two different and complementary
72 policies. The first (and most natural) strategy deals with the reduction of water consumption, as
73 water savings result in energy savings. This strategy involves a set of actions covered by the
74 term "water demand management". The first step is not to use more water than necessary (in
75 short, to optimise the water delivered to the crop). These needs are directly linked to

76 climatology and to soil moisture. Traditionally, great efforts to quantify the proper amount of
77 water required in scheduled irrigation have been made. Studies in this area include those related
78 to climate prediction (WMO, 2010), the use of soil moisture sensors (Greenwood et al., 2010),
79 deficit irrigation strategies (Geerts and Raes, 2009) and remote sensing and agro-climatic water
80 balance models (Bastiaanssen et al., 2007; Droogers et al., 2010).

81

82 The second is linked to the optimisation of the design and operation of irrigation networks from
83 an energy-related point of view. This has been an active research area since pressure irrigation
84 began (Allen and Brockway, 1984), and in recent years, for the aforementioned reasons, it has
85 been attracting increased attention. Irrigation networks have to be dimensioned (Farmani et al.,
86 2007; Daccache et al., 2009, González -Cebollada et al., 2011) taking into account energetic
87 implications. Furthermore they require pumping stations (Moradi-Jalal et al., 2004; Moradi-Jalal
88 and Karney, 2008; Moreno et al., 2010a) and complementary elements (Kale et al., 2008;
89 Armindo al., 2011) to be implemented to minimise energy expenditure. And once the system is
90 working, its management should also be optimised from the energy perspective (Jimenez-Bello,
91 2010; Lamaddalena and Khila, 2012).

92

93 It should be highlighted that the delivery scheduling method in an irrigation system
94 demonstrates different levels of energy consumption. These schedule types may be classified
95 (Replogle and Gordon, 2007), in order of increasing flexibility, as rigid (rotation,
96 predetermined), central control, intermediate control (arranged) or flexible (on-demand,
97 modifiable). Several studies have shown that between these two extremes, the more flexible the
98 schedule is, the more energy hungry the system becomes (Rodriguez et al., 2009; Moreno et al.,
99 2010b). Moreover, other approaches have been carried out to show the influence of
100 management systems on energy consumption in farm systems, considering the life cycle
101 assessment of a crop (Rodrigues et al.,2010), and the energy gain of crops and water

102 productivity (Chen and Baile, 2009; Guzman et al., 2008). The use of pressurised (or not)
103 irrigation networks is shown to be a key factor in these analyses.

104

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

113

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

119

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

126

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

137

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

145

146 As commented before, some performance indicators have been defined for agricultural water
147 networks (while those used in urban networks also apply here). These indicators show the
148 information necessary to carry out an analysis of energy consumption throughout the system.
149 The current energy analyses (Moreno et al., 2010c; Rodriguez et al., 2011) are summarised in
150 just one indicator, shaft energy per volume (injected or consumed, kWh m⁻³). The fact that these
151 studies do not disaggregate energy expenditure means that they do not effectively identify or

152 diagnose the weaknesses of the systems they consider. The results obtained with the new
153 performance indicators show where the head losses are produced.

154

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

158

159

160 **Nomenclature**

161 $C_{e,i}$ Emitter coefficient at node i ($\text{m}^{(3-\alpha)} \text{s}^{-1}$)

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

163 C_1 Context Information – Energy nature (dimensionless)

164 C_2 Context Information – Network energy requirement (dimensionless)

165 $E_{dissipated}(t_p)$ Energy losses due to friction for the simulation period (MJ)

166 $E_f(t_p)$ Friction energy in pipes for the simulation period (MJ)

167 $E_h(t_p)$ Friction energy in hydrants for the simulation period (MJ)

168 $E_{input}(t_p)$ Input energy for the simulation period (MJ)

169 $E_l(t_p)$ Energy through leaks for the simulation period (MJ)

170 $E_{\min,useful}$ Minimum useful energy needed in a frictionless, leak-free network served with the minimum
171 required pressure (MJ)

172 $E_{\min,flat}$ Minimum theoretical energy needed in an ideal network, frictionless, leak-free and
173 flat (MJ)

174 $E_n(t_p)$ Energy supplied by the reservoirs for the simulation period (MJ)

175 $E_{output}(t_p)$ Output energy for the simulation period (MJ)

176 $E_p(t_p)$ Energy supplied by pumping stations for the simulation period (MJ)

177 $E_u(t_p)$ Energy supplied to users for the simulation period (MJ)

- 178 $E_v(t_p)$ Friction energy in valves for the simulation period (MJ)
- 179 $E_{wasted}(t_p)$ Energy wasted in leakage and dissipation for the simulation period (MJ)
- 180 h_{mi} Minimum required piezometric head at node i (m water column, m.w.c.)
- 181 h_h Head at the sprinklers (m.w.c.)
- 182 $h_i(t_k)$ Piezometric head at node i at time t_k (m.w.c.)
- 183 $h_{ni}(t_k)$ Piezometric head at the reservoir i at time t_k (m.w.c.)
- 184 $h_{pi}(t_k)$ Piezometric head of the i pump at time t_k (m.w.c.)
- 185 h_{sj} Piezometric head at the sprinkler j (m.w.c.)
- 186 I_1 Performance indicator – excess of supplied energy (dimensionless)
- 187 I_2 Performance indicator – network energy efficiency (dimensionless)
- 188 I_3 Performance indicator – energy dissipation (dimensionless)
- 189 I_4 Performance indicator - leakage energy (dimensionless)
- 190 I_5 Performance indicator – standards compliance (dimensionless)
- 191 I_6 Performance indicator – characterisation of energy losses (dimensionless)
- 192 I_{61} Performance indicator – energy losses in pipes (dimensionless)
- 193 I_{62} Performance indicator – energy losses in valves (dimensionless)
- 194 I_{63} Performance indicator – energy losses in hydrants (dimensionless)
- 195 n Number of demand nodes of the network (dimensionless)

- 196 n_i Number of time intervals ($t_p = n_i \cdot \Delta t$) (dimensionless)
- 197 n_h Number of hydrants of the network (dimensionless)
- 198 n_l Number of pipes of the network (dimensionless)
- 199 n_n Number of reservoirs (dimensionless)
- 200 n_p Number of pumps (dimensionless)
- 201 n_v Number of valves (dimensionless)
- 202 m Number of sprinklers (dimensionless)
- 203 N Rotation speed of the pumping unit using one variable frequency drive (r.p.m.)
- 204 N_0 Nominal rotation speed of the pumping unit (r.p.m.)
- 205 $\left(\frac{P_m}{\gamma} \right)_i$ Minimum required pressure at node i (m.w.c.)
- 206 $q_{hj}(t_k)$ Flow rate at hydrant j at time t_k ($\text{m}^3 \text{s}^{-1}$)
- 207 $q_j(t_k)$ Flow rate at line j at time t_k ($\text{m}^3 \text{s}^{-1}$). This term is divided into flow rate that it is consumed
- 208 and lost through leaks $q_j(t_k) = q_{lj}(t_k) + q_{uj}(t_k)$
- 209 $q_{li}(t_k)$ Leakage flow rate at node i at time t_k ($\text{m}^3 \text{s}^{-1}$)
- 210 $q_{lj}(t_k)$ Flow rate at line j at time t_k ($\text{m}^3 \text{s}^{-1}$) that finally is lost through leaks
- 211 $q_{ni}(t_k)$ Flow rate supplied by reservoir i at time t_k ($\text{m}^3 \text{s}^{-1}$)
- 212 $q_{pi}(t_k)$ Flow rate supplied by pumping station i at time t_k ($\text{m}^3 \text{s}^{-1}$)

- 213 $q_{ui}(t_k)$ Consumed flow rate at node i at time t_k ($\text{m}^3 \text{s}^{-1}$)
- 214 $q_{uj}(t_k)$ flow rate necessary to satisfy the users demand that circulates at line j at time t_k ($\text{m}^3 \text{s}^{-1}$)
- 215 $q_{vj}(t_k)$ Flow rate at valve j at time t_k ($\text{m}^3 \text{s}^{-1}$)
- 216 t_k Time in the steady state simulation (s)
- 217 t_p Total time of simulation (s)
- 218 X Energy lost by friction of the leaking water flow (dimensionless)
- 219 z_i Elevation of node i (m)
- 220 $\forall_L(t_p)$ Total leakage volume for the simulation period (m^3)
- 221 $\forall_N(t_p)$ Total volume injected for the simulation period (m^3)
- 222 $\forall_U(t_p)$ Total volume consumed by users for the simulation period (m^3)
- 223 $\vartheta_{u,i}(t_p)$ Total demand of node i during the simulation period t_p (m^3)
- 224 α Emitter exponent (dimensionless)
- 225 γ Specific weight of water (N m^{-3})
- 226 $\Delta h_j(t_k)$ Friction losses in line j at time t_k (m.w.c.)
- 227 $\Delta h_{hj}(t_k)$ Friction losses in hydrant j at time t_k (m.w.c.)
- 228 $\Delta h_{vj}(t_k)$ Friction losses in valve j at time t_k (m.w.c.)
- 229 Δt Time interval of integration ($\Delta t = t_{k+1} - t_k$) (s)
- 230

231
232

2 METHODOLOGY

233 2.1 Case study

234 To illustrate the audit procedure, the programmed sprinkling system used for watering the
235 garden of the Universidad Politécnica of Valencia is analysed (figure 1). The irrigation area of
236 this garden has grown through time and new species have been added to the grass meadow
237 (*Festuca arundinacea*, *Pennisetum clandestinum* and *Poa annua*). There are over 50 deciduous,
238 31 evergreen, 16 coniferous, and 13 palm (or similar) tree species and over 20 different shrub
239 species. Nowadays, the plot is divided into hydro-zones which are grouped according to the
240 landscape coefficient method (Costello and Jones, 1999) depending on water needs and crop
241 evapotranspiration values. The reference crop evapotranspiration has been calculated from local
242 weather data using the Penman-Monteith method (Allen et. al., 1998). For the months of
243 greatest water need, and depending on the hydrozone, overall water needs are 1.7 and 3.9 l m⁻²
244 day, corresponding respectively to the water demand of the least and most exposed areas of the
245 garden.

246

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

252

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

259

260 Groundwater is fed to the system by two identical pumping units (with a characteristic curve
261 described by the equation $h_{pi}(t_k) = -0.155 \cdot (q_{pi}(t_k))^2 - 0.794 \cdot (q_{pi}(t_k)) + 93.55$, where
262 $q_{pi}(t_k)$ and $h_{pi}(t_k)$ are, respectively, the flow rate ($\text{m}^3 \text{s}^{-1}$) and the head (in metres of water
263 column, m.w.c.; a unit defined as the pressure exerted by a column of water of 1 m in height at
264 4 °C at the standard acceleration of gravity) at time t_k supplied by the pump i . The flow and
265 pressure downstream of the pumping station is measured with a Woltmann meter (class B)
266 equipped with a pulse emitter (1 pulse = 100 litres) and a pressure transducer respectively (full
267 scale 1 MPa, accuracy $\pm 1\%$).

268

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

273

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

281

282 **2.2 Energy audit of irrigation networks**

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

287

288 In order to perform the analysis in an extended period (t_p , which can take values such as 1 year,
 289 1 month, 1 day, etc.), it is necessary to divide duration time into n_i intervals of time (Δt_k ; 300,
 290 600, 900, 3600 seconds, etc.). Thus, the total energy consumed in the extended period
 291 ($t_p = n_i \cdot \Delta t_k$) is obtained from the sum of the energies consumed in each time interval of the
 292 steady state simulation.

293

294 **2.2.1 Energy supplied by the reservoir**

295 The external energy supplied by reservoirs is:

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

296 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,
 297 respectively, the flow rate ($\text{m}^3 \text{s}^{-1}$) and piezometric head (m.w.c.) supplied from each of the
 298 water tanks at time t_k , where Δt_k is the time interval (s).

299

300 **2.2.2. Energy supplied by pumping stations**

301 The shaft work supplied by the pumps is:

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

302 where $q_{pi}(t_k)$ and $h_{pi}(t_k)$ are respectively the flow rate pumped by the station ($\text{m}^3 \text{s}^{-1}$) and the
 303 pump head (m.w.c.) at time t_k . This calculation needs to be done for the n_p pumping stations

304 that supply shaft work to the system at each discrete time t_k . This energy is water energy and
 305 by considering the performance of each pumping unit (an essential parameter for energy
 306 optimisation) the electrical equivalent can be calculated. In this paper, and since the focus is on
 307 new concepts, these energy losses have not been included in the analysis.

308
 309 **2.2.3 Energy delivered to users at consumption nodes**

310 The energy delivered to users is:

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

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

313

314 **2.2.4 Energy through leaks**

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

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

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

320

321 **2.2.5 Friction energy dissipation**

322 The energy dissipated by friction is divided into energy dissipated in pipes, in control valves
 323 and in hydrants. As previously mentioned, the latter two of these parameters are specifically

324 introduced to take into account the singularities of the irrigation networks. These elements can
 325 be present in urban water networks, but their influence is much lower (from an energetic point
 326 of view) than in irrigation networks. For instance, pressure control valves are common in
 327 irrigation networks and their energy dissipation becomes an important factor. Similarly, the
 328 particular configuration of an irrigation system may also indicate poor energy management, and
 329 therefore local hydrant losses can affect overall network performance.

330

331 **2.2.6 Energy dissipation in pipes**

332 The energy dissipated due to friction in pipes is:

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

333 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
 334 at time t_k (this term is the difference in piezometric heads between the initial and final nodes),
 335 $q_{uj}(t_k)$ and $q_{lj}(t_k)$ are, in line j , the flow rate necessary to satisfy the users demand and the
 336 flow rate that finally is lost through leaks, respectively. Therefore, the total flow rate in line j ,
 337 $q_j(t_k)$, is the sum of the two previous values.

338

339 **2.2.7 Energy dissipation in hydraulic valves**

340 The energy dissipated in hydraulic valves is:

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

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

344

345 **2.2.8 Energy dissipation in hydrants**

346 The energy dissipated in hydrants is:

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

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

350

351 **2.3 Final balance**

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

354

$$\begin{aligned} 355 \quad E_{input}(t_p) &= E_n(t_p) + E_p(t_p) = E_u(t_p) + E_l(t_p) + E_f(t_p) + E_v(t_p) + E_h(t_p) = \\ 356 \quad &= E_{output}(t_p) + E_{dissipated}(t_p) = E_u(t_p) + E_{wasted}(t_p) \end{aligned} \quad (8)$$

357 Equation (8) states that the energy supplied by reservoirs and pumps to the water coming into
 358 the network is equal to the energy delivered to the users (throughout the water supplied) plus the
 359 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

360 balance, energy losses can be evaluated and efficient actions aimed to improve system's
361 efficiency can be planned.

362

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

378

379 **2.4 Tools to assess performance system**

380 **2.4.1 Context information and Performance Indicators in irrigation networks**

381 Context information and Performance Indicators defined elsewhere for water supply systems
382 (Cabrera et al., 2010) are also valid for irrigation networks. In the following paragraphs, their
383 mathematical expressions and a new performance indicator for irrigation networks are presented
384 (table 2). For a better understanding of these indicators, two terms are explained here. The first
385 is the minimum useful energy ($E_{\min,useful}$), the energy when delivering the flow at each node

386 from the minimum required head ($h_{mi}=z_i+\left(\frac{P_m}{\gamma}\right)_i$). The second deals with the theoretical
387 minimum required energy for a flat, leak-free and frictionless network ($E_{\min,flat}$).

388

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

400

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

409

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

415

416 **2.5 Simulation stage**

417 The main features of the network are:

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

$$422 \quad q_{hi}(t_k) = \sum_{j=1}^{j=m} C_{sj} \cdot h_{sj}^\alpha = \left(\sum_{j=1}^{j=m} C_{sj} \right) \cdot h_h^\alpha \quad (9)$$

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

430 In the simulation model, nodes were grouped into a single characteristic equation that
431 represents all emitters of each subunit. Thus, the head losses at each subunit are

432 assumed to be negligible, which means that the inlet pressure at each rotating or spray
433 sprinkler is equal to that existing downstream of the electrovalve.

434 2. The behaviour of each hydrant is simulated by setting a variable pressure drop to each
435 electrovalve. Three diameters (32, 50 and 63 mm) and six different brands are used in
436 the garden (resulting in 15 different types of hydrant). The relationship between
437 pressure drop and flow through the hydrant has been characterised in the laboratory
438 (figure 2 shows an example) and these results have been compared with the
439 information provided by the manufacturer. This requires each hydraulic element and its
440 behaviour to be identified once again in the simulation model. The minimum required
441 pressure at the nodes for the correct operation of the sprinklers takes a value of

442 $\left(\frac{P_m}{\gamma}\right)_i = 15$ m.w.c. This value has been adopted with regard to technical

443 recommendations and the practical experience of the technicians and gardeners. At
444 lower values of pressure, the pop-up and proper functioning are not guaranteed.

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

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

$$464 \quad q_{li}(t_k) = C_{e,i} \cdot h_i(t_k)^\alpha \quad (10)$$

465 where $C_{e,i}$ ($\text{m}^{(3-\alpha)} \text{s}^{-1}$) is the emitter coefficient assigned to each node of the system,
466 $h_i(t_k)$ (m.w.c.) represents pressure drops experienced by the water when passing
467 through the hole and α is the exponent of the emitter. A value of $\alpha = 0.5$ is adopted
468 herein. With the above expression, the leaks in the model are pressure driven demand.
469 Leaks are not typically represented in this way because most hydraulic simulation
470 software, including EPAnet2.0, represents water consumption as independent of
471 pressure (demand driven).

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

482

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

489

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

498

499 In the model, the water consumed at the end nodes is water used for irrigation while the water
500 consumed at intermediate nodes is leaking water (water losses that do not meet their goal). All
501 the information recovered in the garden is added to the model in the hydraulic simulation
502 software (EPANet or any other) and the calibration process starts. The objective of the
503 calibration is to observe a good response between the simulated (model predicted) and the
504 observed values (pressures and flows at several points of the network) over the entire simulation
505 period (1 week). The calibration parameters considered here have been the unknown roughness
506 coefficients (the simulations have been carried out using the Darcy-Weisbach equation to
507 calculate the head losses) and the emitter coefficients to achieve better agreement between the
508 observed and modelled pressures and flows respectively (using 5 transducers and one data-

509 logger). A heuristic process in order to select the location of pressure transducers has been
510 carried out. This process was used to obtain a representative sample of the pressure levels
511 throughout the network for three days in July (when the water demand reaches its maximum).

512

513 **2.6 Scenarios tested**

514 The case study presents the energy analysis of an irrigation system with different leakage rates
515 and with different type of pressure regulation. Case I and Case III represent the current
516 irrigation network, with a volumetric efficiency slightly higher than 75% and a leakage flow
517 rate of $2.166 \cdot 10^{-7} \text{ m}^3 (\text{s}^{-1} \text{ m}^{-1})$ or the equivalent (and more usual $0.78 \text{ m}^3 (\text{km h})^{-1}$, which
518 expresses that that every hour, 0.78 m^3 are lost in every kilometre of pipe) typical values
519 oscillate between $0.2\text{-}2 \text{ m}^3 (\text{km h})^{-1}$ in water networks; OFWAT, 2010). Case II and IV
520 represent the initial state of the network (or the leak-free situation) with small leakage rates
521 (96% volumetric efficiency and leak rates of $1.66 \cdot 10^{-8} \text{ m}^3 (\text{s}^{-1} \text{ m}^{-1})$, equivalent to
522 $0.06 \text{ m}^3 (\text{km h})^{-1}$).

523

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

532

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

537

538 **3. RESULTS AND DISCUSSION**

539 **3.1 Results of the water audit**

540 The results of the water audit for the Cases are:

- 541 ▪ Input water flow: $v_N(t_p) = 4.18 \cdot 10^{-3} \text{ m}^3 \text{ s}^{-1}$ (equivalent to $0.132 \text{ hm}^3 \text{ year}^{-1}$) (Cases I and
542 III) and $3.26 \cdot 10^{-3} \text{ m}^3 \text{ s}^{-1}$ ($0.103 \text{ hm}^3 \text{ year}^{-1}$) (Cases II and IV).
- 543 ▪ Delivered water: $v_U(t_p) = 3.14 \cdot 10^{-3} \text{ m}^3 \text{ s}^{-1}$ ($0.099 \text{ hm}^3 \text{ year}^{-1}$) (for all the Cases).
- 544 ▪ Real losses: $v_L(t_p) = 3.14 \cdot 10^{-3} \text{ m}^3 \text{ s}^{-1}$ ($0.033 \text{ hm}^3 \text{ year}^{-1}$) (Cases I and III) and
545 $0.13 \cdot 10^{-3} \text{ m}^3 \text{ s}^{-1}$ ($0.004 \text{ hm}^3 \text{ year}^{-1}$) (Cases II and IV).

546

547 **3.2 Results of the energy audit**

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

551

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

556

557 Another approach to better energy efficiency in irrigation networks deals with the pressure
558 regulation problem. The head loss at the pressure reducing valve (PRV) in Case I and II is
559 $79-55=24$ m.w.c., and the annual energy loss of the valve is 23832MJ (equivalent to 6.62 MWh)
560 (98% of the energy dissipated in the hydraulic valves, table 3). Therefore, the elimination of the
561 control valve and the use of variable speed pumps (Cases III and IV) will improve the energy
562 efficiency of the system as the energy dissipated in hydraulic valves decreases.

563

564 There are some constraints (VFD price and reliability) that affect the worldwide implementation
565 of this control technique (Pemberton, 2005). The new control system meets the water flow (1-
566 18.5 l s^{-1}) and pressure (55 m.w.c.) requirements of the network through the day. The maximum
567 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
568 new rotation speed and N_0 is the nominal rotation speed of the pumping unit) while the
569 minimum water flow (1 l s^{-1}) is achieved at a rotation speed equal to $N = 0.77 \cdot N_0$. The
570 energy values for these new cases are given in table 3.

571

572 The comparison of the real scenario data with those after removal of the hydraulic valve (Case I
573 and III, table 3) shows annual energy savings of $111143.9-85212.1=25931.8$ MJ (equivalent to
574 $30.87-23.67 = 7.20$ MWh year^{-1}). It may seem small, but it represents 23% of the energy spent
575 in the process and it also represents 198MJ (0.055 kWh) for each m^3 supplied to the system.
576 Considering that the maximum power of the pumps is 12 kW (16.4 HP) and pump speed device
577 (PSD) is supplied with 3-phase 440V, it results in a 3000 € per PSD (maximum power equal to
578 20 HP). In short, the investment is 6000 € (as there are two pumps operating in parallel and
579 consequently 2 PSDs are required). Moreover, if considering that the energy costs are
580 0.15 € kWh^{-1} , the payback period of this alternative is 5.55 years and the annual energy savings
581 are 1080 €. This payback period has been obtained only considering the pressure reduction and
582 it will be shortened if other factors are taken into account since the delivery scheduling methods

583 of irrigation also show themselves to be of key importance when obtaining the energy
584 consumption in irrigation networks.

585

586 **3.3 Indicator determination and discussion**

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

589

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

598

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

604

605 **3.3.1 Performance Indicators at Cases I and II**

606 The first indicator (I_1) shows the system's incoming energy with respect to the minimum
607 useful energy, i.e. the outgoing energy at the nodes in the event that all nodes maintain the
608 minimum pressure flow throughout the day. This energy is 4.33 times higher than the minimum
609 useful energy, and if leaks are eliminated, there will be a small improvement of the system, to
610 3.36 (Case II).

611

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

618

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

622

623 The indicator I_5 shows the ratio between the energy delivered to users and the energy when
624 delivering the flow at the minimum required head, and thus it quantifies the additional energy
625 delivered to users (as a consequence of the additional head). The values of this indicator are
626 good and typical of pressurised networks ($I_5 = 2.04 -2.05$; Cases I and II). The closer to one, the
627 better. Therefore, its higher value and better management (Case II) compared to the original
628 network (Case I) reveal that the heads at all the nodes of the network are higher and as a

629 consequence, more energy savings can be obtained following future energy policies. The value
630 obtained here indicates that the network is energetically well-managed (although this is easy as
631 it is a flat network, as indicated by C_2). However, it is always possible to improve energy
632 efficiency, and irrigation indicators serve to identify the major energy losses and potential
633 improvements of the system.

634

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

643

644 In Case I the energy dissipated by leakage is 0.4% of the input energy ($I_2 + I_3 + I_4 = 1.004$;
645 $X = 0.004$). In Case II, leak-free, X is 0.

646

647 The data from the water and energy audits can be used to calculate the energy indicator
648 expressed as kWh m³, which is highly dependent on the topography of the terrain. It has the
649 following values:

- 650 • Energy consumed per unit volume injected into the network: 841.62 KJ m⁻³ (0.23 kWh
651 m⁻³) in both cases (which means that 0.23 kWh are consumed to inject one cubic meter

652 of water into the system), a figure that coincides with the estimate made by Corominas
653 (2010).

654 • Energy consumed per unit volume consumed by the network: 1121.3 and 859.68 KJ m⁻³
655 (0.31 and 0.24 kWh m⁻³) Case I and II, respectively (values that express that in order to
656 irrigate one cubic meter of water, 0.31 kWh in Case I and 0.24 kWh are consumed).
657 These values are greater than the previous one as they consider energy that is lost due to
658 leaks.

659

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

663

664 **3.3.2 Performance Indicators at Cases III and IV**

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

669

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

676

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

681

682 The energy dissipated by leakage is 0.2% of the total input energy ($I_2 + I_3 + I_4 = 1.002$;
683 $X=0.02$) in Case III, and 0 in Case IV (leak-free system). The energy consumed per unit volume
684 injected to the network is 0.18 kWh m^{-3} in both cases (a low value, typical of an energetically
685 well-managed network), while the energy consumed per unit volume used is 0.24 and 0.18
686 kWh m^{-3} (Case III and IV, respectively).

687

688 **4 CONCLUSIONS**

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

698

699 The key output is a case study to show how the methodology can quantify the energy consumed
700 in irrigation networks and to calculate the energy benefits derived from an efficient management
701 of the irrigation network of the Universidad Politécnica de Valencia. The annual energy savings
702 resulting from the use of a new control system as compared to current operations are
703 (25931.8 MJ, equivalent to 7.20 MWh year⁻¹), a substantial value for a small irrigation system.
704 Two case studies (Cases II and IV) have also shown significant annual energy savings in leak-
705 free systems (24995 and 18435 MJ), respectively. Therefore, two ways of reducing energy
706 losses in the network under study ($E_{wasted}(t_p)$) have been addressed, namely by reducing
707 friction losses and leakage. The adaptation of the energy audit to irrigation systems has proved
708 to be a powerful tool for the development of energy efficient strategies.

709

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

719

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722

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725

6. REFERENCES

726 Allen, R.G., and Brockway, C.E., 1984

727 *Concepts for Energy-Efficient Irrigation System Design*

728 Journal of Irrigation and Drainage Engineering. ASCE. Vol. 110, No. 2, June, 1984. pp

729 99 – 106

730

731 Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998).

732 *Crop evapotranspiration; Guidelines for computing crop water requirements*

733 FAO Irrigation and Drainage Paper No. 56, Roma.

734

735 Almandoz J., Cabrera E., Arregui F., Cabrera Jr. E., Cobacho R., 2005

736 *Leakage assessment through water networks simulation*

737 J. of Water Resources Planning and Management. ASCE. Nov-Dec. 2005 pp 458-466

738

739 Armindo, R.A., Botrel, T.A., and Garzella, T.C., 2011

740 *Flow rate sprinkler development for site-specific irrigation*

741 Irrigation Science, 2011, Volume 29, Number 3, Pages 233-240

742

743 Avellá, LL., García-Mollá, M., 2009.

744 *Institutional factors and technology adoption in irrigated farming in Spain: Impacts on*

745 *water consumption.*

746 The Management of Water Quality and Irrigation Technologies. ISBN 978-1-84407-

747 670-3.

748

749 Bastiaanssen, W.G.M; Allen, R.G., Droogers, P., D'Urso, G., Steduto, P., 2007.

750 *Twenty-five years modeling irrigated and drained soils: State of the art.*

751 Agricultural Water Management. 92, pp 111-125

752

753 Cabrera E., Pardo M.A., Cobacho R., Arregui F.J. y Cabrera E. Jr., 2010

754 *Energy Audit of Water Networks*

755 J. of Water Resources Planning and Management. ASCE. Nov-Dic. 2010 pp 669-677

756

757 Calejo M.J., Lamaddalena N., Teixeira J.L., and Pereira L.S., 2008

758 *Performance analysis of pressurized irrigation systems operating on-demand using*
759 *flow-driven simulation models*

760 Agricultural Water Management 95 (2008), pp 154-162

761

762 CEC (California Energy Commission), 2005

763 *California's Water- Energy Relationship. Final staff report. CEC 700 – 2005 – 011 SF*

764 California Energy Commission. State of California. November 2005

765

766 Chen, G. and Baile, C. 2009.

767 *Development of a framework and tool to asses on-farm energy uses of cotton*
768 *production.*

769 Energy Conversion and Management. 50. Pp. 1256-1263

770

771 Córcoles, J.I., de Juan, J.A., Ortega, J.F., Tarjuelo, J.M. and Moreno, M.A., 2012

772 *Evaluation of irrigation systems by using benchmarking techniques*

773 Journal of Irrigation and Drainage Engineering, Vol. 137, No. 3, March 2012, pp. 225-

774 234

775

776 Corominas, J., 2010

777 *Agua y energía en el riego en la época de la sostenibilidad*

778 Ingeniería del Agua. Vol, 17, nº3. September 2010. pp. 223-234 (In Spanish)

779

780 Costello, L. R. and Jones, K. S. 1999.
781 *A guide to estimating irrigation water needs of landscape plantings in California.*
782 WUCOLS III.
783 University of California Cooperative Extension. California Department of Water
784 Resources.
785

786 Daccache, A., Lamaddalena, N., and Fratino, U., 2009
787 *On-demand pressurized water distribution system impacts on sprinkler network design*
788 *and performance*
789 Irrigation Science, 2009, Volume 28, Number 4, Pages 331-339
790

791 DoE (Department of Energy), 2006
792 *Energy Demands on Water Resource. Report to Congress on the Interdependency of*
793 *Water and Energy.*
794 US Department of Energy. Washington DC. USA
795

796 Droogers, P., Immerzeel, W.W., Lorite, I.J., 2010.
797 *Estimating actual irrigation application by remotely sensed evapotranspiration*
798 *observations.*
799 Agricultural Water Management. 97 pp (1351-1359)
800

801 Farmani, R., Abadia, R., Savic, D., 2007
802 *Optimum Design and Management of Pressurized Branched Irrigation Networks*
803 Journal of Irrigation and Drainage Engineering. ASCE. November/December, 2007 pp
804 528-537
805

806
807 Geerts, S., Raes, D., 2009
808 *Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry*
809 *areas.*
810 Agricultural Water Management. 96 pp 1275-1284
811
812 González-Cebollada, C., Macarulla, B., and Sallán, D., 2011
813 *Recursive Design of Pressurized Branched Irrigation Networks*
814 Journal of Irrigation and Drainage Engineering. ASCE. June, 2011 pp 375-382
815
816 Greenwood, D.J., Zhang, K., Hilton, H.W., Thompson, A.J., 2010
817 *Opportunities for improving irrigation efficiency with quantitative models, soil water*
818 *sensors and wireless technology.*
819 Journal of Agricultural Science. 148 pp 1-16
820
821 Guzman, G.I., and Alonso, A.M., 2008.
822 *A comparison of energy use in conventional and organic olive oil production in Spain.*
823 Journal of Agricultural Systems. 98. Pp 167-176
824
825 Jimenez-Bello, M.A., Martínez, F., Bou V. and Ayala, H., 2010
826 *Methodology for grouping intakes of pressurised irrigation networks into sectors to*
827 *minimise energy consumption*
828 Journal of Agricultural Engineering Biosystems engineering. 105 (2010) 429 – 438
829
830 Kale, R.V., Singh, R.P., and Mahar, P.S., 2008
831 *Optimal Design of Pressurized Irrigation Subunit*
832 Journal of Irrigation and Drainage Engineering. ASCE. March/April, 2008 pp 137-146

833

834 Lamaddalena, N. and Khila, S. 2012

835 *Energy saving with variable speed pumps in on-demand irrigation systems*

836 Irrigation Science. Volume 30, Number 2 (2012), 157-166,

837

838 Lambert, A and McKenzie, R. (2002)

839 *Practical Experience in using the Infrastructure Leakage Index.*

840 IWA Conference “Leakage Management – A Practical Approach”, Cyprus,

841 November 2002,

842

843 Llamas, M.R., and Martínez Santos, P., 2005

844 *Intensive Groundwater Use: Silent Revolution and Potential Source of Social Conflicts*

845 Journal of Water Resources Planning and Management. ASCE. Sept. – Oct. 2005 pp

846 337 - 341

847

848 Luc, J.P., Tarhouni, J., Calvez, R., Messaoud, L., and Sablayrolles, C., 2006

849 *Performance Indicators of irrigation pumping stations: application to drill holes of*

850 *minor irrigated areas in the kairouan plains (Tunisia) and impact of malfunction on the*

851 *price of water*

852 Irrigation and Drainage, John Wiley & Sons, Ltd., 55: 85–98 (2006)

853

854 Makin, I., Burton, M., and Malano, H.M., (Editors), 2004

855 *Benchmarking in the Irrigation and Drainage Sector*

856 Irrigation and Drainage, Special Issue, June 2004, pp 117 - 214

857

858 Malano, H. and Burton, M., 2001

859 *Guidelines for benchmarking performance in the irrigation and drainage sector*

860 FAO, Food and Agriculture Organization of the United Nations. Rome
861
862 MARM, 2006.
863 *Plan de choque de modernización de regadíos*
864 Ministerio de Medio Ambiente, Medio Rural y Marino.
865 <http://www.plandechoque-ahorrodeagua.es> (In Spanish)
866
867 Moradi-Jalal, M. and Karney, B., 2008
868 *Optimal design and operation of irrigation pumping stations using mathematical*
869 *programming and Genetic Algorithm (GA)*
870 Journal of Hydraulic Research Vol. 46, No. 2 (2008), pp. 237–246
871
872 Moradi-Jalal, M., Rodin, S.I., and Mariño, M.A., 2004
873 *Use of Genetic Algorithm in Optimization of Irrigation Pumping Stations*
874 Journal of Irrigation and Drainage Engineering. ASCE. September/October, 2004 pp
875 357-365
876
877 Moreno, M. A., Córcoles, J., Moraleda, D., Martinez, A. and Tarjuelo, J. M. 2010a
878 *Optimization of Underground Water Pumping*
879 Journal of Irrigation and Drainage Engineering. ASCE. June 1, 136(6), 414-420 2010
880
881 Moreno, M.A., Córcoles, J., Tarjuelo, J.M. and J.F. Ortega, 2010b,
882 *Energy efficiency of pressurised irrigation networks managed on-demand and under a*
883 *rotation schedule*
884 Journal of Agricultural Engineering Biosystems engineering. Elsevier, 107 (2010)
885 349 – 363
886
887 Moreno M. A., Ortega J. F., Córcoles J. I., Martínez A., Tarjuelo J. M., 2010c

888 *Energy analysis of irrigation delivery systems: monitoring and evaluation of proposed*
889 *measures for improving energy efficiency*
890 Irrigation Science, 2010, Volume 28, Number 5, Pages 445-460
891
892 OFWAT, (2010)
893 *Service and delivery – performance of the water companies in England and Wales*
894 *2009-10 report Supporting information.*
895 http://www.ofwat.gov.uk/publications/los/rpt_los_2009-10
896
897 OFWAT, (2007)
898 *Alternative approaches to leakage target setting: final report*
899 WRc Ref: UC7485, November 2007
900 http://www.ofwat.gov.uk/regulating/reporting/rpt_com_leakmethrev
901
902 Playan, E., Mateos, L., 2006.
903 *Modernization and optimization of irrigation systems to increase water productivity.*
904 Agricultural Water Management. 80, 100–116.
905
906 Pemberton M., 2005
907 *Variable speed pumping: myths and legends.*
908 World Pumps 460:22–24
909
910 Pulido-Calvo, I., Roldán, J., López R., Gutiérrez J.C., 2003
911 *Demand Forecasting for Irrigation Water Distribution Systems*
912 Journal of Irrigation and Drainage Engineering. ASCE. November/December, 2003 pp
913 431- 422
914
915 Pereira, L.S., Oweis, T., Zair, A., 2002

916 *Irrigation management under water scarcity.*
917 Agricultural Water Management. 57. Pp 175-206
918
919 Pérez, L., Rodríguez, J. A., Camacho, E., López R., 2009
920 *Quality of Service in Irrigation Distribution Networks: Case of Palos de la Frontera*
921 *Irrigation District (Spain)*
922 Journal of Irrigation and Drainage Engineering. ASCE. November/December, 2009 pp
923 755- 762
924
925 Replogle, J.A., Gordon, E., 2007
926 *Delivery and distribution systems.*
927 Design and Operation of Farm Irrigation Systems, 2nd edition.
928 American Society of Agricultural and Biological Engineers. ISBN 1-892769-64-6
929
930 Rodrigues, G.C., Carvalho, S., Paredes, P., Silva, G.F., Pereira, L.S. 2010.
931 *Relating energy performance and water productivity of sprinkler irrigated maize, wheat*
932 *and sunflower under limited water availability.*
933 Journal of Agricultural Engineering Biosystems. 106. Pp. 195-204
934
935 Rodriguez, J.A., López, R., Carrillo, M.T., Montesinos, P., Camacho, E. 2009
936 *Exploring energy saving scenarios for on-demand pressurised irrigation networks*
937 Journal of Agricultural Engineering Biosystems.104. Pp 552-561
938
939 Rodríguez, J.A., Camacho, E. and Blanco, M (2011)
940 *Evaluation of water and energy use in pressurized irrigation networks in southern*
941 *Spain.*
942 Journal of Irrigation and Drainage Engineering. ASCE Vol 137 nº (10), pages 644-650.

943

944 Rossman, L. A., 2000

945 *EPANET 2: User's manual,*

946 U.S. Environmental Protection Agency, Cincinnati.

947

948 UKWIR, 1994

949 *Report E: Interpreting Measured Night Flows.*

950 UK Water Industry. Engineering and Operations Committee. London, United Kingdom.

951

952 WMO (World Meteorological Organization), 2010

953 *Guide to agricultural meteorological practices. Chapter 5: Weather and climate*
954 *forecasts for agriculture*

955 World Meteorological Organization. WMO N°.134. Edition 2010. Geneva, Switzerland

956

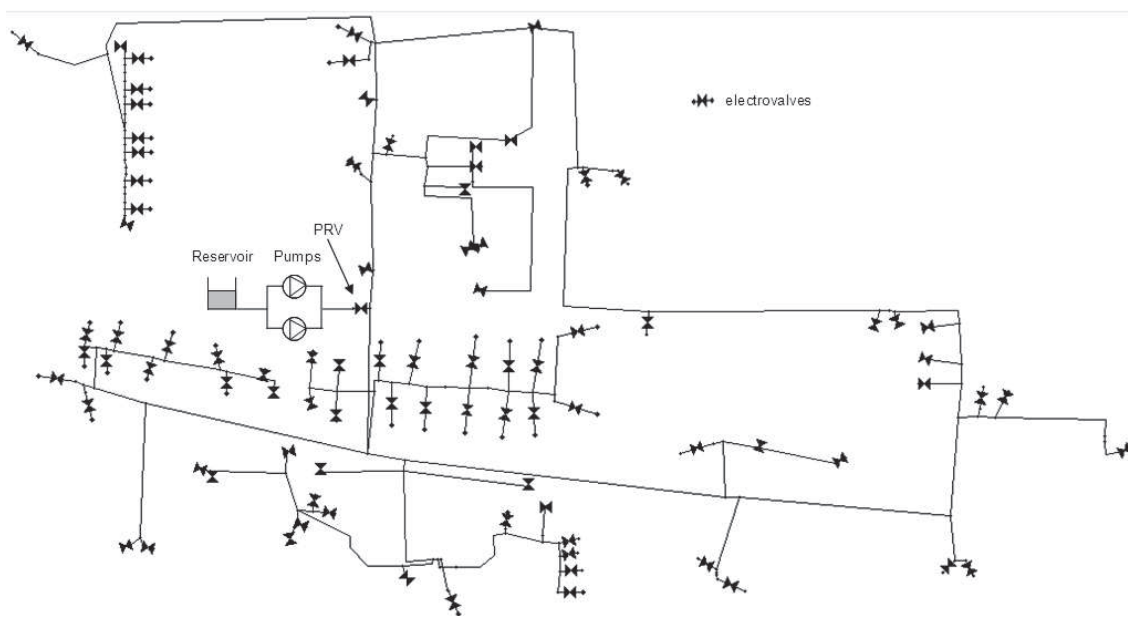


FIGURE 1. SIMPLIFIED LAYOUT OF THE NETWORK

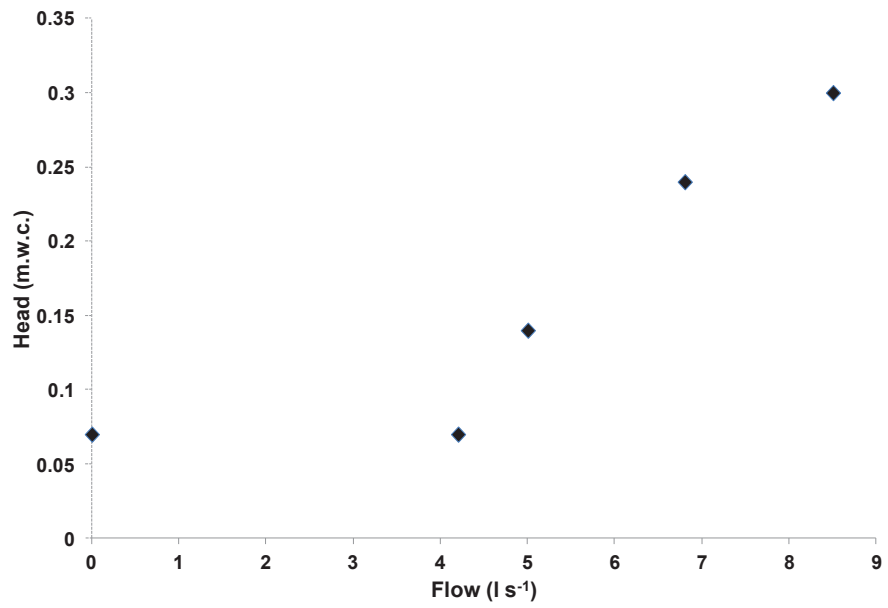


FIGURE 2. EXAMPLE OF WATER LOSS IN A HYDRANT OF THE NETWORK

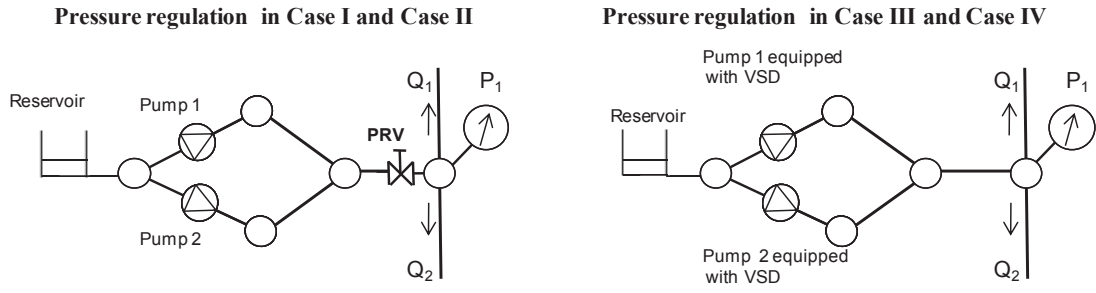


FIGURE 3. TYPES OF PRESSURE REGULATION

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

Year	Area (Thousand ha)	Water use (hm³)	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 2. CONTEXT INFORMATION AND ENERGY EFFICIENCY INDICATORS

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

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%)