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Practical Paper

Regulating reservoirs in pressurized irrigation water supply systems

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ABSTRACT

A regulating reservoir between the water supply source and the delivery system buffers the system from fluctuating demands. In addition, the system can reduce energy costs, by storing water pumped during off-peak energy tariff times and by improving the operation of pumping stations. A model is proposed to determine a regulating reservoir's capacity and establish an annual pumping schedule that accounts for energy costs. The optimal reservoir size and operation minimize the sum of the amortized reservoir construction and annual pumping costs (annual total cost). The solution was determined using a dichotomic searching procedure that includes one algorithm to calculate the optimal reservoir dimensions using Newton's method and another algorithm to determine the optimal annual pumping to the reservoir based on the concept of 'emptying period'. The model was applied to a pressurized irrigation delivery system located in southern Spain. The analysis used historical hourly water demand data. A cluster analysis was used to screen non-typical demand data from the data set before extracting a typical temporal demand pattern. The analysis indicated that the addition of a regulating reservoir with optimal size and operation scheme was cost effective. Total costs can be further reduced by adjusting the demand pattern to better match with off-peak energy tariff times.

Key words | demand profile, energy savings, pump efficiency, pump scheduling, regulating capacity

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INTRODUCTION

On-demand irrigation water supply systems require in-line reservoirs from which water can be drawn to meet the demand. The intent of this reservoir is to make up the difference between the irrigators' demands and the system's available supply. This way the construction of reservoirs allows an equalization of pumping schemes that is not possible by pumping directly into the delivery system. This allows pumping stations to operate near optimum energy efficiency (Mays 2000; Pulido-Calvo *et al.* 2002). Likewise if time-of-day energy tariff is available, the reservoir can be used for storing water that is pumped during off-peak hours to be used during peak hours (Sabet & Helweg 1989; López-Luque *et al.* 1993; Shvartser *et al.* 1993; Mays 2000; Pulido-Calvo 2001).

Numerous decisions must be made in the design of a reservoir, including size, location, type, and expected operation. This paper focuses on the hydraulic aspects of irrigation reservoir volume design (size and expected operation) as opposed to structural, safety, contamination, or instrumentation aspects. It is assumed that reservoir type and location are known.

A regulating reservoir is used to enable the source and pumping facilities to operate at a predetermined rate, depending on the utility's preference. Some options for

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operating pumping facilities include the following: 1) Flow adjustment to roughly match demand and minimize use of storage; 2) Constant rate operation to simplify management and reduce demand charges; 3) Off-peak pumping to take advantage of time-of-day energy pricing. Alternative 1 has a high operation cost and a low storage construction cost. Alternative 2 has lower operation costs than the first but with higher construction costs. Alternative 3 has the lowest operation cost and has the highest reservoir construction cost. The preferred combination is that which results in the minimum total cost, which includes both pump costs and the amortized reservoir construction costs. The addition of a regulating reservoir is not economically feasible if it results in an increased total cost (Sabet & Helweg 1989). In this paper, a model is proposed to determine a regulating reservoir's capacity and establish the scheduling of a pump system to give the minimum total cost for any particular demand.

The fraction of daily water that must be stored depends on the water delivery system and the type of operation. For town water supply systems and off-peak pumping, the typical value of regulating capacity needed is a fraction of 0.25–0.50 of the maximum daily demand (Fuertes *et al.* 1996; Mays 2000). A review of the methods used to determine the storage capacity in town water supply systems is reported by Lauria (1983) and Sabet & Helweg (1989).

The highest amounts of regulating capacity needed are for systems with highly-peaked daily demand curves, and the lowest amounts are for those with flatter demand curves. Nel & Haarhoff (1996) proposed a method for sizing municipal water storage tanks, based on the premise that the consumer demand is determined by the cumulative effect of a multitude of stochastic variables. Demand fluctuations are also relevant to irrigation supply systems given seasonal changes in crop water demand. Hirose (1997) proposed an algorithm for determining the design capacity of a regulating pond in a pipeline irrigation system in terms of the average hourly water demand. Mehta & Goto (1992) developed a model for the determination of the required minimum storage capacity of irrigation ponds at a desired reliability level with a given intake operating rule to meet the fluctuating water demands. The storage capacity was found to vary by about 30%–40% of the maximum daily demand depending on the cropping pattern.

None of the previous methods consider the economics of storage sizing with respect to a time-of-use energy tariff. Sabet & Helweg (1989) proposed the addition of a 'peaking storage tank' to reduce the operational cost of municipal water where time-of-use energy tariffs are used. The peaking storage tank stores water pumped from the source of supply during off-peak periods when energy costs are less than tariffs charged during periods of peak water demand. Analyses over a 24-h period showed that low off-peak energy costs made the addition of peaking storage tanks economically attractive and reduced peak energy use.

This paper aims to propose a model to determine the storage capacity that permits water to be pumped when energy tariffs are lowest, and establish an annual pumping schedule in accordance with time-of-use energy tariffs so as to allow farmers to irrigate on demand. The optimal size of the regulating reservoir is that which results in the minimum total cost, which includes both the storage construction cost and the pump operation cost. The determination of an optimum reservoir design and long-term optimum operation rule for pumping to the reservoir is of interest in the model developed. Integration of the design phase with the operation schedule in an optimization method is the main purpose of this paper. Using the current available data for an irrigation water supply system (hydraulic characteristics and water demand), we propose the addition of a regulating reservoir and estimate an operating scheme to give the minimum total cost. The use of the approach given here is not limited by the irrigation system. The same question can be applied to the problem of design and management of tanks and pump stations of an urban water supply, for example.

MATERIAL AND METHODS

Formulation of objective function

The addition of a regulating reservoir is feasible if a reduction in the total cost of providing water is achieved. The energy cost is one of the most important cost components for any water supply system (Sadowski *et al.* 1995; Nitivattananon *et al.* 1996). The energy cost is 95% of the life cost of a typical water pump-set (Yates & Weybourne 2001). Therefore in this paper, the annual total cost is defined as the sum of the annual operational cost of the pumps and the amortized reservoir construction cost. The model proposed minimizes the objective function:

$$C_{total} = \left\{ \sum_{t=1}^{NE} \sum_{p=1}^{nb} \left[\frac{\gamma Q_p(t) H_p(t)}{\eta_p(t)} C_{Ep}(t) \right] \Delta t + \frac{r(1+r)^T}{(1+r)^T - 1} C_I \right\} \quad (1)$$

where C_{total} is the total annual cost; NE is the number of time steps of the optimization procedure; nb is the number of pumps; γ is the specific gravity of the water; $Q_p(t)$ is the p pump discharge during the time step t; $H_p(t)$ is the discharge energy head of the p pump at the time t; $\eta_p(t)$ is the p pump efficiency at the time t; $C_{Ep}(t)$ is the energy cost of the p pump during the time step t, in €/kWh; Δt is the length of the time step t; C_I is the reservoir construction cost, in €; r is the interest rate; and T is the useful life of the reservoir.

This objective function is subject to:

- Limitations on pump discharge and discharge energy head that are functions of the hydraulic characteristics of the pumps and their operation schemes.
- Max-min reservoir volumes:

$$V_{min} \leq V(t) \leq V_{max} \quad \forall t \quad (2)$$

where V_{min} and V_{max} are the minimum and maximum useful regulating capacities, respectively, and $V(t)$ is the useful stored volume in reservoir in the time step t.

- Mass balance:

$$V(t) - V(t-1) = [Q(t) - Demand(t)]\Delta t \quad \forall t \quad (3)$$

- Known initial and final target reservoir volumes:

$$V(NE) = V(0) \quad (4)$$

$$\sum_{t=1}^{NE} Q(t) = \sum_{t=1}^{NE} Demand(t) \quad \forall t \quad (5)$$

The optimization period is divided into hourly intervals because the demands display a pronounced daily cycle, and energy tariffs are based on time-of-day. There is one difficulty in formulating this model. The cost function is non-linear in terms of power and pump discharge. As a result, an iterative solution of the optimization procedure is generally required (Figure 1). Given that the amortized

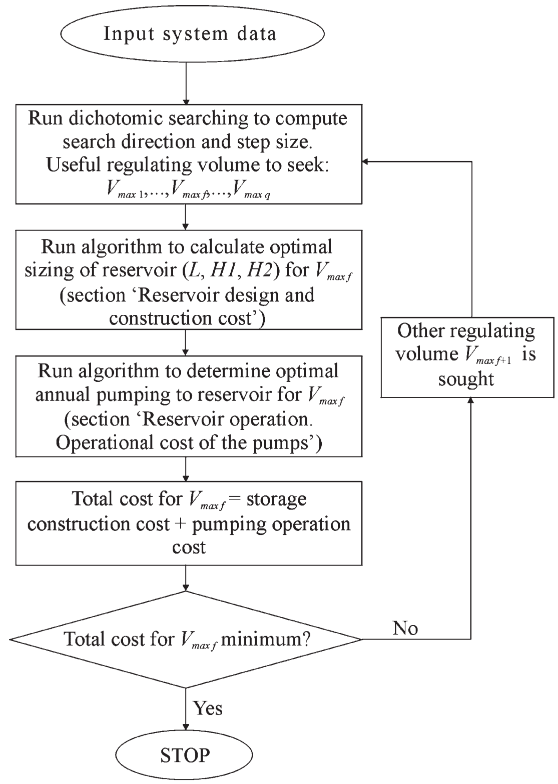

Figure 1 | Flow chart of the optimization model.

reservoir construction cost increases as the volume of the reservoir is incremented while the annual operational cost of the pumps decreases, the minimum total cost has been determined using dichotomic searching procedure (Hillier & Lieberman 2001). With this procedure possible regulating capacities are sought and the iterative process stops when the total cost is minimum. The sought range of regulating or useful reservoir capacity is among the highest hourly demand ($V_{max\ 1}$, Figure 1) and the demand of the ten days of maximum consumption of the irrigation season ($V_{max\ q}$, Figure 1). An algorithm has been developed to determine the optimal annual pumping to the reservoir for a given regulating capacity (section 'Reservoir operation. Operational cost of the pumps').

Other factors affect the required reservoir capacity: A minimum storage capacity for emergencies and excess capacity to prevent reservoir overflow due to rain or mistakes in pump operations. This way, in this paper the total reservoir volume is the regulating volume plus a lower freeboard, equal to 20% of the useful volume, and an upper freeboard which

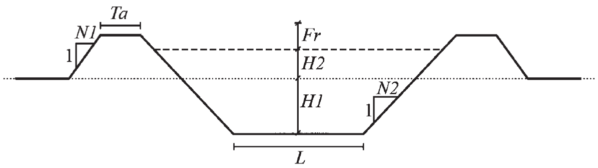

Figure 2 | Regulating reservoir cross-section and parameters.

corresponds to the freeboard *Fr* (Figure 2) (Jowitt & Germanopoulos 1992; Amigó & Aguiar 1994). An algorithm has been developed to determine the optimal reservoir dimensions (*L*, *H*1 and *H*2 in Figure 2) for a given regulating volume (section 'Reservoir design and construction cost').

The preparation for optimization model includes setting up a data structure to manipulate and process the following: 1) Water supply system configuration; 2) Water demand data; 3) Structure of electricity tariff (Input system data, Figure 1).

Water demand: mean hourly irrigation demand pattern based on cluster analysis

The hourly irrigation water demand during a day generally follows a particular pattern. However these data usually are not available or are limited (Pulido-Calvo 2001). The theoretical daily crop water requirements can be estimated from daily climatic data and crop data (Doorenbos & Kassam 1979; Smith 1990). Consequently, the daily crop water requirements can be disaggregated to hourly demand based on generated hourly irrigation demand patterns.

In this paper some hourly demand data were available. With these data, a non-hierarchical cluster analysis was applied to obtain an hourly demand pattern or patterns for generation of hourly irrigation demand data. Using this generated pattern or patterns, the daily irrigation demand was disintegrated into hourly demand.

The cluster analysis technique was chosen for its ability to divide the data set into homogeneous and distinct groups having members with similar characteristics. The cluster analysis is a generic term for a variety of statistical methods that can be used to evaluate the similarity of individual objects in a set. A simple example would be gathering a set of pebbles of different size, shape, and colour from a stream shore and sorting similar pebbles into the same pile. This is an example of physical cluster analysis. Statistical methods of cluster analysis achieve this mathematically. The objects in the statistical methods of cluster analysis are data rather than real objects (e.g. pebbles). The purpose of cluster analysis is to divide a data set into groups of similar variables. Each group is to some extent homogeneous and distinct from other groups (Shukla *et al.* 2000).

For the purpose of this study, these groups were classified as similar hourly demand variations of different days. Using the reported hourly flow demand data, the days were grouped homogeneously so that similar hourly demand variations for different days were assigned to the same group, while different variations were grouped separately. A mathematical criterion to calculate the classification and to judge the quality of the classification must be used. This question can be addressed by the K-means clustering algorithm. In general, the K-means method will produce exactly *K* different clusters of greatest possible distinction, with the goal to (1) minimize variability within clusters and (2) maximize variability between clusters. K-means clustering tries to move cases in and out of groups (clusters) to get the most significant ANOVA results. As the result of a K-means clustering analysis, the means for each cluster on each dimension (hours of day) are examined to assess how distinct our *K* clusters are. In this paper, the means for each cluster of all dimensions characterize a mean hourly water demand pattern. Ideally, very different means for most, if not all dimensions, used in the analysis are obtained. The magnitude of the *F* values (Snedecor's statistic) from the analysis of variance performed on each dimension is another indication of how well the respective dimension discriminates between clusters (Daniel 1990; Webster & Oliver 1990; Hair *et al.* 1998).

To obtain unitary hourly demand patterns and ensure comparability, the data were previously standardized or scaled [demand (t)/maximum demand]. The analysis requires that the number of groups or clusters be established beforehand. Given that the number of groups was not known a priori, the test was repeated, forming 2 to 8 groups in order to determine which classification best suited the problem objective or would provide the clearest interpretation of the results.

Reservoir design and construction cost

The use of low cost materials such as soils or lands has been widely used in the construction of reservoirs for storing irrigation water. In addition to economic considerations, these storage facilities are characterized by their technological simplicity and flexibility in adapting to the morphological features of the locality. The need for waterproof materials that are both resistant and cost efficient in constructing these storage facilities has led to the use of flexible sheets manufactured from synthetic materials that are commonly known as 'geomembranes'. These materials have been in use since the sixties (Amigó & Aguiar 1994) and today are the most widely (and almost exclusively) used technique for constructing storage facilities for agricultural purposes.

Reservoir construction cost calculations assume a reservoir with trapezoidal cross-section (with a square base) and polyethylene water proofing material. Cross-section geometric parameters are given in Figure 2. Cost of the reservoir is a function of excavation, waterproofed surface area, and occupied surface area ('Mas Bové' Agricultural Center 1986; Edwards *et al.* 1992).

The total reservoir volume VT (m^3) is given by:

$$VT = L^2(H1 + H2 + Fr) + 2LN2(H1 + H2 + Fr)^2 + 1.33\,N2^2\,(H1 + H2 + Fr)^3 \tag{6}$$

where L is the length (m) of the base of the reservoir, $H1$ is the depth (m) of excavation below the original ground surface, $H2$ is the above-ground depth (m) of water storage, Fr is the freeboard (m), and $N2$ is the inside levee slope (Figure 2).

The cost of reservoir excavation is proportional to the excavated volume VX (m^3), which is calculated as:

$$VX = L^2\,H1 + 2\,L\,N2\,H1^2 + 1.33\,N2^2\,H1^3 \tag{7}$$

As it is desirable to minimize the excavation cost, VX is set equal to the volume of fill used to construct the levees VL (m^3), where the coefficient CF compensates for excavation loss:

$$VL = 4\left[L + 2\,N2\,(H1 + H2 + Fr) + 2\,Ta + 2\,N1(H2 + Fr)\right] \times \left[0.5(N1 + N2)(H2 + Fr)^2 + Ta(H2 + Fr)\right] \tag{8}$$

$$VL = VX(1 + CF) \tag{9}$$

where $N1$ is the outside levee slope and Ta is the top width (m) of the levees (Figure 2).

An iterative solution to calculate the dimensions $H1$, $H2$ and L for any storage capacity sought in dichotomic searching procedure (optimization procedure) is required. In practice, the quantities $N1$, $N2$, Ta, Fr and CF may be considered fixed with values dependent on local construction methods and guidance from technical assistance agencies. In this case, the values of $N1 = 2, N2 = 3, Ta = 5$ m, $Fr = 1$ m and $CF = 10\%$ are considered. Due to safety, it is also common to construct irrigation reservoirs so that the total storage depth ($H1 + H2$) is in the range of 2 to 12 m. Greater storage depth increases the pressure on the base and slopes of the reservoir, and increases the risk of reservoir collapse and lining rupture from overstraining of the waterproof membrane. These factors are accounted for in the model by the requirement that $N1$, $N2$, Ta, Fr and CF be fixed inputs, and the total storage depth ($H1 + H2$) is limited to 2 to 12 m.

The dimensions of L, $H1$ and $H2$ for a given reservoir capacity are computed using an iterative scheme. The procedure starts with a trial value of ($HT = H1 + H2$) and with equation (6) L is obtained subject to $L > (H1 + H2)$. The values of $H1$ are calculated using equations (7)–(9), with $H2 = HT - H1$, using Newton's method (Hillier & Lieberman 2001). Then ($HT = H1 + H2$) is incremented and new values of L, $H1$ and $H2$ are computed. The iterative process stops when the reservoir cost for a given reservoir capacity is minimum.

Reservoir operation. Operational cost of the pumps

An algorithm has been developed to determine the reservoir's optimal operation for a given regulating capacity. The algorithm is based on the concept of 'emptying period' (López-Luque *et al.* 1993). This is defined as the hourly interval ($i < j \le i + k$) whereby at the initial hour t_{i+1} the reservoir has a useful stored volume and at the final hour t_{i+k} there is a deficit (when the reservoir is in deficit it is below the lower freeboard). There will be several emptying periods throughout the irrigation season. If V_j is the useful stored volume in hour j, the deficit volume VR_j is:

$$VR_j = V_{\max} - V_j \tag{10}$$

where V_{max} is the maximum useful regulating volume. The initial value of V_i $(t = 0)$ is $V_{\max}$, that is, the algorithm is first applied when the reservoir is filled to capacity.

The 'potential hourly supply' (*PHS*) is defined as the volume supplied to the reservoir in one hour when pumping at the peak rate. The decision variable vector $\bar{E}(E_i, \ldots, E_j, \ldots, E_{i+k})$ represents the volumes pumped at each hour *j*. At each hour *j*, several pumpings can be carried out in different emptying periods $(u, v, \ldots, z)$: $E_j = E_{j,u} + E_{j,v} + \ldots + E_{j,z}$.

The reservoir deficit at the end of any emptying period *v* should be corrected by incrementing the volume of water stored at any hour *j* during that period $(i < j \leq i + k)$. The algorithm will select the hour *j* when energy tariffs are lowest during the emptying period *v*. The volume to be pumped in hour *j* is conditioned by:

- The reservoir deficit at the end of the emptying period *v*, $-V_{i+k,v}$ (Figure 3).
- The difference between potential hourly supply and the volume pumped at hour *j* during any emptying period *u* prior to *v*, $PHS - E_{j,u}$ (Figure 4: In this case, there is no volume pumped at hour *j* during an emptying period *u* prior to *v*, $E_{j,u} = 0$ and $E_{j,v} = PHS$).
- The minimum deficit volume of the hours between hour *j* selected for pumping and the final hour $(i + k)$ during emptying period *v*, min $(VR_{j,v}, VR_{j+1,v}, \ldots, VR_{i+k,v})$ (Figure 5).

The volume to be incremented at hour *j* and emptying period *v* by pumping will be:

$$\Delta(V_{j,v}) = \min[-V_{i+k,v}, \min(VR_{j,v}, VR_{j+1,v}, \ldots, VR_{i+k,v}), PHS - E_{j,u}] \tag{11}$$

Once the volume is incremented at hour *j*, by incrementing $E_{j,v} = \Delta(V_{j,v})$, the available reservoir volumes V_j for the interval between hour *j* selected for pumping and the final hour $(i + k)$ of the emptying period *v* will be incremented at an equal magnitude (Figures 3–5). And the deficit of the reservoir at the final hour $(i + k)$ of emptying period *v* $(-V_{i+k,v})$ will be eliminated or corrected. One of the three following conditions is satisfied:

- The deficit at hour $i + k$ $(-V_{i+k,v})$ is eliminated (Figure 3), thus meeting the demands of emptying period *v* [equation (12)]. The following hour $(i + k + 1)$ is immediately analyzed and, in the case of deficit, will be corrected as described. The emptying period will then be equal to the previous emptying period and incremented by one hour: $(i < j \leq i + k + 1)$.

$$\Delta(V_{j,v}) = -V_{i+k,v} \tag{12}$$

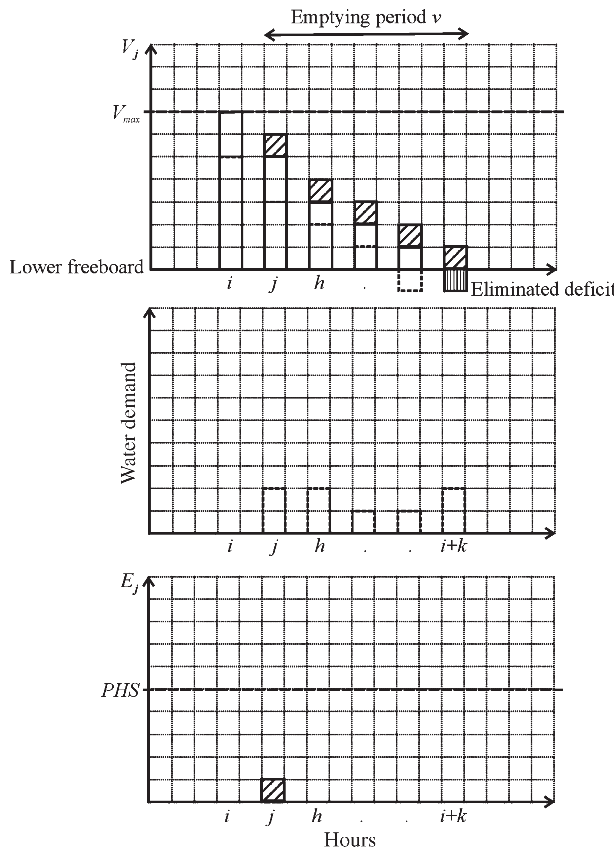

Figure 3 | Volume to be pumped at hour *j* ($E_{j,v} = \Delta V_{j,v}$) conditioned by the deficit at the end of the emptying period *v* (hour $i + k$: $-V_{i+k,v}$). The deficit is eliminated, thus satisfying demand during the emptying period *v*: $\Delta V_{j,v} = -V_{i+k,v}$. Hour *j* corresponds to the lowest energy tariff during the given emptying period *v*.

- The deficit at hour $i + k$ is not eliminated, but reduced (Figure 4). The new deficit is calculated by equation (13), with an increase in volume given by equation (14). As supply at hour *j* will be equal to the *PHS*, this hour cannot be used to correct the new deficit. Thus, the hour *j* must be reassigned to the emptying period *v* to correct the new deficit. This new hour will be the second hour

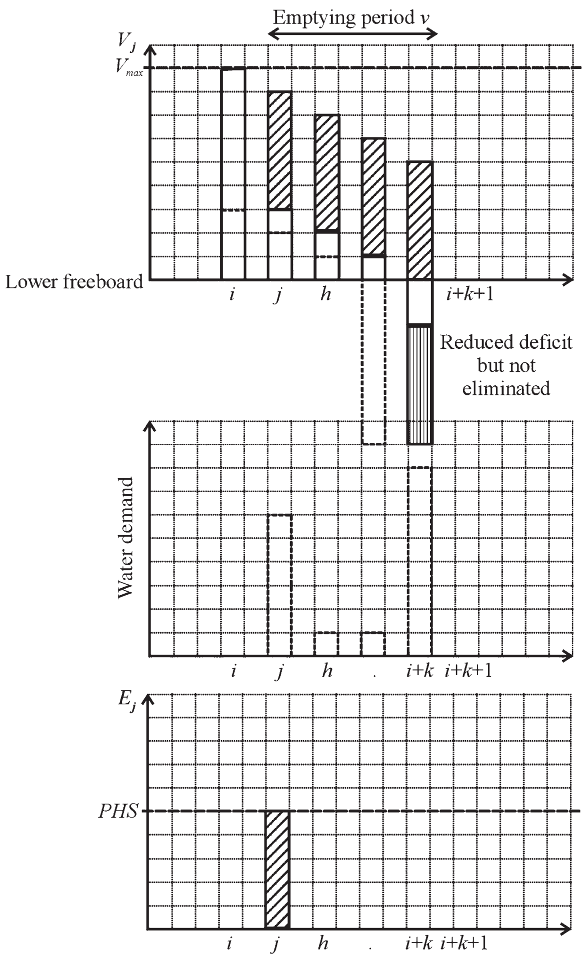

Figure 4 | Volume to be pumped at hour j ($E_{j,v} = \Delta V_{j,v}$) conditioned by the potential hourly supply (PHS). Deficit at hour $i + k$ ($-V_{i+k,v}$) was not eliminated, but has been reduced: $\Delta V_{j,v} = PHS$. Hour j corresponds to the lowest energy tariff during the given emptying period v.

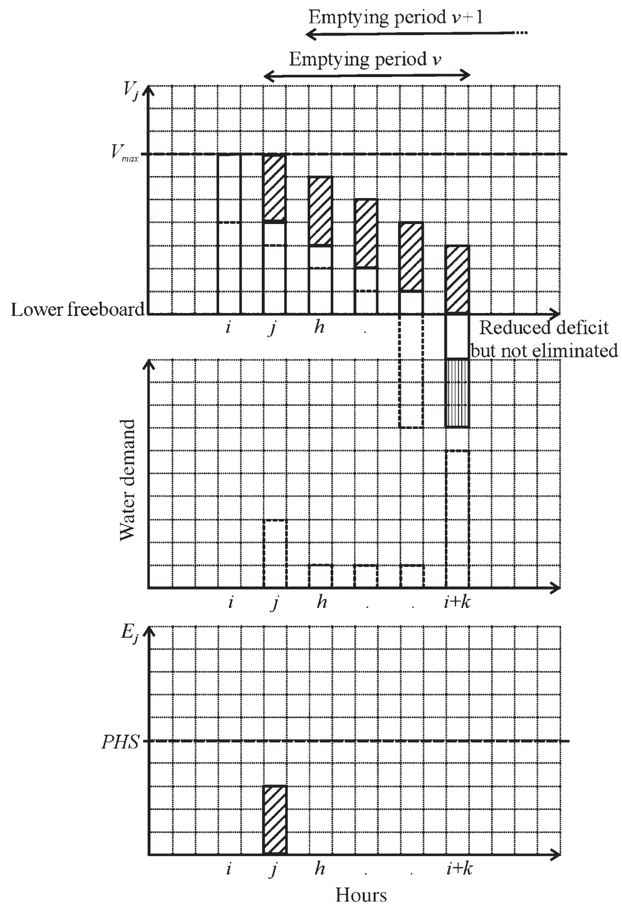

Figure 5 | Volume to be pumped conditioned by lower deficit volume ($VR_{j,v}$) between the hour selected for pumping (hour j) and the final hour of the emptying period v (hour $i + k$). Deficit was not eliminated at final hour ($-V_{i+k,v}$), but has been reduced: $\Delta V_{j,v} = VR_{j,v}$. Hour j corresponds to the lowest energy tariff during the given emptying period v.

with lowest energy tariffs during the emptying period v.

$$-V_{i+k,v} = -V_{i+k,v} + \Delta(V_{j,v}) \quad (13)$$

$$\Delta(V_{j,v}) = PHS - E_{j,u} \quad (14)$$

- The deficit at hour $i + k$ has not been eliminated, but reduced [equation (13)], with an increase in volume given by equation (15) (Figure 5). The emptying period will have been reduced and the new period initiated at hour h with ($j < h \leq i + k$).

$$\Delta(V_{j,v}) = \min(VR_{j,v}, VR_{j+1,v}, \ldots, VR_{i+k,v}) \quad (15)$$

Equations (12)–(15) represent the possible cases after pumping in the hour j of emptying period v to satisfy a deficit $-V_{i+k,v}$. The same procedure is carried out for the new deficit and the new emptying period until the iterative process is completed for the entire operating period (irrigation season). Thus vector $\overline{\overline{E}}$ will obtain the distribution of volumes pumped at each hour t during the irrigation season for any storage volume. $\overline{\overline{E}}$ will determine the power consumption P for each hour t and hence the energy cost.

The operation cost of a water supply system is affected by the combination of pumps used. Pump performance is expressed by energy head discharge H-Q and power consumption discharge P-Q curves (manufacturers'curves). This curve may be approximated by a quadratic equation

(Sabet & Helweg 1989; Yin *et al.* 1996; Mays 2000; Moradi-Jalal *et al.* 2003; Pulido-Calvo *et al.* 2003). Second-order polynomial equations for H-Q and P-Q are calculated for each pump type and for pump combinations using least-square regressions.

Pumping stations generally work best when pumped at a steady rate because the efficiencies are best, and then the power consumption losses are smaller. The pump efficiency (η) is the ratio of the energy imported to the water (pump output power or supplied power $= \gamma \cdot H \cdot Q$) to the energy delivered to the pump shaft (pump input power or absorbed power or power consumption $P = \gamma \cdot H \cdot Q/\eta$). The pump regulating efficiency (η_{reg}) is the ratio of the energy required at the water (required power $= \gamma \cdot H_{req} \cdot Q$, with H_{req} the required energy head in the water supply system) to the energy imported to the water (pump output power). Given the characteristics of the distribution system and the hourly water demands, the required energy head H_{req} in the pumping to the reservoir is calculated applying the energy equation. The friction head losses are calculated applying the Darcy-Weisbach equation and the friction factor is estimated by means of the Colebrook-White equation.

MODEL APPLICATION

The proposed methodology was applied to the demand pressurized system of the irrigation district of Fuente Palmera, located in the Guadalquivir valley (southern Spain). The mean water consumption in the zone is $16.5 \pm 5.9\,\text{hm}^3$ annually and must be drawn from the Guadalquivir River. The average irrigated area is approximately 5,000 ha and is irrigated by sprinkling on demand.

The pressurized irrigation system has two pumping stations in series. The first station (4 pumps in parallel) carries water from the Guadalquivir River to a $5{,}000\,\text{m}^3$ tank, which is the aspiration chamber for the second station (6 pumps in parallel) which discharges directly into the distribution line. Given that the storage capacity of this tank does not allow the two pumping stations to operate independently, it is used to provide pressure to the branched pipeline system. The energy head discharge $[H(\text{m}) - Q(\text{m}^3/\text{h})]$ and power consumption discharge $[P(\text{hp}) - Q(\text{m}^3/\text{h})]$ curves (manufacturers'curves) of both pumping stations are:

$$\left\{ \begin{array}{l} H = 103.2 + 0.01(Q/n) - 0.00002(Q/n)^2 \\ P = n[261.3 + 0.2(Q/n) - 0.00004(Q/n)^2] \end{array} \right\} \quad (16)$$

first pumping station

$$\left\{ \begin{array}{l} H = 130.9 + 0.02(Q/n) - 0.00002(Q/n)^2 \\ P = n[354.4 + 0.3(Q/n) - 9 \cdot 10^{-9}(Q/n)^2] \end{array} \right\} \quad (17)$$

second pumping station

where n is the number of pumps that are performing each hour.

The main water supply system carries water from the booster station (second pumping station) to 78 different groups of farmers, each one of whom has only one outlet. The minimum, maximum, and average areas of the group of farmers are 21.6, 218.3, and 67.4 ha, respectively. From the main network outlets, the water is distributed to the plots through a secondary pipe network that is underground and fixed. The average area of the plots is 6.25 ha.

Nine of the more representative crops were selected according to areas occupied in a period of 14 consecutive irrigation seasons (from 1984-1985 to 1997-1998): cotton, sunflower, wheat, sugar beet, olive, corn, sorghum, citric fruits and melon/watermelon (Figure 6).

The energy tariff times are: 8 off-peak hours (0.026 €/kWh in low electrical season –May, June, August and September– and 0.029 €/kWh in average electrical season –March, April, July and October–), 12 average

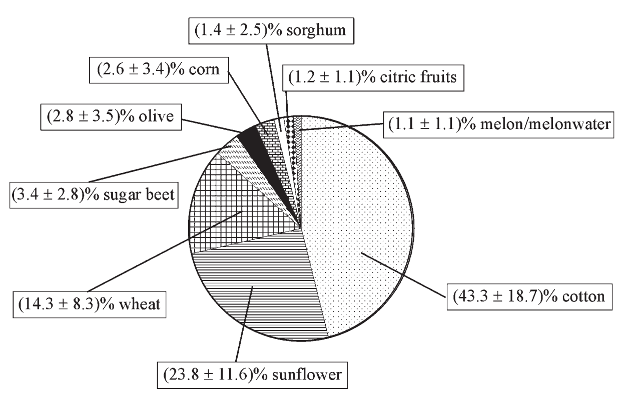

Figure 6 | Cropping pattern.

hours (0.045 €/kWh in low electrical season and 0.050 €/kWh in average electrical season) and 4 peak hours (0.076 €/kWh in low electrical season and 0.085 €/kWh in average electrical season) per day. The off-peak hours are 12 p.m. to 8 a.m. and the peak hours are 10 a.m. to 2 p.m. All other hours are considered average energy tariff.

Theoretical daily crop water requirements

Theoretical crop water requirements are directly related to crop evapotranspiration (ET_c). Theoretical crop water requirements can be estimated by multiplying the reference evapotranspiration (ET_0) by a crop coefficient (k_c). The crop coefficient k_c takes into account the crop type and crop development to adjust the ET_0 for that specific crop (Doorenbos & Kassam 1979; Smith 1990).

In this paper, the crop data required to estimate theoretical water requirements for the cropping pattern of each irrigation season (k_c values and duration of the development stages) were obtained from studies performed near the area and from other studies (Doorenbos & Kassam 1979; Smith 1990; Reca *et al.* 2001; Pulido-Calvo *et al.* 2003). Climatic data were obtained from the meteorological station located at the Córdoba airport, near the irrigation district. Series of daily rainfall and temperature data of each irrigation season were collected. Mean annual rainfall in the area is 608 mm, with a standard deviation of 229 mm. The climate is typically Mediterranean with wet winters and very dry summers.

The daily reference evapotranspiration (ET_0) was estimated using Hargreaves method (Hargreaves & Samani 1985; Hargreaves 1994). This formula requires only temperature data and has been used in previous work in this and similar areas with very good results (Mantovani *et al.* 1992; Mantovani 1993; Amatya *et al.* 1995). The theoretical daily irrigation requirements of the cropping patterns have been calculated considering estimated ET_0 and effective rainfall. The effective rainfall has been assumed as 70% of the total rainfall. This proportion has been used in this and similar areas (Smith 1990; Reca *et al.* 2001). Mean theoretical irrigation water requirements in the month of maximum consumption (July) are 153 mm. The mean total theoretical irrigation requirements are 476 mm.

Some hourly flow demand data were available for the 1988, 1989, 1990, 1991, 1992, 1996 and 1997 irrigation seasons.

RESULTS

Generation of hourly irrigation water demand

A linear regression model [Demand (m^3/day) = 9244.3 + 0.52 Requirements (m^3/day)] was applied to determine the relationship between daily reported water use and theoretical daily irrigation water requirements for the crops during each of the aforementioned years. The results were good [coefficient of determination $R^2 = 0.62$; Snedecor's statistic $F(1;469) = 403$; level of statistical significance $p < 0.001$; number of data $N = 471$]. Due to the high cost of pumping water in the district (maximum energy head requirements are 100 m) water use is lower than the theoretical requirements.

Using the available records of hourly water delivered by the irrigation system, the cluster analysis was initiated with two homogeneous groups. Cluster 1 includes 413 days while cluster 2 includes the remaining 58 days. Satisfactory values were obtained for the indicator of goodness of separation F with significance levels of $p < 0.001$. In subsequent trials with a larger number of groups, the aforementioned group that included 413 days was maintained. The other 58 days were included in the remaining groups, thereby reducing the number of cases per homogeneous group with a larger number of clusters (Figure 7). These last groups appear randomly at any time during the irrigation season. We considered the 58

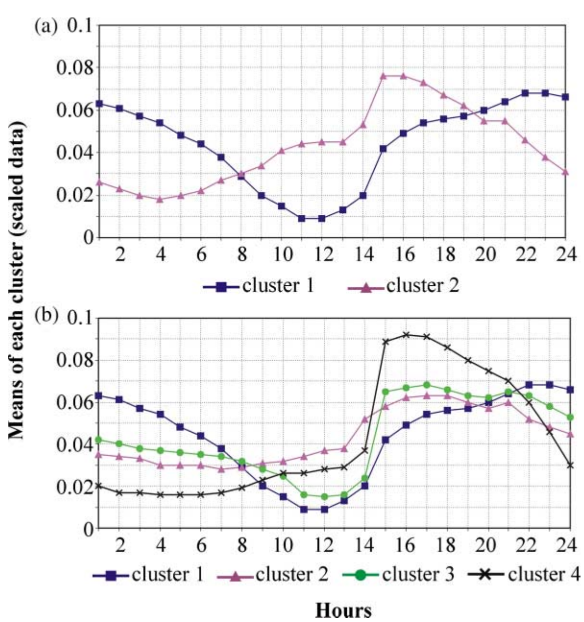

Figure 7 | Non-hierarchical cluster analysis: a) two groups; b) four groups.

days to represent atypical cases and therefore selected the hourly demand pattern of 413 days (cluster 1).

The model that relates recorded daily use and theoretical water requirements (regression model), together with the selected mean-hourly irrigation-demand pattern, allowed us to determine the mean hourly irrigation demand for the irrigation district. Using the generated demand pattern, the daily irrigation demand is disaggregated into mean hourly demand (Figure 8).

Optimal design and operation of regulating reservoir

Input data for the model include a regulating reservoir useful life of 20 years, 5% interest rate and opportunity cost incurred by the loss of annual income (0.026 €/m^2) due to the alternative use of the area occupied by the reservoir. Other parameters that influence the cost of the reservoir include the cost of waterproofing material (2.40 €/m^2 for high-density, 1.5 mm thick polyethylene) and soil excavation (2.70 €/m^3).

The optimal useful capacity for storing water is determined to be 65,000 m^3, which is 41% of the maximum daily demand (158,000 m^3/day) and 0.42% of total demand (15,400,000 m^3) for the irrigation district. A lower and upper freeboard is added to this volume, thus obtaining a total volume of 91,000 m^3 for the regulating reservoir. The dimensions L, $H1$ and $H2$ (Figure 2) are 48.63 m, 5.32 m and 6.68 m, respectively.

With regard to energy consumption, the cost of the first pumping station with the regulating reservoir (153,000 €/year) is 33% less than the cost of pumping directly to the water supply system (226,000 €/year) (current performance of the pumping stations that discharge the water demand of each hour). The total cost, which includes the storage construction cost and the cost of operation of the pumps, is 12% less with the regulating reservoir and investment is amortized in two years time (Table 1). Thus, energy costs are considerably reduced when a reservoir is used to adapt pumping hours to time-of-use energy tariffs. This results in a decrease in average and peak energy use and an increase in off-peak energy use, and greater pump efficiencies.

The optimal operating scheme for the first pumping station with the reservoir demonstrates that only off-peak energy tariff times should be used at the start of irrigation. As water demands increase, the use of off-peak hours will be incremented until the peak rate is pumped during all of the 8 off-peak hours (June 2nd). This operating scheme will be maintained until average energy tariff times are needed

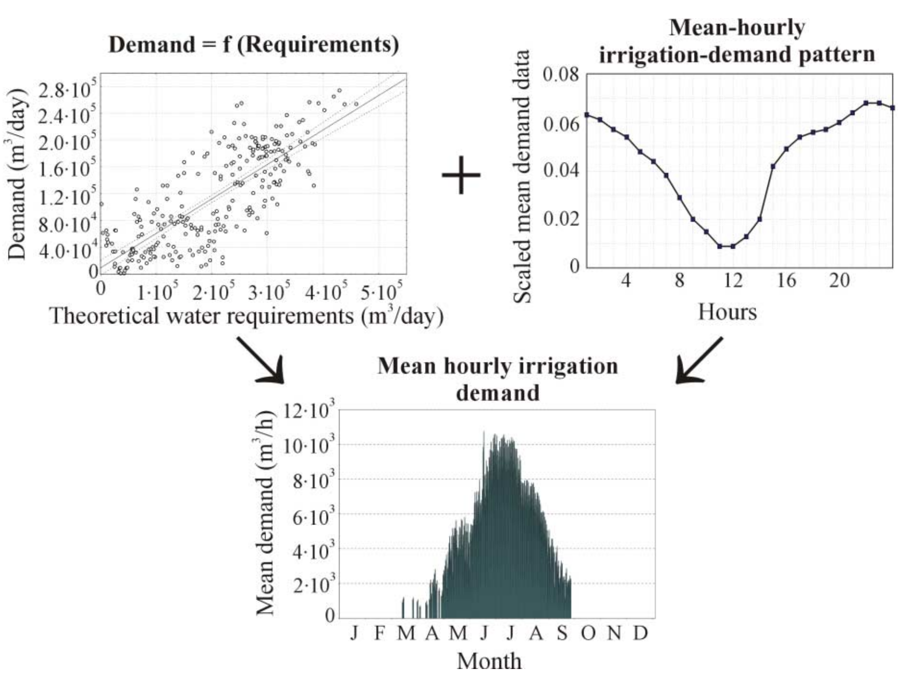

Figure 8 | Disaggregation of daily water demand to hourly demand using the mean-hourly irrigation-demand pattern.

Table 1 | Costs (€/year) of water supply system with and without regulating reservoir. These costs are calculated from simulation using the synthetic demand series

	Alternatives			
	Without reservoir (current situation of irrigation district)	**With reservoir (historical water demand pattern)**	**With reservoir (water demand pattern of alternative A of Figure 11)**	**With reservoir (water demand pattern of alternative B of Figure 11)**
Regulating reservoir (amortized costruction cost)	–	12,000	12,000	9,000
First pumping station (operation cost)	226,000	153,000	151,000	141,000
Second pumping station (operation cost)	304,000	304,000	261,000	222,000
Total cost (€/year)	530,000	469,000	424,000	372,000

(June 6th) to meet demand. The use of average hours also increases during periods of maximum water demand (June 21st-July 27th) although all the hours will not be used and potential hourly supply will not be pumped. Pumping at these times subsequently decreases, becoming null at the end of August (August 20th) when water will only be pumped to the reservoir during off-peak hours. It is not necessary to pump water to the regulating reservoir during peak energy tariff times (Figure 9).

The frequency distribution of pump efficiencies and regulating efficiencies for the first pumping station during the entire season with and without a regulating reservoir are shown in Figure 10. Mean pump efficiency ($\bar{\eta}$) and mean pump regulating efficiency ($\bar{\eta}_{reg}$) for the first pumping station are 79.91% and 92.82%, respectively, with a regulating reservoir, and 77.22% and 85.49% without one. When comparing the frequency distributions of both situations (with and without a regulating reservoir) by means of the χ^2 test, significant differences are obtained in the distributions of pump efficiency ($\chi^2 = 685.81$; $p < 0.001$) and in the distributions of pump regulating efficiency ($\chi^2 = 2131.82$; $p < 0.001$).

Effect of various factors on regulating reservoir's capacity and total costs

Mean hourly demand pattern

Two types of hourly water demand patterns are analyzed which differ from the historical pumping records to examine their effect on the storage capacity of the reservoir and the total costs. Both patterns are shown in Figure 11.

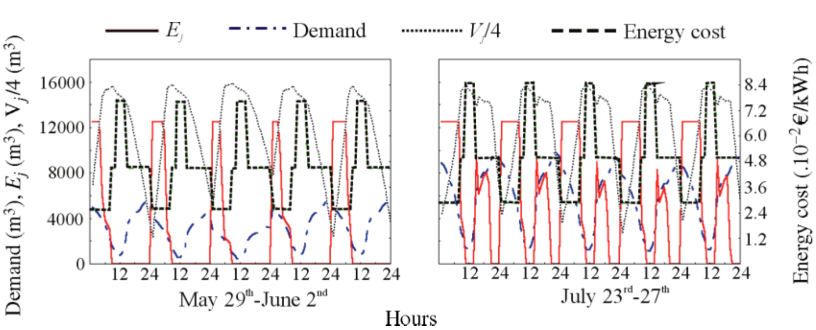

Figure 9 | Optimal operating scheme for the first pumping station with regulating reservoir having two operating cycles (represented to scale $V_j/4$).

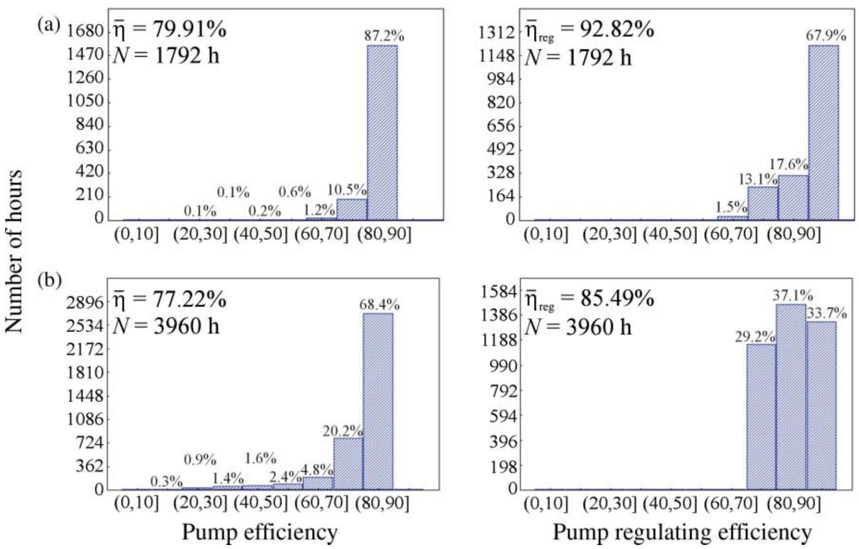

Figure 10 | Frequency distribution of pump efficiencies (η) and pump regulating efficiencies (η_{reg}) for the first pumping station: a) with regulating reservoir and b) without regulating reservoir (N = number of pumping hours).

In the initial and final stages of the irrigation season, with much smaller demanded volumes than in the period of maximum consumption, the maximum of off-peak hours are used, avoiding the average and peak hours. When water requirements increase, other hours must be used. Water cannot be pumped solely during off-peak hours during peak demand periods because pipes and pumps are not large enough to supply the required discharge. From this point on, alternative A matches to the historical demand pattern. Alternative B, however, corresponds to a maximum use of off-peak hours and an equivalent use during average hours (8 to 10 h and 14 to 24 h) avoiding peak hours.

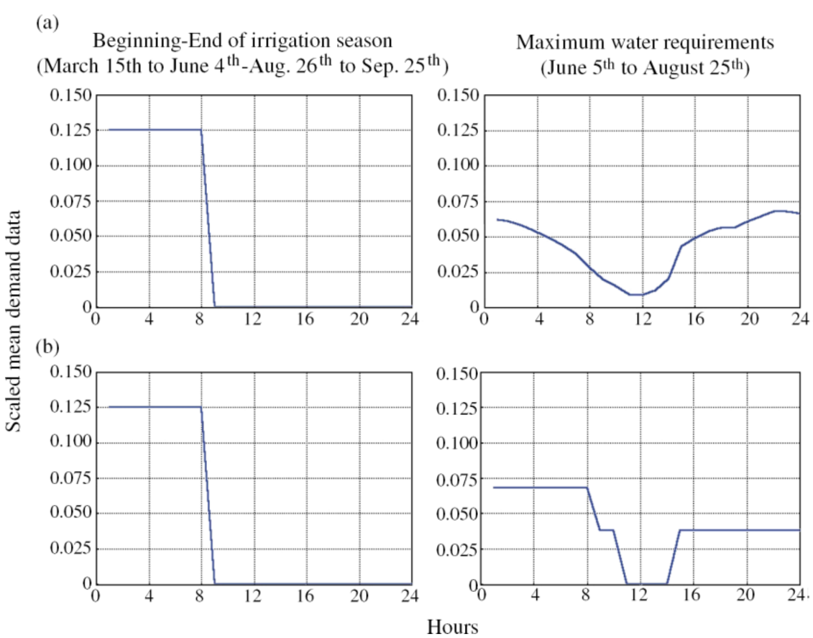

Figure 11 | Two types of water demand patterns. The curves have different forms at the beginning and end of the irrigation season and the period of maximum water requirements.

For alternative A, the model produces the same results for the optimal regulating reservoir design as those obtained for the historical demand pattern in the irrigation district. The optimal operating scheme for pumping water to the reservoir is also similar, although the cost of energy consumption for the pump station that discharges directly into the distribution system (second pumping station) is 14% less (Table 1) as a result of pumping during off-peak hours at the beginning and end of the irrigation season.

For alternative B, the optimal regulating volume of the reservoir is 50,000 m^3, which is 32% of maximum daily demand in the irrigation district. This volume is lower than that obtained for the historical demand pattern. The cost of energy consumption is also lower (Table 1). Significant differences (27%) can be seen in energy costs for the pump station that discharges directly into the distribution system as a higher use of off-peak hours is carried out. The optimal scheme for pumping water to the regulating reservoir is similar to the aforementioned schemes: water is pumped only during off-peak hours until it becomes necessary to pump during average hours in order to meet demand. The use of average hours then increases during periods of maximum demand, although less pumping is needed with this new demand pattern since water requirements are lower at these times, resulting in an 8% decrease in energy costs when pumping to the regulating reservoir (first pumping station).

Structure of energy tariff

A sensitivity analysis was carried out in order to evaluate the effect of different structures of the energy tariff with the historical demand pattern. Table 2 shows the specific structures that have been evaluated: two-step and three-step energy tariffs. The model produces the same results for the optimal regulating reservoir design and the optimal operating scheme for pumping water is also similar to the aforementioned schemes previously. The difference in the total costs for the three structures of energy tariffs was between 2% and 10%.

Table 2 | Structures of energy tariffs

	Hours/day			Cost (€/kWh) low electrical season			Cost (€/kWh) average electrical season		
Energy tariff times	**Two-step energy tariff***	**Three-step energy tariff** (current situation)**	**Three-step energy tariff*****	**Two-step energy tariff**	**Three-step energy tariff (current situation)**	**Three-step energy tariff**	**Two-step energy tariff**	**Three-step energy tariff (current situation)**	**Three-step energy tariff**
Off-peak hours	20	8	8 (Monday to Friday) 24 (Saturday and Sunday)	0.045	0.026	0.026	0.050	0.029	0.029
Average hours		12	10 (Monday to Friday)		0.045	0.045		0.050	0.050
Peak hours	4	4	6 (Monday to Friday)	0.063	0.076	0.090	0.070	0.085	0.100

*The peak hours are 10 a.m. to 2 p.m.
**The off-peak hours are 12 p.m. to 8 a.m. and the peak hours are 10 a.m. to 2 p.m.
***The off-peak hours are 12 p.m. to 8 a.m. and the peak hours are 10 a.m. to 4 p.m.

DISCUSSION

The addition of a regulating reservoir is feasible if a reduction in the total cost of providing water is achieved. The economic analysis indicates that the addition of a regulating reservoir with optimal size and operation scheme is cost effective. At the optimal storage size and operation scheme, the total cost is approximately 469,000 €/year, which is a 12% decrease in the total cost. In the current situation of the irrigation district without regulating reservoir, the total cost is 530,000 €/year.

The optimal pumping scheme to the reservoir is obtained by pumping exclusively during off-peak hours when energy tariffs are lower and pumping at average energy tariff times only during periods of maximum water requirements. This operating scheme also results in more steady and continuous pumping and better pump efficiencies than pumping directly into the distribution network. Both factors demonstrate that direct pumping of a fluctuating flow demand results in 33% higher energy costs than pumping to the reservoir. The addition of the optimal reservoir in this case reduces the peak and average energy use, increases pump efficiencies and helps in electrical load levelling.

The optimal regulating volume is approximately 40% of maximum daily demand, somewhat less than that obtained by Sabet & Helweg (1989) and Nel & Haarhoff (1996) for urban water supply systems with hourly demand patterns with minimum nocturnal consumption (off-peak hours) and similar diurnal consumption (average and peak hours). However, this result is much lower than that recommended by other authors (Amigó & Aguiar 1994) who suggest a volume which corresponds to the regularization of flow on the day of maximum water demand. This low value is due to the fact that the cost of constructing storage facilities remains high and often entails a large investment with respect to the cost of the other elements of the system.

The resulting storage capacity means that water must be pumped on a daily basis and logically depends on the water demand variations for successive days during the irrigation season. Minimum storage capacity is therefore obtained with the hourly demand pattern that best adapts to time-of-use energy tariffs, resulting in greater energy savings and lower total cost.

Given that agreement is necessary between the desired height of the structural sections, optimal storage capacity, total volume of extracted soil, and the balance between extracted material and the material used in the dyke, the storage capacity is determined by the landform of the construction site. A trapezoidal cross-section reservoir with the square base has been used in the model developed in this paper. This type of reservoir may not be used if the terrain is not suitable. However, the model developed herein can be considered an initial approach to the design of storage facilities under these circumstances.

However, it should be noted that the provision of a regulating reservoir is not always the most suitable solution, as energy savings may not warrant the initial investment. This may be the case, for example, when the reservoir is located too far from the benefited area or the pumping station, resulting in friction head losses in the pipelines which would necessitate greater energy requirements and thereby increase total cost. To obtain these results it would be necessary to perform a comparative cost study with concrete data from the water supply system under study.

SUMMARY AND CONCLUSIONS

The construction of a regulating reservoir between the water supply source and the pipe network is proposed in order to reduce energy costs for a water distribution system. The aim of the model developed is to minimize the total cost of the pressurized water delivery system (storage construction cost and pump operation cost). For the supply system studied here, the optimal storage capacity of the regulating reservoir is determined to be approximately 40% of the maximum daily water demand, with daily pumping during off-peak energy tariff times and some average energy tariff times. Analyses show that low off-peak energy costs make the construction of regulating reservoir economically attractive and reduce peak energy use, which results in electrical load levelling. Operating schemes, which include regulating reservoirs, result in more steady and continuous pumping, with higher pumping efficiencies and lower energy costs, than pumping directly into the distribution network. When demand is more closely adapted to time-of-use energy tariffs, the optimal regulating volume is lower, thereby reducing total costs of the delivery system.

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