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SELECTION AND OPERATION OF PUMPING STATIONS OF WATER DISTRIBUTION SYSTEMS

Inmaculada Pulido-Calvo**[*] **and Juan Carlos Gutiérrez-Estrada
Dpto. Ciencias Agroforestales, Escuela Politécnica Superior,
Campus Universitario de La Rábida, Universidad de Huelva,
21819 Palos de la Frontera (Huelva), Spain

Abstract

The energy cost is one of the most important cost components in the water supply systems. Since large amounts of electricity are required to pump, transport and apply water, the profitability of some business, as irrigation districts or fishfarms, which use the water as production resource, is heavily dependent upon energy costs. Methodologies that can maximize energy cost savings while satisfying system performance criteria should be sought for the design and management of the water distribution systems. Some of these methods can be: (a) to improve the selection and/or operation of pumping stations; and (b) to include a regulating reservoir between the water supply source and the delivery system.

The alternative (a), related with the optimal design of pumping stations, refers to the selection of pump type, capacity and number of pump groups that results in minimum design and operating costs for a given water demand. With the alternative (b), 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. Also, the inclusion of reservoirs allows an equalization of pumping schemes that is not possible by pumping directly into the water delivery system. This allows pumping stations to operate near optimum energy efficiency.

In this chapter, one model that includes both alternatives was presented. To implement this optimization process, two algorithms were developed: (a) Algorithm for selection of least cost or optimum pump combinations in water supply systems and to evaluate the system's energy costs; and (b) Algorithm to determine the reservoir 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. This model was applied to the water distribution systems of one irrigation district and one fishfarm located in southern Spain. The analysis indicated that the optimal selection of pump groups and/or the addition of a regulating reservoir was/were energy cost effective.

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[*] Corresponding author: E-mail addresses: ipulido@uhu.es (I. Pulido-Calvo), juanc@uhu.es (J.C. Gutiérrez-Estrada)

1. Introduction

The rapid increase in energy prices that has occurred during the last decades has created the need for increased emphasis on efficient energy use. In many water distribution systems, due to large amounts of energy are required to pump, transport and apply water, improved management of pumps leading to a reduction in energy usage and operational cost must therefore be regarded as a priority when more efficient network operation is sought. In solving this problem, account should be taken of the efficiencies of the pumps, the structure of the electricity tariff, the consumer-demand pattern, and the possibility of a regulation reservoir in the system. The interaction between the pump controls, the resulting pump power consumptions, and the energy head and flow regime in the network will have to be considered through the nonlinear network hydraulics and pump characteristics.

It can be seen that the problem of optimal pump scheduling is one of high complexity for which a formal approach is required. The formulation of the optimization problem must be such that sufficient representation of the network hydraulic characteristics and pumping costs is included, without the resulting solution being too complex for its computer implementation. The need for an efficient solution is emphasized by the fact that the rapidly varying nature of consumer demands requires pump schedules to be obtained in real time for the full benefits of optimal control to be achieved (Jowitt and Germanopoulos, 1992).

As a result, simplifying assumptions have been made to reduce the dimensionality and complexity of the optimal pump scheduling problem in urban water supply systems (Quimpo and Shamsi, 1991). The methods ranged from heuristic methods (Walski, 1984; Tarquin and Dowdy, 1989), to mathematical modeling methods. These methods have been studied using several techniques such as linear programming (Jowitt and Germanopoulos, 1992; Crawley and Dandy, 1993); dynamic programming (Sabet and Helweg, 1985; Ormsbee *et al*., 1989; Zessler and Shamir, 1989; Biscos *et al*., 2003) and nonlinear programming (Brion and Mays, 1991; Cembrano *et al*., 2000). Hierarchical-descomposition methods were also suggested (Joalland and Cohen, 1980; Nitivattananon *et al*., 1996). Another alternative has been the application of expert systems that combine heuristic procedures with algorithmic calculations (Shepherd and Ortolano, 1996; León *et al*., 2000).

In the case of irrigation water supply systems, a number of studies have suggested methods to reduce energy costs for pumping. Buchleiter and Heermann (1986, 1990), Moradi-Jalal *et al*. (2003) and Planells *et al*. (2005) have developed methods to optimize the type and number of pumps as well as scheduling the operation of irrigation pumps, considering both the initial investment and the cost of consumed energy. Stetson *et al*. (1975) showed that significant peak electrical demand reduction could be achieved by shifting irrigation to off-peak hours where pumping plants have sufficient capacity to replace the water consumed by the crop. Some power suppliers have implemented load shedding programs to reduce the operating load on the transmission and delivery system during periods of peak demand. Typically, these programs result in irrigation pump shutoff on a predetermined rotational schedule and get savings in the form of discounts on the power bill to the irrigators. This way, authors like Buchleiter *et al.* (1984), Duke *et al.* (1984) and Heermann *et al.* (1984) made an automatic control system which sets priorities for load interruption in irrigation pump based on soil and crop water status.

The main goal of the most of the aforementioned investigations in urban and irrigation water supply systems is to define the optimal scheduling of the pumping station over a 24-h period. For every hour, the solution must identify the pump, or pump combination, which should be working in order to satisfy the water demand at minimum cost. Nearly all of these works are limited to the operation phase of a given or defined water supply system. In the case of the inland intensive fishfarms, in spite of the high energy costs required for pumping, it is surprising to find few studies in the literature based on the optimum design and management of the water supply systems (Kerr, 1981; Pulido-Calvo *et al*., 2006a, 2008).

Major difficulties in the optimization of water supply system operation include the following: (a) Size and configuration differences among water distribution systems. Large computational time and memory requirements occur in a large system and long planning period (most of the existing models for water supply system operation only assume a 24-h water demand pattern-short planning period-), and; (b) The discrete pump discharges. When pump speeds are considered fixed, the solutions for pump discharges are a discrete set of feasible operating points (Nitivattananon *et al*., 1996).

In this chapter, hourly demand histograms during the annual operation period were considered (long planning period). The full demand during the annual operation period must be satisfied through the designed pumping station. The annual water demand curve allows to select pump combinations which result in the lowest annual total cost (annual depreciation cost and annual operation cost), and that the energy cost evaluation of the delivery system is determined in a more approximate form in comparison with the 'traditional' methods that consider only the point of maximum necessity operation (Stetson *et al*., 1975; Lansey and Mays, 1989; Jowitt and Germanopoulos, 1992; Breytenbach *et al*., 1996).

The construction of a regulation reservoir between the source of water supply and the distribution network is frequent in the water distribution systems. This system is motivated by the need to narrow the temporal gaps between supply and demand and thus to enhance the degree of freedom in water consumers (Mehta and Goto, 1992; Nel and Haarhoff, 1996; Hirose, 1997; Pulido-Calvo *et al*., 2006b). Therefore, the construction of a regulation reservoir or tank may reduce the operational cost of water supply systems because is used for storing water that is pumped from wells or other sources of supply during off-peak periods when energy costs are less for use during periods of peak electrical demand with high energy costs (Sabet and Helweg, 1989).

This chapter presents the development and application of an optimization model that considers the aforementioned difficulties. The objective is to choose pump combinations and a storage capacity that allow to elevate the water in the hours with the most advantageous energy cost and to establish an operation of pumping adapted with the time-of-use energy tariff while satisfying water demands and system hydraulic requirements. The optimal storage capacity is that which results in the minimum total cost, which includes the annualized value of the capital cost of the system (pumps and reservoir) and the operating costs (energy cost). The determination of an optimum pumps and 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.

Once the optimization process and the method solution were identified, a program for a personal computer was written to find the optimal design and operation of the pumping stations and/or regulating reservoir. This program was named DYGOSIA v.1.0 and was written in Microsoft Visual Basic® programming language. The mathematical model development in this chapter forms the basis of DYGOSIA v.1.0 software. The model was verified by applying the developed software to two existing water distribution systems in an irrigation district and in an inland intensive fishfarm, located in the southern Spain.

2. Formulation of Objective Function

The model described in this chapter minimizes an objective function equal to the sum of the equivalent annual value of the capital cost C_I (in €) for T years when present capital cost is invested at r percent interest (fixed cost = depreciation cost of pumps and reservoir) and the operating cost (variable cost = energy cost):

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

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 step t; $\eta_p(t)$ is the p pump efficiency at the time step t; $C_{Ep}(t)$ is the energy cost of the p pump during the time step t, in €/kWh; and Δt is the length of the time step t.

This objective function is subject to:

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

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

  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, that is to say, the difference of the useful stored volume in reservoir between the time steps t and t-1 must be equal to the difference between

the pump discharge $Q_p(t)$ and the water demand Demand(t) of the delivery system at time step t:

$$V(t) - V(t-1) = [Q(t) - \text{Demand}(t)]\,\Delta t \qquad \forall t \tag{3}$$

The optimization period is divided into a discrete control hourly intervals because the demands display a pronounced daily cycle, and energy tariffs are based on time of day.

3. Model Analysis and Solution

There are two difficulties in formulating this model. First, the cost function tends to be non-linear in terms of pump discharge and discharge energy head. Second, a computational time problem occurs when a large number of time steps for a planning period is considered in the model. As a result, an iterative solution of the optimization problem is generally required. The preparation for optimization includes setting up a data structure to manipulate and process the following: Water supply system configuration; Water demand data; Structure of electricity tariff; Data files of pump groups and reservoirs. The steps in the development of the optimization model can be explained as follows:

(a) Decomposition

There are two types of decomposition, including:

- Spatial decomposition. The system is decomposed into several subsystems. Local optimization can be carried out for each subsystem. Then, the subsystems are synthesized to form the overall system. The first subsystem is composed of the pumping station that elevates the water from the supply source until the regulation reservoir. The rest of subsystems are composed of the possible booster pumps (or pumps in series) that are normally placed on a distribution line some distance from water source and serve to increase the pressure to downstream points on the line.
- Time decomposition. The operation of this optimization model is divided into two levels, long- and short-term models. The two models cover a planning period (annual season) and an operational period (a day), respectively. The annual period is divided into daily time steps and the daily period is divides into hourly time steps for the purpose of the optimization procedure.

(b) Water demand

The model is based on the water hourly demands because the energy tariffs are based on time of day and because a regulation reservoir is usually designed to satisfy the fluctuating water demand during a day. The hourly demand patterns during the annual operation period can be calculated with historical data of the water hourly demand. When historical data of water demand are not available, simulation models are generally used (Pulido-Calvo *et al*., 2006b).

(c) Long-term Model

The purpose of the long-term model is to choose pump combinations and a storage capacity that allow to elevate the water in the hours with the most advantageous energy cost, to select the most appropriate electricity tariff and to establish an operation of pumping adapted with the time-of-use energy tariff while satisfying water demands and system requirements during the annual season. It is expected that the computational time for this model may be long. For this reason, the procedure starts with an initial solution for the selection of the pump combinations. The combinations that give the maximum requirements of flow and energy head of distribution network are chosen as initial solution and are used in the optimization algorithm of the design and operation of the pumping stations and the regulation reservoir (see section 4).

(d) Short-term Model

The short-term model is used to update the solutions of the long-term model. This model is similar to the long-term model, except for the following item. The operational period must be short and appropriate for real-time operation. Typically, the operating plan is prepared for a period of twenty-four hours ahead, because the demands display a pronounced daily cycle, and energy tariffs are based on time of day. The real-time operation is based on the forecast of water demands. To accomplish this requirement, the historical data of the water demand must be considered. Methodologies for water demand forecasting can be time series approach, regression models or computational neural networks (Griñó, 1992; Jain *et al*., 2001; Zhou *et al*., 2002; Pulido-Calvo *et al*., 2003; Bougadis *et al*., 2005; Alvisi *et al*., 2007; Pulido-Calvo *et al*., 2007; Firat *et al*., 2008). The results from the short-term model include which combination of pumps operates and their schedules for all the pump stations.

4. Initial Solution for the Selection of the Pump Combinations

Individual pump performance is expressed by energy head discharge, H-Q, and power consumption discharge, P-Q, curves. The H-Q and P-Q data points obtained from manufacturer's curves were entered for each pump size and type (range of pump discharge : 1-5000 m^3/h and range of pump head: 1-180 m). Generally, several pumps of similar sizes may operate in parallel to satisfy the different flow and head requirements at the pumping station. Second order polynomial equations for H-Q and P-Q were calculated for each pump type and for all possible pump combinations using least square regression techniques (Sabet and Helweg, 1989; Mays, 2000; Moradi-Jalal *et al*., 2003; Pulido-Calvo *et al*., 2003b). The polynomial coefficients were stored in data files.

Given the characteristics of the distribution system and the hourly water demands, the required energy head at each time period in the pumping to the water delivery 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 (Mays, 2000).

Several pump combinations can satisfy the maximum requirements of flow and energy head of the water distribution system. The search procedure for selecting pump combinations divides the maximum flow in 2, 3, ..., n times. This way, for each value of division k ($2 \leq k \leq n$), are chosen the pumps that give the flow (Q/k) with energy head equal or higher than the maximum requirements at the water distribution network. If a pump combination can supply the flow but not at required energy head, a penalty is added to discourage selection of this combination. The pump combinations are also chosen with efficiency (required power/consumed power) equal or higher than 30% (large losses of power consumption are avoided). These pump combinations are only those that use in the optimization algorithm of the design and operation of the pumping stations and regulation reservoir.

5. Long-Term Model for the Optimal Design and Operation of Pumping Stations and Regulation Reservoir

The formulation of the optimal pump scheduling problem relies on the following set of assumptions:

(a) Pump Groups

Each pumping station includes one or more combinations of parallel pumps. A parallel pump combination can be a source or booster combination. A source combination pumps water from a borehole source into the origin reservoir. A booster combination pumps water out of an origin reservoir and into destination network distribution. The pumping station including a source combination is referred to as the source station. A pumping station including only booster combinations is referred to as a booster station.

(b) Regulation Reservoir Design

For high regulating capacities, the use of low cost materials such as soils or lands has been widely used in the construction of reservoirs for storing water. The cost of theses reservoirs has as relevant factors: the reservoir excavation, the surface to waterproof and the land surface where is the reservoir. The reservoir is assumed to be square (Pulido-Calvo *et al*., 2006b). A reservoir cross section with relevant geometric parameters is given in Figure 1. As indicated, N1 is the outside levee slope (horizontal to vertical), N2 is the inside levee slope, Ta is the top width (m) of the levees, 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, and F is the freeboard (m). The total storage volume VT (m^3) is given by:

$$VT = L^2\ (H1 + H2 + F) + 2\ L\ N2\ (H1 + H2 + F)^2 + 1.33\ N2^2\ (H1 + H2 + F)^3 \tag{4}$$

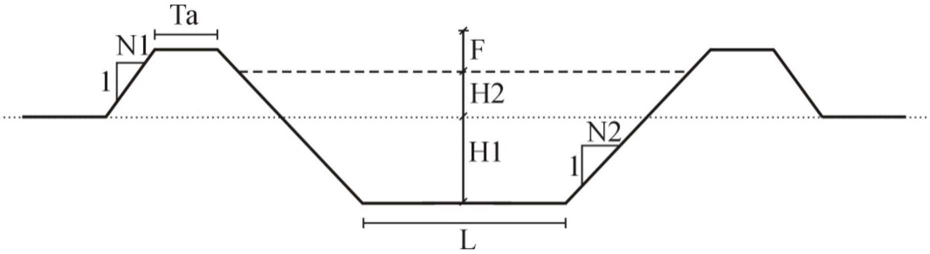


Figure 1. Reservoir cross-section and parameters

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

$$VX = L^2\ H1 + 2\ L\ N2\ H1^2 + 1.33\ N2^2 H1^3 \tag{5}$$

It is desirable to minimize the excavation cost, and this occurs when VX is equal to the volume of fill used to construct the levees. The volume VL (m^3) comprised by the levees is calculated from:

$$VL = 4\left[L + 2\ N2\ (H1 + H2 + F) + 2\ Ta + 2\ N1\ (H2 + F)\right]\left[0.5\ (N1 + N2)\ (H2 + F)^2 + Ta\ (H2 + F)\right] \tag{6}$$

$$VL = VX\ (1 + CF) \tag{7}$$

where CF is the cut to fill ratio.

In practice, the quantities N1, N2, Ta, F 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, F = 1 m, and CF = 10% are considered. Due to safety, it is also common to construct reservoirs so that the total storage depth (H1 + H2) is in the range of 2 to 12 m. These factors are accounted for in model by the requirement that N1, N2, Ta, F and CF be fixed inputs. An iterative solution to calculate the dimensions H1, H2 and L for any capacity is required. The procedure starts with a trial value of (H1 + H2) and with the equation (4) is obtained L subject to L > (H1 + H2). The values of H1 are calculated with (7) using Newton numerical method. Then (H1 + H2) is incremented and new values of H1, H2 and L are computed. The iterative process stops when the capital cost of the reservoir is minimum.

(c) 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' (Pulido-Calvo *et al.*, 2006b). This is defined as the hourly interval ($i < j \leq i+k$) whereby at the initial hour t_{i+1} the reservoir has an 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:

$$VR_j = V_{max} - V_j \tag{8}$$

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 $\overline{E}$ (E_i,..,E_j,..,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,..,z): $E_j = E_{j,u} + E_{j,v} + \dots + E_{j,z}$.

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, $-V_{i+k,v}$.
- The difference between potential hourly supply and the volume pumped at hour j during any emptying period u prior to v, PHS – $E_{j,u}$.
- The minimum deficit volume of the hours between hour j selected for pumping and the final hour (i+k) during emptying period v, min ($VR_{j,v}$, $VR_{j+1,v}$,..., $VR_{i+k,v}$).

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

$$\Delta(V_{j,v}) = \min\left\lfloor -V_{i+k,v}, \min(VR_{j,v}, VR_{j+1,v}, \dots, VR_{i+k,v}), PHS - E_{j,u} \right\rfloor \tag{9}$$

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. 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, thus meeting the demands of emptying period v [eq. (10)]. 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: $(i < j \leq i+k+1)$.

$$\Delta(V_{j,v}) = -V_{i+k,v} \tag{10}$$

- The deficit at hour i+k is not eliminated, but reduced. The new deficit is calculated by eq. (11), with an increase in volume given by eq. (12). 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 with lowest energy tariffs during the emptying period v.

$$-V_{i+k,v} = -V_{i+k,v} + \Delta(V_{j,v}) \tag{11}$$

$$\Delta(V_{j,v}) = \mathrm{PHS} - E_{j,u} \tag{12}$$

- The deficit at hour i+k has not been eliminated, but reduced [equation (11)], with an increase in volume given by eq. (13). The emptying period will have been reduced and the new period initiated at hour h with $(j < h \leq i+k)$.

$$\Delta(V_{j,v}) = \min(VR_{j,v}, VR_{j+1,v}, \ldots, VR_{i+k,v}) \tag{13}$$

Eqs. (10)-(13) 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 $\overline{E}$ will obtain the distribution of volumes pumped at each hour t during the irrigation season for any storage volume. $\overline{E}$ will determine the power consumption P for each hour t and hence the energy cost.

6. Short-term Model for the Optimal Operation of Pumping Stations and Regulation Reservoir

This chapter evaluates the performance of linear multiple regressions and feed forward computational neural networks (CNNs) trained with the Levenberg–Marquardt algorithm (Sheperd, 1997) for the purpose of daily water demand modeling. The models are established using data recorded from the water distribution systems. The input or independent variables used in various CNN and multiple regression models are: (a) water demands from previous days; (b) water demands and climatic data (rainfall, maximum, minimum and average temperatures, relative humidity and wind speed) from previous days.

To assess the performance of the neural networks and the multiple regressions during the validation phase and therefore to identify the best short-term model, two measures of accuracy were applied: determination coefficient R^2 and efficiency coefficient E (Pulido-Calvo *et al*., 2007).

7. Model Applications

The proposed methodology was applied to the demand pressurized system of the irrigation district of Fuente Palmera and to the water delivery of Hidrorecursos S.A., an intensive eel fishfarm, both located in the southern Spain. The purpose of these applications was to simulate the costs that would have been incurred if the pumping stations were designed according to model developed in this paper, and to compare these costs with the actual costs.

Input data for the model include a regulating reservoir and pumps 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 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 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.

7.1. Water Distribution System of An Irrigation District

The demand pressurized system of the irrigation district of Fuente Palmera, located in the Guadalquivir valley (southern Spain), has an annual water consumption of 16.5 ± 5.9 hm^3 and must be drawn from the Guadalquivir River. The average irrigated area is approximately 5,000 ha and is irrigated by sprinkling on demand.

Nowadays the pressurized irrigation system has two pumping stations in series (Figure 2). The first station (4 pumps in parallel; each pump group has an electric motor that operates at 990 rpm and the power motor is 2,500 hp) carries water from the Guadalquivir River to a 5000 m^3 tank, that is the aspiration chamber for the second station (6 pumps in parallel; each pump group has an electric motor that operates at 990 rpm and the power motor is 2,500 hp) 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.

Figure 2. *Water distribution system of the 'Fuente Palmera' irrigation district. The main pipes network has 96* control nodes of pressure and flow

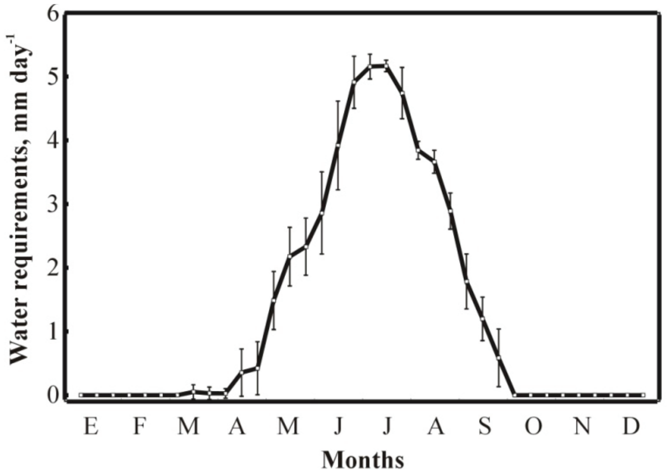


Figure 3. Water requirements of the 'Fuente Palmera' irrigation district.

The main water supply system carries water from the booster station (second pumping station) to 78 different groups of farmers, each one 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 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. The water requirements of this irrigation district are shown in Figure 3.

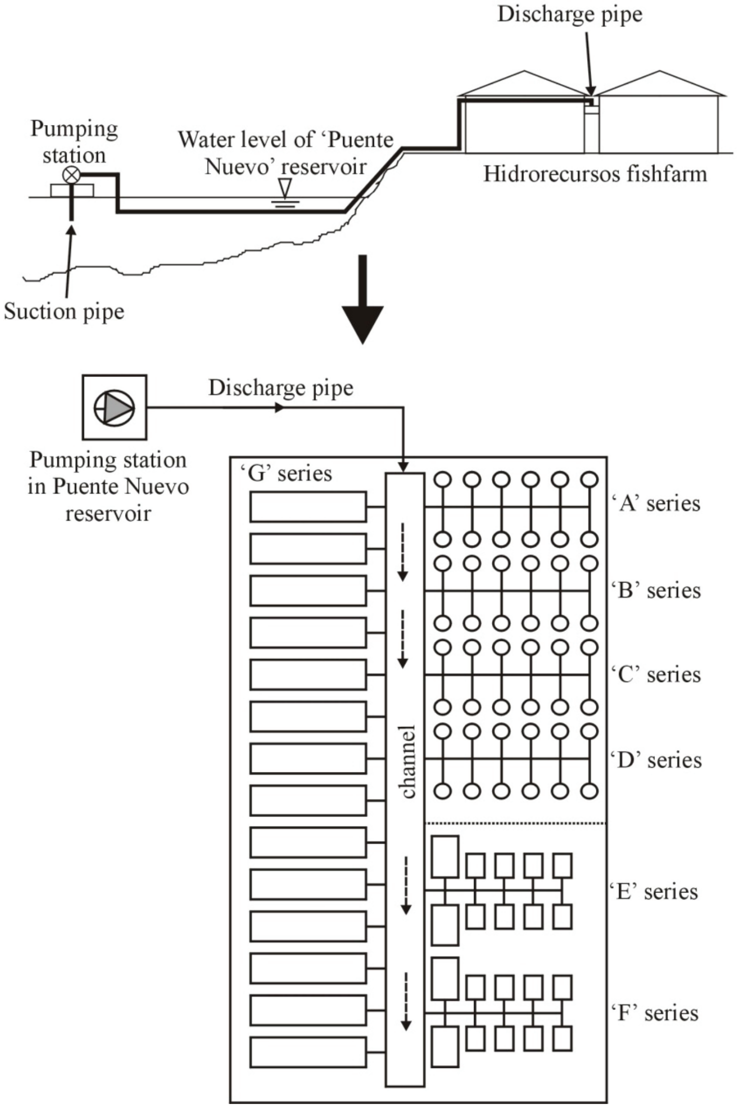


Figure 4. Scheme of the water distribution network of the 'Hidrorecursos' fishfarm.

7.2. Water Distribution System of a Fishfarm

In Hidrorecursos S.A., an intensive eel fishfarm located in the province of Córdoba (southern Spain), the water is pumped from the Puente Nuevo reservoir (Figure 4). The main pumping station has a pump combination with two groups in parallel. Each pump group has an electric motor that operates at 1,480 revolutions per minute (rpm) and the motor power is 300 horsepower (hp) (220.8 kW). In general, the pump operation scheme is at a constant rate and the excess flow is dumped when the water demand is lower.

In this intensive fishfarm, the water is pumped from the Puente Nuevo reservoir to a main channel with slope of 0.1%. The water is then transported by this channel by gravity to seven tanks series that have the spatial configuration shown in Figure 4. The 'A', 'B', 'C' and 'D' series are the nursery tanks (eel weight: 0.3-40 g) that have 12 circular tanks with a capacity of 3.2 m^3 in each series (12 × 3.2 m^3 tanks). The 'E' and 'F' series are the pre-growth tanks (eel weight: 40-110 g) with 8 rectangular tanks of 16 m^3 (8 × 16 m^3 tanks) and 2 rectangular tanks of 32 m^3 (2 × 32 m^3 tanks), respectively. In the last tank 'G' series (14 × 110 m^3 rectangular tanks), the eels grow to commercial weight (150 g). The water requirements of this fishfarm during the years 1999 and 2000 are shown in Figure 5.

7.3. Results: Irrigation District

The least total costs were obtained with the alternative that considers a regulating reservoir between the two pumping stations with the following characteristics: (a) source pumping station with 8 groups in parallel with electric motors of 340 hp/pump and 1,480 rpm; (b) booster station with 7 groups in parallel with electric motors of 340 hp/pump and 1,480 rpm; (c) 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 1) 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 62% less than the cost of pumping directly to the water supply system (407,000 €/year) (current performance of the pumping station that discharge the water demand of each hour). Also, the cost of the second pumping station in the optimal solution (304,000 €/year) is 41% less than the cost of pumping directly to the water supply system (513,000 €/year). The annual total cost, which includes the storage construction cost and the cost of operation and capital of the pumps, is 41% 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 off-peak energy use, and greater pump efficiencies.

Figure 5. Water *demand of the 'Hidrorecursos' fishfarm.*

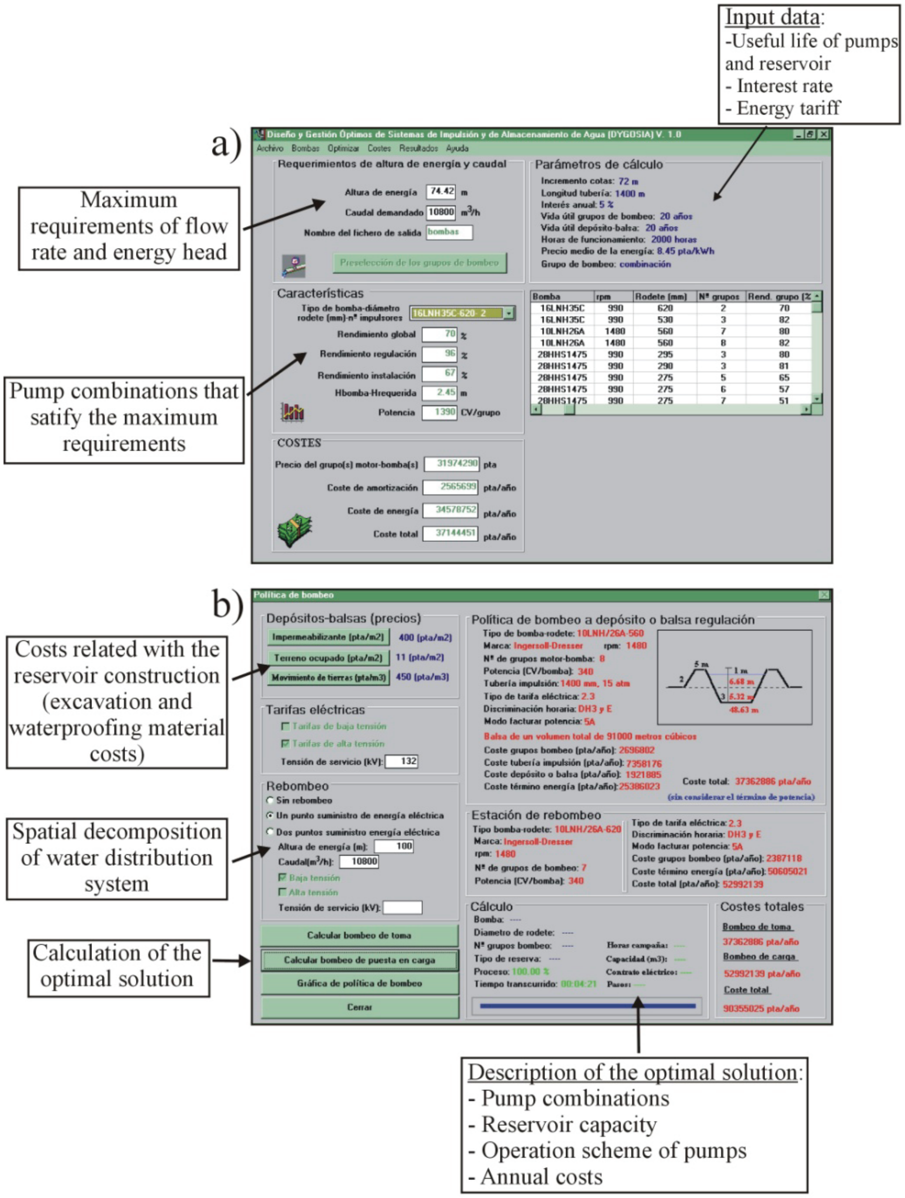
Table 1. Costs (€/year) of water supply system with and without regulating reservoir

	Without reservoir (current situation of irrigation district)	With reservoir (optimal solution)
First pumping station (operation cost) (€/year)	407,000	153,000
Second pumping station (operation cost) (€/year)	513,000	304,000
Total cost (operation cost + amortized capital cost) (€/year)	1,070,000	633,000

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 (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.

The frequency distribution of pump efficiencies and regulating efficiencies for the first pumping station during the entire season with and without regulating reservoir were compared. Mean pump efficiency $(\overline{\eta})$ and mean pump regulating efficiency $(\overline{\eta}_{reg})$ 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 regulating reservoir) by means of the χ^2 test, significant differences are obtained in the distributions of pump efficiency (χ^2 =

685.81; $p < 0.001$) and in the distributions of pump regulating efficiency ($\chi^2 = 2131.82$; $p < 0.001$).



Input data:
- Useful life of pumps and reservoir
- Interest rate
- Energy tariff

Maximum requirements of flow rate and energy head

Pump combinations that satisfy the maximum requirements

Requerimientos de altura de energía y caudal

Altura de energía: 74.42 m
Caudal demandado: 10800 m^3/h
Nombre del fichero de salida: bombas

Parámetros de cálculo

Incremento cotas: 72 m
Longitud tubería: 1400 m
Interés anual: 5 %
Vida útil grupos de bombeo: 20 años
Vida útil depósito-balsa: 20 años
Horas de funcionamiento: 2000 horas
Precio medio de la energía: 8.45 pta/kWh
Grupo de bombeo: combinación

Características

Tipo de bomba-diámetro rodete (mm)-nº impulsores: 16LNH35C-620- 2
Rendimiento global: 70 %
Rendimiento regulación: 96 %
Rendimiento instalación: 67 %
Hbomba-Hrequerida: 2.45 m
Potencia: 1390 CV/grupo

Bomba	rpm	Rodete (mm)	Nº grupos	Rend. grupo (%
16LNH35C	990	620	2	70
16LNH35C	990	530	3	82
10LNH26A	1480	560	7	80
10LNH26A	1480	560	8	82
28HHS1475	990	295	3	80
28HHS1475	990	290	3	81
28HHS1475	990	275	5	65
28HHS1475	990	275	6	57
28HHS1475	990	275	7	51

COSTES

Precio del grupo(s) motor-bomba(s): 31974290 pta
Coste de amortización: 2565699 pta/año
Coste de energía: 34578752 pta/año
Coste total: 37144451 pta/año

Costs related with the reservoir construction (excavation and waterproofing material costs)

Spatial decomposition of water distribution system

Calculation of the optimal solution

Depósitos-balsas (precios)

Impermeabilizante (pta/m2): 400 (pta/m2)
Terreno ocupado (pta/m2): 11 (pta/m2)
Movimiento de tierras (pta/m3): 450 (pta/m3)

Tarifas eléctricas

☐ Tarifas de baja tensión
☑ Tarifas de alta tensión
Tensión de servicio (kV): 132

Rebombeo

○ Sin rebombeo
● Un punto suministro de energía eléctrica
○ Dos puntos suministro energía eléctrica
Altura de energía (m): 100
Caudal(m^3/h): 10800
☑ Baja tensión
☐ Alta tensión
Tensión de servicio (kV):

Política de bombeo a depósito o balsa regulación

Tipo de bomba-rodete: 10LNH/26A-560
Marca: Ingersoll-Dresser rpm: 1480
Nº de grupos motor-bomba: 8
Potencia (CV/bomba): 340
Tubería impulsión: 1400 mm, 15 atm
Tipo de tarifa eléctrica: 2.3
Discriminación horaria: DH3 y E
Modo facturar potencia: 5A
Balsa de un volumen total de 91000 metros cúbicos
Coste grupos bombeo (pta/año): 2696802
Coste tubería impulsión (pta/año): 7358176
Coste depósito o balsa (pta/año): 1921885
Coste término energía (pta/año): 25386023
Coste total: 37362886 pta/año
(sin considerar el término de potencia)

Estación de rebombeo

Tipo bomba-rodete: 10LNH/26A-620
Marca: Ingersoll-Dresser
rpm: 1480
Nº de grupos de bombeo: 7
Potencia (CV/bomba): 340
Tipo de tarifa eléctrica: 2.3
Discriminación horaria: DH3 y E
Modo facturar potencia: 5A
Coste grupos bombeo (pta/año): 2387118
Coste término energía (pta/año): 50605021
Coste total (pta/año): 52992139

Cálculo

Bomba: ----
Diametro de rodete: ----
Nº grupos bombeo: ----
Tipo de reserva: ----
Proceso: 100.00 %
Tiempo transcurrido: 00:04:21
Horas campaña: ----
Capacidad (m3): ----
Contrato eléctrico: ----
Pasos: ----

Costes totales

Bombeo de toma
37362886 pta/año
Bombeo de carga
52992139 pta/año
Coste total
90355025 pta/año

Description of the optimal solution:
- Pump combinations
- Reservoir capacity
- Operation scheme of pumps
- Annual costs

Figure 6. Main windows of DYGOSIA v.1.0 computer program (spanish version).

7.4. Results: Fishfarm

The optimum alternative doesn't imply the inclusion of regulating reservoir. The pump combination has nine groups in parallel. Each pump group has an electric motor that operates at 2,900 revolutions per minute (rpm) and the motor power is 40 horsepower

(29.4 kW). The operator will have to turn on and off the pumps during the annual operation period in accordance with the water requirements. It is clear, by using this optimization model, a decrease of about 92% is obtained in annual operation cost and annual depreciation cost of the initial investment compared to actual situation (average total annual cost of fishfarm pumping station = 72,000 €/year; optimal solution = 6,210 €/year).

Given that the water requirements of the fishfarm are different over the course of a annual operation period, the optimum pump combination is the alternative that operates more closely adapted to system head curve, that is to say, the pump combination with the highest regulating efficiencies during all the annual operation period.

The results showed in sections 7.3 and 7.4 were achieved through the use of the aforementioned inputs as well as the optimization equations implemented in DYGOSIA v.1.0 computer program (Figure 6).

7.5. Water Demand Forecasting for Short-Term Model

For both the neural models and multiple regressions the best values for the evaluation magnitudes R^2 y E were obtained when water demand for the two days prior to forecasting was used as the input or for the independent variables. In all of the models considered, the neural networks provide better forecasts than the multiple regressions. In almost all the neural models, values for R^2 were higher than 0.7 and for E were lower than 30%.

8. Conclusion

The energy required for operating pumping stations in water distribution systems may be significant. Thus, an optimization model has been developed to identify the pump, or pump combination, and reservoir storage capacity which should be working in order to satisfy the water demand at minimum annual total cost (annual operation cost plus annual depreciation cost of the initial investment). The difficulty of the discrete pump discharges have been considered in this model.

To support operational decisions, a computer software package for the model was also coded and applied successfully to two real delivery systems. It was found that the proposed model may significantly reduce the total annual costs.

The model was developed so that it should be applicable for other water supply system by introducing a similar set of data. It will be very effective if the water daily demand simulation is accurate. This approach of water daily requirements is highly related with the available information/data of the facilities. This way, in those water supply systems with a high control level of their operation schemes will allow to carry out a more easy and accurate estimation of water daily demands.

The addition of a regulating reservoir is feasible if a reduction in the total cost of providing water is achieved. The developed economic analysis indicated that the addition of a regulating reservoir with optimal size and operation scheme is cost effective in the irrigation district but not in the fishfarm. The optimal solution with regulating reservoir saved 41% of the annual total cost in the irrigation district. The optimal solution without regulating reservoir saved 92% of the annual total cost in the fishfarm.

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.

In this chapter, consumer water demand forecasting systems that can support decision making of the water delivery administrators are proposed using multiple regressions and computational neural networks. Determination coefficients higher to 92% and efficiency coefficient E higher to 0.91 have been obtained in the validation period, when water demand of the two days prior to forecasting was used as input or independent variables to the neural network. The neural models performed better than the regressions. Short-term demand modeling can be used as input in methods and/or programs for the management of water delivery systems in real time. Furthermore, this approach achieves a better fit of the pumped volumes and the real demand of the distribution network, thereby leading to a more rational use of water and energy resources.

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