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Design and performance analysis of low pressure irrigation distribution systems

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Abstract. Low-pressure pipe distribution systems for surface irrigation provide both off- and on-farm recognized environmental benefits. However, expected benefits can only be attained when adequacy, dependability and equity of systems are high enough to support appropriate conditions for water use on the farm. An innovative methodology for design and analysis is proposed and described, which includes the generation of the demand at the scale of the distribution system and, consequently, the generation of the flow regimes expected during a given period of time, generally the peak month. These flow regimes are utilized for the optimization of pipe sizes using the iterative discontinuous method for several flow regimes. The performance analysis is developed through the system simulation with several flow regimes, which allow the computation of the system adequacy, dependability and equity. An application to one sector of the Sorraia irrigation system illustrates the usefulness of the methodology proposed.

Key words: adequacy, dependability, design, equity, generation of farm demand, low-pressure distributors, pipe size optimization, simulation

Introduction

Low pressure buried pipe distribution systems for surface irrigation constitute a valuable alternative to open channel distributors (van Bentum & Smout 1994; INCID 1998). Operation, maintenance and management of the off-farm systems are easier and less costly than that of surface distributors but investment costs are generally higher. Under the environmental perspective, advantages relate to reduced water losses, more efficient use of agricultural land, reduced damage of land through waterlogging and salinity, reduced damage of water resources, greater transit efficiency, control of aquatic weeds and associated pests, and contribute to control of water-born vectors and of human-related diseases, namely schistosomiasis and malaria.

Benefits are particularly important at farm level because pipe systems enable greater flexibility and reliability of deliveries due to shorter transit times and smaller system losses than open surface systems. Pipe systems facilitate matching of water supplies to crop demand, providing conditions for more efficient water use at farm level, and contribute to the elimination of tail-end equity problems. These systems provide for improved control of water wastes, adopting improved irrigation schedules and, in addition, for reduction of the transport of solutes out of the root zone and for an increase in the efficiency of water use in agricultural production. However, low pressure pipelines are not always the best solution, as analyzed by Burt and Plusquellec (1990).

Appropriate design is an essential condition for achieving the expected benefits. Associating the performance analysis with optimization of pipe sizes provides for the selection of the design alternatives that enable high performances associated with reduced costs.

The design of surface irrigation distribution systems is commonly performed on the basis of an assumed discharge per unit surface (l s^{-1} ha^{-1}) computed from the crop irrigation requirements relative to the peak demand period. These discharges are aggregated at the farm outlets in such a way that they correspond to those discharges usually managed by the irrigators when applying the water to the field. This procedure allows an estimation of the discharges that are expected to flow in each reach of the conduits between successive nodes of the system. Pipes are then sized to satisfy that flow regime. Simulations relative to possible configurations of outlets operating simultaneously, or to alternative crop patterns and irrigation practices are not made. These simple procedures may produce low service performances when design approaches aim at minimizing the network costs and pipe sizing is computed with low flexibility. Therefore, the pipe system may not accommodate for changes in the sequence of outlet opening, i.e. flow regimes different from that used to size the pipes, or changes in irrigation methods and cropping systems, that also imply different flow regimes.

Better service performances may be attained when pipes are sized using several flow regimes, or any other optimization procedure, and when the designed system is simulated later using a different set of generated flow regimes to assess the respective performance. Combining design and performance analysis allow the designer and the user to accept a given design solution based on the values produced for the selected performance indicators or, when these are not satisfactory, to reinitiate the computational procedure with a new set of flow regimes and/or design constraints. The flow regimes may be generated from the simulated demand hydrographs, which are built assuming a random distribution of crops, irrigation methods and irrigation scheduling practices associated with every farm outlet in association with an arranged delivery schedule.

With these objectives, a new design methodology has been developed based on that used for collective pressurized systems (Lamaddalena & Sagardoy 2000). Pipe sizes are optimized using the iterative discontinuous method (Labye 1981) applied to several flow regimes, which have been shown to produce slightly better results than linear optimisation (Lamaddalena 1996; 1997). The performance analysis is adapted from Bethery (1990) and Lamaddalena (1995), who developed the methodology for pressurized systems operating on demand. The selected indicators are adequacy, dependability and equity, whose computation is adapted from that proposed by Molden and Gates (1990). A modeling approach has been developed to perform design and performance analysis following this new methodology. The model performs the computation of the demand hydrographs, the generation of the flow regimes, the optimization of the pipe diameters, and the analysis of performance by simulating the network functioning at several flow regimes. The methodology is presented through an application to the Sorraia irrigation system (Pereira 1988; Pereira et al. 1990) in southern Portugal.

Brief introduction to the modeling approach

The MSGOA model has been developed to perform the generation of the flow regimes, the optimization of the pipe diameters, and the analysis of performance by simulating the network functioning at several flow regimes. MSGOA is written in Turbo Pascal 7.0 for MSDOS and WINDOWS. The model is limited to a system with a maximum of 150 outlets, 10 crops and 10 irrigation methods.

The required input data are listed in Table 1. Data relative to items (a) through (h) are introduced with help of user friendly windows and can be modified from one session to another. System characteristics data (items i through l) are introduced when the sector files are created.

The operation of the model is commanded by a main menu through which the user can select the following options:

(1) the generation of flow regimes,
(2) the optimization of pipe diameters, and
(3) the analysis of performances.

Generated flow regimes and pipe sizes (lengths and diameters) are stored in output files that can be used in subsequent calculations. Model results con-

Table 1. Input data for design and performance analysis.

	Input data	Symbols and units
(a)	upstream discharge, and hydraulic head	$Q_o[l\ s^{-1}]$ $H_o[m]$
(b)	cropping pattern, with indication of the probability of occurrence of each crop k	$C_k[\%]$, with $k = 1, 2, \ldots, NK$
(c)	probability of occurrence of the irrigation methods i, including the respective percentage of automation	$M_i[\%]$, with $i = 1, 2, \ldots, NI$
(d)	soil type distribution where soils s are grouped according to water holding capacity and land slope	$S_s[\%]$, with $s = 1, 2, \ldots, NS$
(e)	net crop irrigation requirements during the peak month	$I_{n,k}[mm]$
(f)	average irrigation intervals and respective range of variation according to the irrigation method and soil type	$f_{i,s}[days]$ $\delta_{i,s}[days]$
(g)	application efficiencies relative to each couple irrigation method – soil type	$eff_{i,s}[\%]$
(h)	daytime hours for water supply as established by the irrigation management agency	$t_D[h]$
(i)	area served and soil type at each outlet j	$A_j[ha]$, with $j = 1, 2, \ldots, NO$
(j)	nominal discharge and minimum head at the outlets	$(Q_n)_j[l\ s^{-1}]$ $(H_{min})_j[m]$
(k)	system layout with identification codes for each node and respective land elevation	
(l)	length of each pipe section between two successive nodes (when analyzing existing systems, the respective diameters are also inputted)	$L[m]$
(m)	diameters and costs of the commercial pipes	$D_p[m]$ $C_p[m^{-1}]$

cerning each one of these three main options may be produced as numerical or graphical outputs after selection by the user.

Generation of flow regimes

Each flow regime is defined as a combination of discharges flowing in the system in correspondence with each configuration of outlets simultaneously operating. In opposition to pressurized irrigation systems operating on demand, where each configuration can be randomly generated (Bethery 1990; Lamaddalena & Sagardoy 2000), flow regimes in low pressure distribution systems have to be obtained from demand hydrographs which respect the arranged delivery schedules (Clemmens 1987) used in surface irrigation systems. Thus, the generation of flow regimes requires: (i) the definition of the irrigation demand schedules for the areas served by each outlet, (ii) their aggregation at system level respecting the available upstream discharge; and (iii) the generation of the hourly demand hydrographs. Values for each hour, which correspond to the discharges at the outlets operating simultaneously at that hour, are then utilized to define the flow regimes.

Computations are made assuming that only one crop can be assigned to the area served by each outlet when the crop distribution over the total area is respected. Because at the design phase the distribution of crops in the areas served by each outlet are not known and, in case of performing the analysis of a given system, that distribution may change from one year to the other, a random procedure is adopted to assign the crops to the areas served by every outlet. Thus, knowing the percentage distribution of each crop in the project area C_k, it can be assumed that the probability for any crop k to occur in the area served by every outlet is equal to C_k. Therefore, adopting a random generation of numbers from 0 to 100 with uniform distribution, and assuming that each probability C_k [%] corresponds to a portion in the interval 0 to 100, it is possible to randomly select the crop k assigned to each outlet. After this operation is concluded for all outlets, it is verified if the simulated crop pattern matches that proposed by summing up the surfaces assigned to each crop to the full area. When more than 10% differences are observed, the operation is repeated until satisfactory results are obtained.

The irrigation methods considered are the traditional short blocked furrows, automated and non-automated furrows and level basins, flooded rice basins, automated and non-automated solid set sprinklers, drip irrigation and line source micro-irrigation. Low pressure pipes do not deliver water for pressurized systems but these can be supplied when appropriate pumps are available on the farm, which is the practice by farmers in the case study area.

The probability for a given irrigation method i to be associated with a soil type s is estimated by m_i S_s [%], and the probability that this irrigation method would be associated with a crop k corresponds to m_i C_k[%]. Because at this stage both the soil type s and the crop k are known for the areas served by every outlet, it is possible to randomly assign an irrigation method to each outlet area when the probability for an irrigation method i to be associated with the crop k and the soil s is known. This probability is estimated by

$$(S_sC_k)_i = \frac{(S_sM_i)(C_kM_i)}{\sum_{i=1}^{NI}(S_sM_i)(C_kM_i)} \quad (1)$$

Using a procedure similar to that indicated for the random assignment of the crops to each outlet service area, the irrigation methods are also randomly defined for each outlet. It then becomes possible to associate a crop, a soil and an irrigation method to each outlet area.

For each couple irrigation method – soil type, the user selects the average time interval between irrigations, $f_{i,s}$ [days], and its range of variation, $\delta_{i,s}$ [days]. These data are used by the model to randomly generate an irrigation interval $(F_{i,s})_j$ [days] for each outlet. The procedure consists of:

1. assigning to each value $(\rho_m)_{i,s}$ [days], in the interval $[(f-\delta), (f+\delta)]_{i,s}$ the lower and upper limits $(R_m)_{i,s} = (\rho_m)_{i,s} - 0.5$ and $(R_{m+1})_{i,s} = (\rho_m)_{i,s} + 0.5$;
2. converting these real numbers R_m into the normal variables $X_m = (R_m - f)/\sigma$, where σ is the standard deviation of $R_m (i = 1, 2, \ldots, n')$;
3. computing from the normal distribution the probabilities $P_m = P(X > X_m)$;
4. randomly generating a real number (0 to 100), which falls in one of the intervals $[P_m, P_{m+1}]$;
5. computing back, from these probabilities, the variables X_m and X_{m+1} and, therefore, R_m and R_{m+1};
6. determining the value $(\rho_m)_{i,s}$ in the interval $[R_m, R_{m+1}]$, which is the estimator for $(F_{i,s})_j$ [days].

The average irrigation depths $(I_{av})_j$ [mm] during the peak period are computed for each outlet from the input data relative to the net monthly irrigation depths $I_{n,k}$ [mm] and the average application efficiencies $eff_{i,s}$ [%] considering the computed irrigation intervals $(F_{i,s})_j$ [days]:

$$(I_{av})_j = 100(I_{n,k}/eff_{i,s})[(F_{i,s})_j/30] \quad (2)$$

The net depths I_n are computed for each crop. In this application the model ISAREG (Teixeira & Pereira 1992) is used. The application efficiencies are those estimated for the area, namely based on those in literature (e.g. Pereira & Trout 1999)

The actual irrigation depths I [mm] are computed from $(I_{av})_j$ (Eq. 2) assuming that they vary with the farmers practice within the interval $[(I_{av})_j(1 - d), (I_{av})_j(1 + d)]$, where d is a fraction of $(I_{av})_j$. Therefore I are estimated by:

$$I = (I_{av})_j(1 + d) - \alpha\left((I_{av})_j 2d\right) \tag{3}$$

where α is a random generated number [0,1]. The final result is rounded up. Adopting this procedure it is assumed that the application efficiencies may vary from one location to the other. The values d shall be selected in agreement with the irrigation method practiced and the respective $eff_{i,s}$ selected. For the present case study the default value for d was 20%.

For each outlet, the first day of irrigation during the peak month is randomly defined between 1 and the minimal value for the time interval between irrigations. The next irrigations dates are scheduled by adding to this sorted date the respective irrigation time intervals $(F_{i,s})_j$. The time duration of each irrigation is computed from the ratio between the actual irrigation depth and the discharge available at the outlet. This allows to establish the daily schedule of the irrigations since the hours in the day when the irrigation management agency supplies water are known from the input data. When automation is considered, irrigation is allowed during the night hours. The irrigation of the rice paddies is assumed to be performed using a constant discharge rate during the night hours or for the 24 hours, as it is currently practiced in the case study area.

After daily irrigation schedules are established at each outlet, the discharges are summed up and a preliminary hourly hydrograph is obtained at the upstream end of the network. When the computed total discharge exceeds the upstream discharge Q_o, the model delays the operation of some outlets until this discharge $Q_o$will not be exceeded. Using a simplified procedure based on the queuing theory, outlets are open only when the system is not saturated. This procedure is applied to the full peak month, which allows production of the hourly hydrographs for every day in this month, as illustrated in Figure 1.

Optimization of pipe diameters

The method used for optimizing the pipe diameters aims at designing a pipe distribution network that is able to provide a minimum hydraulic head at the most unfavourable outlet when delivering the target nominal discharge. Therefore, considering a large set of flow regimes, the pipe sizes are progressively increased from the initial diameters when head losses in a given pipe reach do not allow satisfying that minimum head and discharge.

The iterative discontinuous method (Labye 1981; Labye et al. 1988) for several flow regimes (Lamaddalena 1997; Lamaddalena & Sagardoy 2000) is

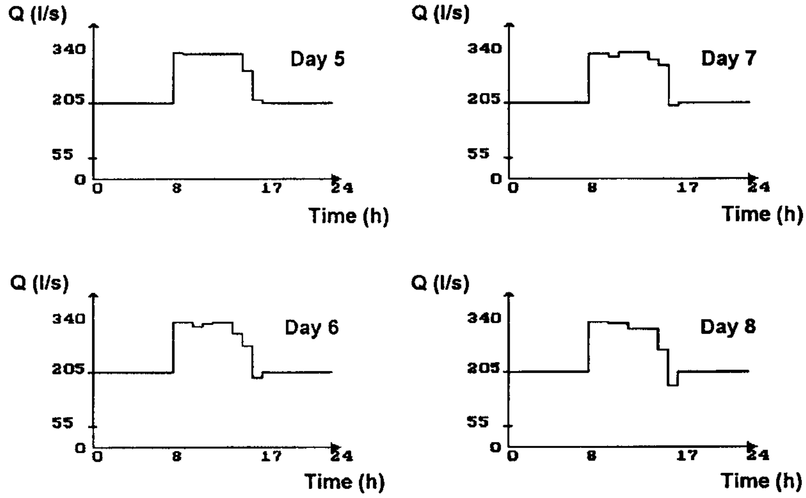

Figure 1. Hourly demand hydrographs for the days 5 through 8 of the peak demand month at the sector 11 of the Sorraia Irrigation System, Portugal.

adopted to optimize the pipe sizes. The flow regimes are those corresponding to every configuration r ($r = 1, 2, \ldots, NC$) of outlets simultaneously operating, which are defined by the hourly demand hydrographs and, therefore, correspond to every hour during the peak demand period. Each flow regime r is characterized by the discharges $Q_{l,r}$ [$m^3\ s^{-1}$] flowing in each section l between two successive nodes. Results for the application of the iterative discontinuous method have been compared with those from linear optimization (Lamaddalena 1997), showing that it could produce optimal pipe sizes having slightly lower costs but higher performances than linear optimization when the number of flow regimes considered is higher than the number of the nodes of the system. For small networks, that number should then be doubled.

For each section l it is possible to compute the minimum commercial diameter $D_{l,min}$ [m], which satisfies the maximum discharge $Q_{l,max}$ in the population $Q_{l,r}$ when the flow velocity v [$m\ s^{-1}$] does not exceed the maximum allowed velocity $v_{max} = 1.5\ m\ s^{-1}$. Thus:

$$D_{l,min} = \left(4\ Q_{l,max}/\pi\, v\right)^{0.5} \quad \text{with } v \leq v_{max} \tag{4}$$

Knowing all minimal diameters, it is possible to compute for every flow regime r the initial piezometric head $(Z_{o,in})_r$ [m] at the upstream end of the system which satisfies the minimum head $(H_{min})_j$ [m] required for appropriate hydraulic functioning at the most unfavorable outlet j ($j = 1, 2, \ldots, NO$) located at the elevation z_j:

$$\left(Z_{o,in}\right)_r = (H_{min})_j + z_j + h_{j,r} \tag{5}$$

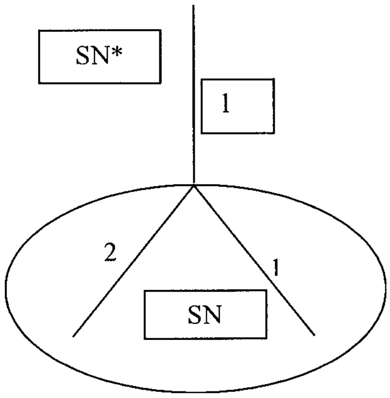

Figure 2. Elementary network scheme.

where $h_{j,r}$ [m] are the total head losses along the pathway connecting the hydrant j to the upstream end of the network. Head losses are computed with the Darcy-Weisbach equation.

The diameters $D_{l,min}$ and the initial piezometric elevation $(Z_{o,in})_r$ constitute the initial set of parameters for the optimization of the pipe diameters. This is performed by an iterative procedure affecting only the flow regimes that produce $(Z_{o,in})_r > Z_o$, where Z_o [m] is the piezometric head available at the upstream end. If $(Z_{o,in})_r \leq Z_o$ the initial solution would be the one accepted. At any iteration iter, the commercial pipe diameters are known and there are no more than two diameters, D_p [m] and D_{p+1}[m] with $D_{p+1} > D_p$, per section (Labye 1966). It is then possible to compute the coefficient:

$$\beta_p = \left(C_{p+1} - C_p\right) / \left(J_p - J_{p+1}\right) \tag{6}$$

where C_p and J_p [m m^{-1}] are, respectively, the cost and the friction loss per unit length of pipe with diameter D_p, and C_{p+1} and J_{p+1} [m m^{-1}] are, respectively, the cost and the friction loss per unit length of pipe with diameter D_{p+1}. Considering any sub-network SN branching at end of the section l, it is possible to minimize the variation of costs ΔC of the network SN* (Figure 2) when, through linear programming, one can find the minimal value for

$$\Delta C = -\beta_{p,SN}\Delta Z - \beta_{p,l}\Delta h_l \tag{7}$$

subject to:

$$\Delta Z + \Delta h_l = \Delta Z' \tag{8}$$

where ΔZ [m] is the variation of the head in the upstream head of SN, and Δh_l [m] is the variation in the head losses at section l due to the changes of pipe diameters. The optimal solution of equations (7) and (8) produce $\Delta Z = \Delta Z'$ and $\Delta h_l = 0$ when $\beta_{p,SN} < \beta_{p,k}$, and $\Delta Z = 0$ and $\Delta h_l = \Delta Z'$ when $\beta_{p,SN} > \beta_{p,k}$. As a result the minimum value for ΔC is

$$\Delta C = -\beta^* \Delta Z' \tag{9}$$

where $\beta^* = \min(\beta_{p,SN}, \beta_{p,k})$. The slope of $\beta_{p,SN}$ is

$$\beta_{p,SN} = \beta_{p,1} + \beta_{p,2} \tag{10}$$

when SN is constituted by two sections (1 and 2) in derivation (Figure 2), and

$$\beta_{p,SN} = \min(\beta_{p,1}, \beta_{p,2}) \tag{11}$$

when sections 1 and 2 are in series; $\beta_{p,1}$ and $\beta_{p,2}$ are the coefficients defined in equation (6) for the branch 1 and 2 (Figure 2), with $\beta_{p,1} = 0$ at the terminal sections having excess of head (at the downstream end node).

The procedure is performed starting the optimization from the downstream sections. The magnitude of ΔZ_{iter} for each iteration iter and flow regime r is:

$$\Delta Z_{iter} = \min\left[EZ_{iter}, \Delta h_{iter}, \left(Z_{o,iter} - Z_o\right)\right] \tag{12}$$

where EZ_{iter} is the minimum observed for the excess of charge [m] in the nodes where the head changes at the iteration iter, Δh_{iter} is the minimum value of the head losses variation [m] in those sections where diameters change during the same iteration, and $(Z_{o,iter} - Z_o)$ is the difference between computed and actual piezometric heads [m] at the upstream end.

The iterative procedure continues until Z_o is satisfied for the flow regime r. The corresponding solution relative to the pipe diameters for every section of the network is then considered the initial solution for the flow regime $r = r + 1$. The procedure is repeated until all flow regimes have been considered. The pipe diameters, which are initially estimated as $D_{l,min}$ (Eq. 4), can never be decreased from one flow regime to the next. A decrease in pipe size would mean that the minimum head at some outlet open in a previous simulated flow regime would not be satisfied. Thus, the final solution provides the pipe sizes that satisfy all flow regimes.

Performance analysis

Many performance indicators have been proposed to evaluate the performance of irrigation systems, generally computed from field-collected data (Bos 1997), including assessment of the quality of the delivery service (Clemmens

& Bos 1990). Reliability defined as the probability of non-failure is one of the performance indicators most commonly used to qualify the level of service or process. This indicator was defined for modern pressurized irrigation systems (Lamaddalena & Pereira 1998; Lamaddalena & Sagardoy 2000) where steady operating conditions are assumed during the peak demand period. Renault and Vehmeyer (1999) give a review of different approaches used to access reliability. According to these authors, the reliability of the irrigation distribution systems is the degree to which water delivery conforms to the expectations of the user and must be viewed as a composite second-order indicator of performance. However, relatively little success has been achieved in obtaining comprehensive measures of reliability of irrigation distribution systems that are computationally feasible and physically realistic (Goulter 1987; Lamaddalena 1997).

In this study, three performance indicators are utilized: adequacy, dependability and equity. The formulation of these indicators is based on the work by Molden and Gates (1990). They are computed from comparing the nominal discharge Q_n [l s^{-1}] and the minimum hydraulic head H_{min} [m] at the outlets with the actual delivered discharge Q_j [l s^{-1}] and hydraulic head H_j [m] available at the same outlets. Q_n and H_{min} are input design variables. H_j is computed from the hydraulic simulation of the system for each configuration of outlets in operation, i.e. for each flow regime r. Q_j are calculated by taking into consideration how H_j compares with the target H_{min}:

$$\begin{aligned} Q_j &= Q_n & &\text{if } H_j \geq H_{min} \\ Q_j &= K_{j,o} H_j^{0.5} & &\text{if } 0 < H_j < H_{min} \\ Q_j &= 0 & &\text{if } H_j \leq 0 \end{aligned} \tag{13}$$

where $K_{j,o}$ is the discharge coefficient relative to the outlet j. This coefficient is provided by the manufacturer of the outlet valves or has to be derived from laboratory tests.

The adequacy represents the ability of the system to deliver the target design discharges at every operating outlet. It can be computed for each time step t of the demand hydrograph, the hour in this application, and each operating outlet j by

$$(p_a)_t = (Q_j/Q_n)_j \tag{14}$$

The system adequacy P_A [0,1] is obtained by integrating over the time the average p_a relative to the NR_t outlets simultaneously operating at each unit time t, i.e., for each simulated flow regime. P_A is given by

$$P_A = \frac{1}{T}\sum_{t=1}^{T}\frac{1}{NR_t}\sum_{j=1}^{NR}(p_a)_t \tag{10}$$

where T is the time [hours] corresponding to the number of (hourly) flow regimes simulated.

The dependability illustrates the ability of the system to deliver the target discharge at each outlet along a given period of time, i.e., it measures the temporal uniformity of deliveries at each outlet. If the performance analysis covers the time T [hours], the temporal uniformity at each outlet j will be $U_{t,j}$ [0,1] given by

$$U_{t,j} = \frac{1}{T}\sum_{t=1}^{T}\left(\frac{Q_j}{Q_n}\right)_t \tag{11}$$

and the time variability of discharges at the same outlet j is

$$V_{t,j} = \frac{1}{T}\sum_{t=1}^{T}\left|U_{t,j} - \left(\frac{Q_j}{Q_n}\right)_t\right| \tag{12}$$

Extending to all the NO outlets of the network, the dependability of the system, P_D [0,1], is

$$P_D = 1 - \frac{1}{NO}\sum_{j=1}^{NO}V_{t,j} \tag{13}$$

The equity measures the spatial uniformity of deliveries during the time T [hours]. The spatial uniformity of discharges delivered to all outlets open during each unit of time, t, i.e. corresponding to a configuration of NR_t outlets simultaneously operating, can be defined by

$$U_{g,t} = \frac{1}{NR_t}\sum_{j=1}^{NR_t}\left(\frac{Q_j}{Q_n}\right)_t \tag{14}$$

and the corresponding spatial variability of discharges is

$$V_{g,t} = \frac{1}{NR_t}\sum_{j=1}^{NR_t}\left|U_{g,t} - \left(\frac{Q_j}{Q_n}\right)_t\right| \tag{15}$$

Considering the full time T under analysis, it results that the system equity P_E [0,1] is approximated by:

$$P_E = 1 - \frac{1}{T}\sum_{t=1}^{T} V_{g,t} \tag{16}$$

Computations of these performance parameters are performed simulating any number of flow regimes during the peak demand period, in general between 240 and 744, respectively for a peak period with 10 and 31 days duration. The analysis may be performed for an existing system or a system being designed. Flow regimes differ from those used for the optimization when the demand hydrographs are generated by adopting different scenarios relative to the cropping patterns, irrigation methods, and/or the irrigation management. The application of the performance analysis in combination with design, particularly when flow regimes differ from those used for design, is very useful because it allows verification of when the designed system satisfies some target values for the indicators. Since the latter are probability estimators, results from the performance analysis allow assigning to the design solution a probabilistic level of satisfaction of deliveries both in spatial and temporal terms. This would allow comparison of different pipe designs or different scenarios for the same network as described in the case study application presented below.

Application

The application of the methodology described above to the sector 11 of the Sorraia irrigation system, Portugal, is presented hereafter. The sector consists of a buried pipeline system, designed and constructed in the fifties, that distributes water to 70 outlets, each one serving an area averaging 5 ha. Rice, representing 37% of the area, maize, tomato and sunflower are the main crops. Rice is irrigated by permanent flooding (paddy) and row crops are dominantly irrigated by short blocked furrows. Graded furrows and level basins are also used. The maximal upstream discharge is Q_o = 340 l s^{-1} and the nominal discharges at the outlets are 10, 15 and 20 l s^{-1}, which relate to the area served. The daily working schedule, resulting from labor union agreements, imposes that irrigation is generally practiced from 8.00 a.m. to 5.00 p.m. only. However, for rice a continuous flow rate close 1 l s^{-1} ha^{-1} is made available 24 hours per day. This schedule is evidenced in the demand hydrographs in Figure 1.

The study intended to test the computational procedures described and to assess the performance of the existing system, as well as to develop design alternatives for the same system that could provide for the adoption of modern farm irrigation systems, including automation tools, and to evaluate these alternatives for different scenarios of crop patterns and farm irrigation management. Therefore, flow regimes were generated for each alternative analyzed as well as the simulation of the hydraulic functioning of the system for both the existing and an alternative layout. The latter was designed using the iterative discontinuous method described above.

Under the present cropping and irrigation conditions, the adequacy (Figure 3a) averages 0.95 but results show poor values for the daytime peak demand hours. This means that the system has the ability to deliver the target design discharges at every operating outlet except during few periods, in the morning, and for peak days. Results for the equity (Figure 3b) show an average $P_E = 0.93$, which indicates that a relatively unequal service is provided among outlets during the peak demand hours. Both the adequacy and equity indicators make evident that service is only excellent during the night hours, when only rice is irrigated (cf. Figure 1). The dependability (Figure 3c) also averages a relatively high value, 0.93, but results show that the service is not highly dependable for some outlets, which are more often located in terminal branches of the network, where pipe diameters are smaller than desirable. In other words, the system is able to deliver the target discharge at all outlets along the simulated peak season period but not for the hydrants located in the less favorable positions and during the peak demand hours.

The analysis performed permits identification of some alternative solutions for improvement: (1) to increase the daily labor schedules, which could decrease the problems during the peak daily demand periods as already identified in previous studies (Pereira 1988; Rijo & Pereira 1987); (2) to enlarge the use of automated farm irrigation systems, thus allowing for irrigation of row crops out of the normal labor hours; and (3) to reinforce the pipe network, including changes in the layout and in the outlet characteristics, adopting $Q_n \geq 30\ l\ s^{-1}$ to allow for modern farm distribution facilities.

Alternative scenarios have been designed with the iterative discontinuous method aiming at responding to the issues indicated above but keeping the upstream discharge unchanged. These scenarios have been designed using 240 flow regimes and were later simulated for performance analysis using 744 flow regimes.

For scenarios where the layout of the system is changed and farm irrigation automation is considered but the cropping pattern remains the same as at present, i.e. the rice being the main crop, results show that the average performances could be excellent if automation would be adopted by all farmers (Figure 4a). However, not all problems could be solved because the demand during daylight hours would remain too high relative to the discharge

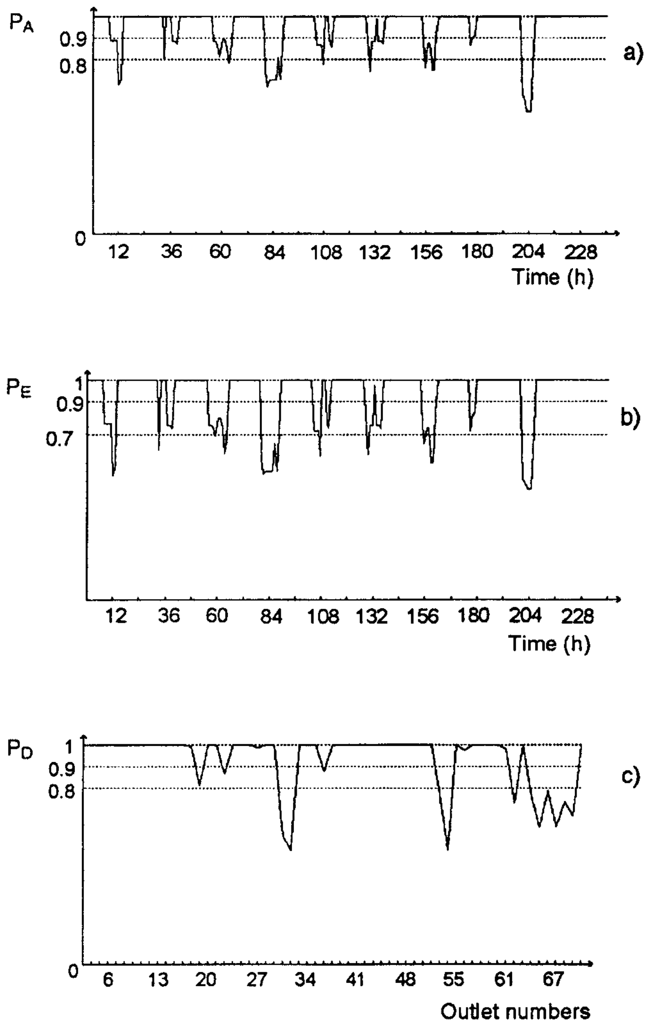

Figure 3. Performances relative to the 10 days peak demand period for the existing network of sector 11, Sorraia Irrigation System: a) adequacy; b) equity; and c) dependability.

available at the upstream end of the system, i.e. the performance would not be constrained by the pipe sizes but by the total available discharge, which has remained unchanged. Performances are lower when the percentage of automation would be smaller. Without automation, results are similar to those obtained at present. These results show that when the upstream discharge cannot be increased an improved service performance is attainable only when farm demand is reduced despite possible improvement of the distribution pipe system.

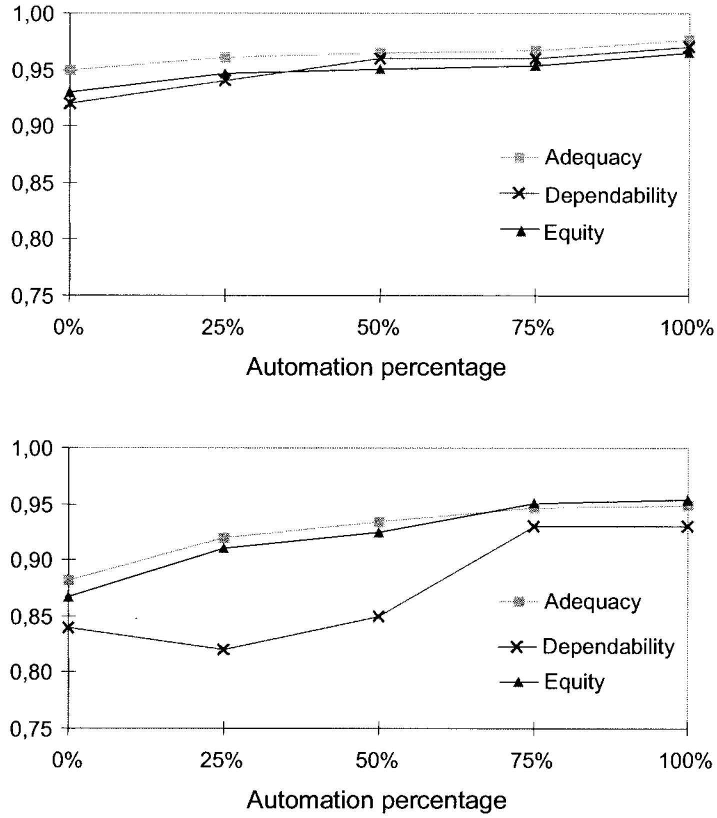

Figure 4. Forecasted system performances in relation to on-farm automation: (a) without changing the cropping pattern, and (b) replacing rice by row crops.

For scenarios where the cropping pattern is modified (Figure 4b) by replacing rice by row crops, the attainable performances are smaller than those where further automation is considered (Figure 4a). This evidences the role of night-time irrigation of the paddies, which contributes to decreasing the demand for the row crops during the daylight-time. In fact, in agreement with results relative to the alternative scenarios for automation, one is not able to fully decrease demand during the peak hours of the day. Therefore, not changing the upstream boundary conditions of the network, the best performance results correspond to a system where the crop pattern would include rice paddies and row crops would be irrigated with automation facilities. The discussion above shows that this design and simulation modeling approach is also useful to analyze how alternative scenarios may behave relatively to distribution system performances.

The model has been applied later for the design of distribution systems in the Mondego irrigation project, central Portugal, and has been confirmed to be appropriate for design. Some of the systems where this design approach was applied are already built or under construction.

Conclusions

A modeling approach for design and performance analysis of low pressure distribution systems is proposed assuming the condition of several flow regimes. The methodology developed for generation of demand at the scale of the distribution system takes into account the deterministic component (crop irrigation requirements) and the random component (e.g. farmers behavior) associated with the irrigation demand. The model allows the prediction of the hourly hydrograph for different crop patterns, irrigation methods and management rules. Therefore, it makes simulation of actual or generated scenarios possible.

The iterative discontinuous method extended to several flow regimes had proved to be a powerful tool to compute the pipe sizes with the minimum cost. Adopting the performance analysis to the systems being designed allows searching for a solution that satisfies not only economic criteria but also a selected target level of performance. The analysis of performance is developed by comparing the discharge and the hydraulic head with the target ones at each open outlet for several flow regimes. The adequacy, dependability and equity indicators can therefore be computed.

The application of the methodology to an existing system and to alternative design and management scenarios shows that it is possible to anticipate the performance of the system and to identify which are the most critical outlets and time periods when performance may be lower. Further work is desirable to fully explore this methodology for decision making.

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List of symbols

A_j	Area served by the outlet j	[ha]
C_k	percentage of occurrence of each crop	[%]
C_p	cost of pipe p per unit length	[m^{-1}]
d	fraction variation of average irrigation depths	[-]
D_l	pipe diameter in section l	[m]
D_p	pipe diameter	[m]
eff	application efficiencies	[%]
EZ_{it}	minimum value of the excess head prevailing at nodes where head changes	[m]
f	average time interval between irrigations	[days]
F	irrigation interval assigned to each outlet j	[-]
h_j	total head losses along the pathway to the hydrant j	[m]
H_j	hydraulic head available at the outlet j	[m]
H_{min}	Minimum hydraulic head required at an outlet	[m]
H_o	upstream hydraulic head	[m]
i	irrigation method (i=1, 2,..., NI)	[-]
I	actual irrigation depths	[mm]
I_{av}	average irrigation depth assigned to each outlet	[mm]
I_n	net irrigation requirements during the peak month	[mm]
iter	iteration number	[-]
j	outlet (j = 1, 2,..., NO)	[-]
J_p	head losses per unit length of pipe p	[m m^{-1}]
k	crop (k = 1, 2,...NK)	[-]
$K_{j,o}$	discharge coefficient relative to the outlet j	[-]
l	pipe section or reach	[-]
L	length of a pipe reach	[m]
M_i	percentage of occurrence of each irrigation method	[-]
NC	number of flow regimes	[-]
NI	number of irrigation methods	[-]
NK	number of crops	[-]
NO	number of outlets	[-]
NR	number of outlets simultaneously operating	[-]
NS	number of soils	[-]
p	pipe size identification	[-]
P	probability	[-]
p_a	adequacy of one outlet operating at the instant t	[-]
P_A	adequacy	[-]
P_D	dependability	[-]
P_E	equity	[-]

Q_j	actual discharge delivered at the outlet j	[$l\ s^{-1}$]
$Q_{l,r}$	discharge flowing at the pipe section l	[$m^3\ s^{-1}$
Q_n	nominal discharge	[$l\ s^{-1}$]
Q_o	upstream discharge	[$l\ s^{-1}$]
r	flow regime (r = 1, 2, ..., NR)	[-]
R	computational real number	[-]
s	soil (s = 1, 2, ..., NS)	[-]
S_s	percentage of occurrence of each soil type	[%]
t	time step	[-]
T	Time duration of the simulation period	[h]
t_D	Daytime duration of deliveries	[h]
U_g	spatial uniformity of the delivered discharges at the outlet j	[-]
U_t	temporal uniformity of the delivered discharges at the outlet j	[-]
v	flow velocity	[$m\ s^{-1}$]
V_g	spatial variability of the delivered discharges at the outlet j	[-]
V_t	temporal variability of the delivered discharges at the outlet j	[-]
X	normal variable	[-]
z_j	land elevation at the outlet j	[m]
Z_o	piezometric head available at the upstream end	[m]
$Z_{o,in}$	initial upstream piezometric elevation	[m]
ΔC	variation of costs	[ ]
Δh	variation of head losses at a section l	[m]
ΔZ	variation of head upstream of a section l	[m]
α	random number	[-]
β_p	slope of the straight-line in the plane P = f(J)	[m^{-1}]
δ	range of variation of the irrigation intervals	[days]
ρ	computational integer variable	[-]
σ	standard deviation	[-]