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in

Lamaddalena N. (ed.).
Annual Meeting of the Mediterranean Network on Collective Irrigation Systems (CIS_Net)

Bari : CIHEAM
Options Méditerranéennes : Série B. Etudes et Recherches; n. 31

2000
pages 51-63

ASSESSING THE PERFORMANCE OF LOW PRESSURE DISTRIBUTION IRRIGATION SYSTEMS USING THE LABYE'S ITERATIVE DISCONTINUOUS METHOD

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Abstract

Low pressure irrigation distribution systems for surface irrigation provide for recognized environmental benefits at both off- and on-farm. However, expected benefits can only be attained when design provides for appropriate systems performance and adequate water use at farm. An innovative methodology for analysis and design is proposed, which includes the generation of farm demand and flow regimes for the peak demand period, the optimisation of pipe sizes using the Labye's iterative discontinuous method, and the performance analysis from simulations with several flow regimes. An application to one sector of the Sorraia irrigation system illustrates the method proposed.

1. Introduction

Low pressure buried pipe distribution systems for surface irrigation constitute a valuable alternative to open channel distributors (van Bentum and Smout, 1994). Under the environmental perspective, advantages relate to minimal seepage losses, more efficient use of agricultural land, reduced damage of land through waterlogging and salinity, reduced damage of water resources,

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greater transit efficiency, control of aquatic weeds and associated pests, control of disease vectors, and control of human water illness, 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 make easier matching water supplies to crop demand, thus providing conditions for more efficient water application at farm level, and contribute to eliminate tail-end equity problems. This results in improved conditions for controlling water wastes, for reducing the transport of solutes out of the root zone, and for increasing the efficiency of water in agricultural production.

Appropriate design is an essential condition for achieving the expected benefits. Associating the performance analysis with the optimisation of pipe sizes provides for the selection of the design alternatives that enable high performances associated with reduced costs. With these objectives, a new design methodology has been developed based on that used for collective pressurized systems. Pipe sizes are optimised using the iterative discontinuous method (Labye, 1981) applied to several flow regimes (Lamaddalena, 1996, 1997), and the performance analysis is adapted from Bethery (1990) and Lamaddalena (1995) to compute the appropriate indicators for reliability, dependability and equity.

2. Performance Indicators

Three performance indicators are utilized: reliability, dependability and equity. These indicators are computed from comparing the nominal discharges, Q_n [$l\ s^{-1}$], and the minimum hydraulic head, H_{min} [m], required at the outlets with the actual delivered discharges, Q_j [$l\ s^{-1}$], and the hydraulic head H_j [m] at each outlet j. Q_n and H_{min} are input design variables, while H_j is computed from the hydraulic simulation of the system for each configuration of outlets in operation, i.e. for each flow regime, and Q_j are calculated as follows:

$$Q_j = Q_n \qquad \text{if } H_j \geq H_{min}$$
$$Q_j = K_{j,o} \quad H_i \qquad \text{if } 0 < H_j < H_{min} \qquad 1)$$

$Q_j = 0$ if $H_j \leq 0$

where $K_{j,o}$ is the discharge coefficient relative to the outlet j (j = 1, 2,..., N).
The *reliability* represents the ability of the system to deliver the target design discharges at every operating outlet. It can be computed for each hour and each operating outlet by $p_a = Q_j / Q_n$. The system reliability P_A [0,1] is obtained by integrating over the time the average probability p_a relative to the R outlets simultaneously operating at each unit time, i.e., for each simulated flow regime. P_A is given by

$$P_A = \frac{1}{T} \sum_{t=1}^{T} \left(\frac{1}{R} \sum_{j=1}^{R} p_a \right)_t \quad 2)$$

where T is the time [hours] corresponding to the number of 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 duration T [hours], the temporal uniformity at each outlet j will be $U_{T,j}$ [0,1] given by

$$U_{t,j} = \frac{1}{T} \sum_{t=1}^{T} \frac{Q_j}{Q_n} \quad 3)$$

and the time variability of discharges at the outlet j is

$$V_{t,j} = \frac{1}{T} \sum_{t=1}^{T} \left| U_{T,j} - \frac{Q_j}{Q_n} \right| \quad 4)$$

Extending to all the N outlets of the network, the dependability of the system is

$$P_D = 1 - \frac{1}{N} \sum_{j=1}^{N} V_{t,j} \quad 5)$$

The *equity* measures the spatial uniformity of deliveries during the time duration T [hours]. The spatial uniformity of discharges delivered during each unit of time, corresponding to a configuration of R outlets simultaneously operating, can be defined by

$$U_{S,t} = \frac{1}{R} \sum_{j=1}^{R} \frac{Q_j}{Q_n} \quad 6)$$

and the corresponding spatial variability of discharges is

$$V_{S,t} = \frac{1}{R} \sum_{j=1}^{R} \left| U_{S,t} - \frac{Q_j}{Q_n} \right| \quad 7)$$

Considering the full time T under analysis, it results for the system equity P_E [0,1]

$$P_E = 1 - \frac{1}{T} \sum_{t=1}^{T} V_{S,t} \quad 8)$$

Computations of these performance parameters are performed simulating any number of flow regimes during the peak demand period, in general between 240 (10 days peak period) and 744 (31 days). The analysis may be performed for an existing system or a system being designed. Flow regimes may differ from those used for the optimisation when the demand hydrographs are generated using different scenarios relative to the cropping patterns and/or the irrigation management.

3. Computation

3.1. Input data

The programme MSGOA, in Turbo Pascal 7.0, has been developed to perform the generation of the flow regimes, the optimisation of the pipe diameters, and the analysis of performance by simulating the network functioning at several flow regimes.

Input data are the following:

a upstream discharge, Q_0 [l s^{-1}], and hydraulic head, H_0 [m];

b cropping pattern, i.e. the probability of occurrence of each crop, C_c [%];

c irrigation methods and the respective probability of occurrence, M_i [%];

d net crop irrigation requirements during the peak month, $I_{n,c}$ [mm];

e average time intervals between irrigations, m [days], and the respective range of variation, a [days], depending on the irrigation method and soil type;

f application efficiencies for each couple irrigation method-soil type, e_a [%];

g day time schedule for water supply as established by the management agency;

h nominal discharge, Q_n [l s^{-1}], and minimum head, H_{min} [m], at the outlets;

i soil type, including land slope type for the areas served by each outlet, which provides the soil type distribution S_s [%];

j system layout, with identification codes for each node and the respective land elevation;

k lengths of each pipe section between two successive nodes and, when analysing existing systems, the respective diameters; and

l characteristics of the commercial pipes, mainly diameters and costs.

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 are introduced through the sector files.

The model is operated through a main menu where the user can select:

- the generation of flow regimes,
- the optimisation of pipe diameters, and
- the analysis of performances.

Generated flow regimes and pipe sizes (lengths and diameters) are stored in output files to be used in subsequent calculations. Results for each one of the three main options above can be given in numerical or graphical formats.

3.2. 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 (Lamaddalena, 1997; Bethery, 1990), flow regimes have to be obtained from demand hydrographs which respect the arranged delivery schedules used in surface irrigation systems. Thus, the generation of flow regimes requires: first, the definition of the irrigation demand schedules for the areas served by each outlet; then, their aggregation at system level respecting the available upstream discharge; and, finally, 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 assigning only one crop to the area served by each outlet but assuming that the crop distribution over the total area is respected. Thus, knowing the percentage distribution of each crop in the project area C_c, it can be assumed that the probability for any crop c to occur in the area served by each outlet is equal to C_c. Therefore, adopting a random generation of numbers from 0 to 100 with uniform distribution, and assuming that each probability C_c [%] corresponds to a portion in the interval 0 to 100, it is possible to randomly select the crop c assigned to each outlet.

After this operation is concluded for all outlets, it is verified if the simulated crop pattern matches to the one proposed by summing to all area the surfaces assigned to each crop. When more than 10% differences are observed, the operation is repeated until satisfactory results are obtained.

The irrigation methods considered in this version 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.

The probability for a given irrigation method i to be associated with a soil of type s is estimated by M_i S_s [%], and the probability that it would be associated with a crop c corresponds to M_i C_c [%]. Considering that the soil type s and the crop c are known for the areas served by every outlet, it is possible to assign an irrigation method to each outlet area when the probability for an irrigation method i to be associated with the crop c and the soil s be known. This probability is estimated by

$$\left(S_s\, C_c\right)_i = \frac{\left(S_s\, M_i\right)\left(C_c\, M_i\right)}{\sum_{i=1}^{n}\left(S_s\, M_i\right)\left(C_c\, M_i\right)} \qquad 9)$$

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 becomes then 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, m [days], and the respective range of variation, a [days]. These data are then used to randomly generate an irrigation interval F [days] for each outlet. The procedure consists in:

1. assigning to each value V_i [days] in the interval [(m - a), (m + a)] the lower and upper limits $R_i = V_i - 0.5$ and $R_{i+1} = V_i + 0.5$;

2. converting these real numbers R_i into the normal variables $X_i = (R_i - m) / \sigma$, where σ is the standard deviation of R_i (i = 1, 2,..., n');

3. computing from the normal distribution the probabilities $P_i = P\ (X > X_i)$;

4. randomly generating a real number (0 to 100) which falls in one of the intervals [P_i, P_{i+1}];

5. computing back, from these probabilities, the variables X_i, X_{i+1} and R_i, R_{i+1};

6. determining the value V_i in the interval [R_i, R_{i+1}], which is the estimator for F [days].

The average irrigation depths D_{av} [mm] during the peak period are computed from the input data relative to the net monthly irrigation requirements $I_{n,c}$ [mm] and the application efficiencies e_a

[%], considering the computed irrigation intervals F [days]:

$$D_{av} = 100 \; (I_n \,/\, e_a) \; (F \,/\, 30) \qquad 10)$$

The actual irrigation depths D [mm] are computed from D_{av} considering that they can vary within the interval [D_{av} (1 - d), D_{av} (1 + d)], where d is a fraction of D_{av}:

$$D = D_{av}\left(1 + d\right) - \alpha\left(D_{av}\, 2d\right) \qquad 11)$$

where α is a random generated number [0,1]. The final result is rounded up.

For each outlet, the first day of irrigation during the peak month is randomly defined between 1 and the minimal value for the irrigation interval, F. The following irrigations are scheduled by adding the respective irrigation intervals F. The time duration of each irrigation is computed from the ratio irrigation volume/discharge available at the outlet. This allows to establish the daily schedule of the irrigations taking into consideration the schedule imposed by the irrigation management agency for the water supplies, known from input data. When automation is considered, the irrigation is supposed to be continued during the night hours. Rice irrigation is assumed to be performed with a constant discharge rate during the night hours or for the 24 hours.

After the daily irrigation schedules are established for 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_0, the model delays the operation of some outlets until this discharge Q_0 will not be exceeded. Using a simplified procedure based on the queuing theory, outlets are open only when the system do not become saturated. This procedure is applied to the full peak month, which allows to produce the hourly hydrographs for every day in the month, as illustrated in Fig. 1.

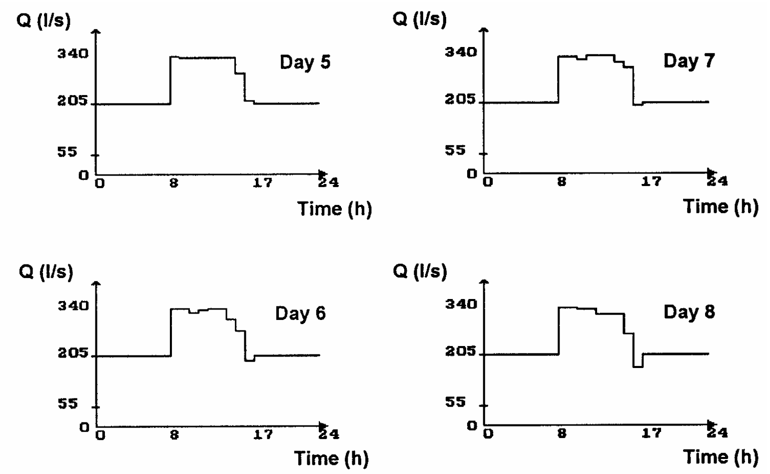

Fig. 1. Hourly discharge hydrographs for the days 5 through 8 of the peak month (sector 11 of the Sorraia irrigation system).

3.3. Optimisation of pipe diameters

The iterative discontinuous method (Labye, 1981) for several flow regimes (Lamaddalena, 1997) is adopted to optimise the pipe sizes. The flow regimes are those corresponding to every configuration r (r = 1, 2, ..., C) of outlets simultaneously operating, as defined from the hourly demand hydrographs. Each flow regime r is characterized by the discharges $Q_{k,r}$ [m^3 s^{-1}] flowing in each section k between two successive nodes.

For each section k it is possible to compute the minimum commercial diameter $D_{k,min}$ [m] which satisfies the maximum discharge $Q_{k,max}$ in the population $Q_{k,r}$ when the flow velocity V do not exceeds the maximum allowed velocity

V_{max} [m s^{-1}]. Thus:

$$D_{k,min} = \left(4Q_{k,max} / \pi V\right)^{0.5} \quad \text{with } V \le V_{max} \qquad 12)$$

Knowing all minimal diameters, it is possible to compute for every flow regime r the piezometric head $(Z_{o,in})_r$ [m] at the upstream end of the system which satisfies the minimum head $H_{j,min}$ [m] required at the most unfavourable outlet j (j = 1,2,..., R) located at the elevation Z_j.

$$\left(Z_{o,in}\right)_r = H_{j,min} + Z_j + h_{j,r} \qquad 13)$$

where $h_{j,r}$ [m] are the total head losses along the pathway connecting the hydrant j to the upstream end of the network.

The diameters $D_{k,min}$ and the upstream charges $(Z_{o,in})_r$ constitute the initial set of parameters for the optimisation. This is performed by an iterative procedure interesting only the flow regimes which produce $(Z_{o,in})_r > Z_o$, where Z_o [m] is the piezometric head available at the upstream end. At any iteration i, when for each section k two pipe diameters D_p and D_{p+1} are considered, it is possible to establish the ratio

$$\beta_p = \left(P_{p+1} - P_p\right) \Big/ \left(J_p - J_{p+1}\right) \qquad 14)$$

between the unit price decrease and the unit head loss [m m^{-1}] increase when changing from diameter D_p to D_{p+1}, with $D_{p+1} > D_p$. Considering any sub-network SN branching at end of the section k, it is possible to minimize the variation of costs ΔP of SN* (comprising k and SN) when, through linear programming, one can find the minimal value for

$$\Delta P = -\beta_{p,SN}\, \Delta Z - \beta_{p,k}\, \Delta h_k \qquad 15)$$

with

$$\Delta Z + \Delta h_k = \Delta Z' \qquad 16)$$

where ΔZ is the variation in the upstream head [m], and Δh_k is the variation in the head losses [m] in the section k due to the changes of pipe diameters.

$$\beta_{p,SN} = \beta_{p,1} + \beta_{p,2} \qquad 17)$$

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

$$\beta_{p,SN} = \min\,(\beta_{p,1},\ \beta_{p,2}) \qquad 18)$$

when sections 1 and 2 are in series. Equation 15 produces $\Delta Z = \Delta Z'$ and $\Delta h_k = 0$ when $\beta_{p,SN} < \beta_{p,k}$, and $\Delta Z = 0$ and $\Delta h_k = \Delta Z'$ when $\beta_{p,SN} > \beta_{p,k}$. It results that the minimum value for ΔP is

$$\Delta P = -\beta^*\, \Delta Z',$$

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

The procedure is performed starting the optimisation from the downstream sections. The value $\beta_{p,SN} = 0$ is used at the terminal sections until the excess charge disappears in the downstream end node. The magnitude of ΔZ for each iteration i and flow regime r is the minimum among EZ_i, Δhi and $(Z_{o,i} - Z_o)$. EZ_i is the minimum value for the excess of charge [m] in the nodes where the head changes at iteration i, Δh_i is the minimum value of the head losses variation [m] in those sections where diameters change during the same iteration, and $(Z_{o,i} - Z_o)$ 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 start to be estimated as D_{min} (Eq. 12), can never be decreased from one flow regime to the next. Thus, the final solution provides the pipe sizes which satisfy all flow regimes.

2. Application

The methodology described above has been applied to the sector 11 of the Sorraia irrigation system, Portugal. A buried pipeline system, designed and constructed in the years 1950, 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, with few areas adopting graded furrows and level basins. The maximal upstream discharge is $Q_0 = 340\ l\ s^{-1}$. Nominal discharges at outlets are 10, 15 and 20 $l\ s^{-1}$ according to the area served. The daily labour schedule, resulting from labour unions agreements, imposes that irrigation is practiced from 8.00 a.m. to 5.00 p.m. or, for rice, with a continuous flow for the 24 hours of the day. This is evidenced in the demand hydrographs in Fig. 1.

The study intended to assess the performance of the existing system and to develop design alternatives for the same system including the adoption of modern on-farm irrigation systems.

Under the present cropping and irrigation conditions, the reliability (Fig. 2a) averages 0.95 but shows poor values for the day time peak demand hours. Results for the equity (Fig. 2b) show that unequal service is provided among outlets during the same peak demand hours, with an average P_E = 0.93. Both indicators make evident that service is only excellent during the night hours, when rice is irrigated (cf. Fig. 1).

The dependability (Fig. 2c) also averages 0.93 but shows that service is not dependable for some outlets, which are mostly located in terminal branches of the network, having small diameters.

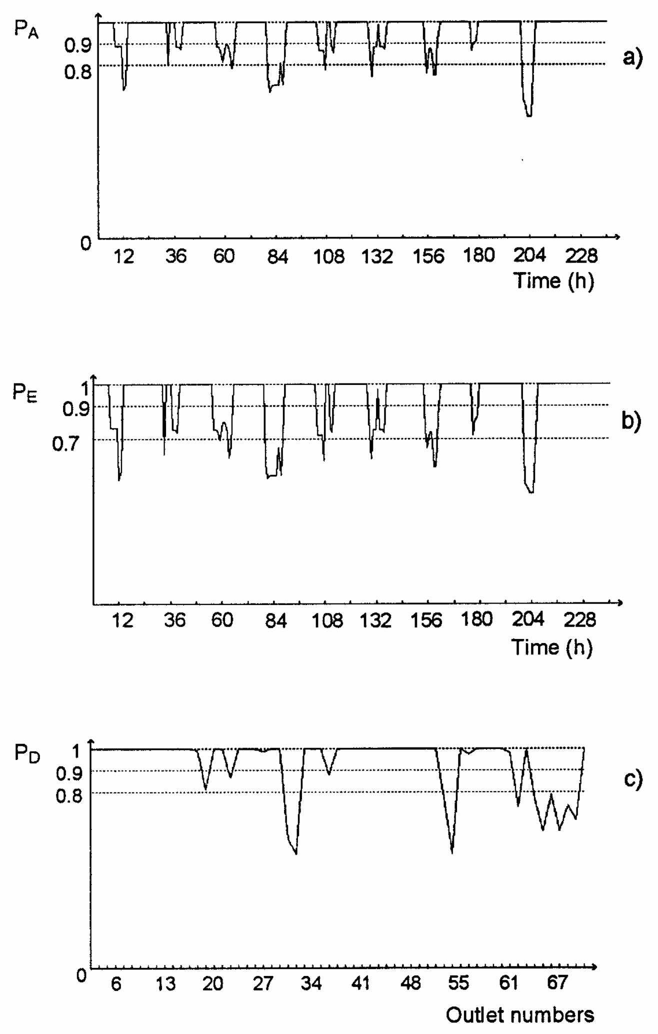

Fig. 2. Reliability, equity and dependability relative to the 10 days peak demand period for the existing network of sector 11, Sorraia system.

When performing the analysis for the "reinforced" network optimised at 240 flow regimes, all the three indicators show values close to 1, with only very few values below 0.90 (Douieb *et al.*, 1998: Pereira *et al.* 1998). The alternative designed for a new layout, adopting Q_n = 30 l s^{-1} at each outlet, and assuming that automation would overcome the delivery time restrictions, so that farmers could irrigate out of daylight hours shows that performance indicators increase when farm automation also increases and that performances are higher when rice is kept in the cropping pattern.

2. Conclusions

The methodology proposed for design and analysis of low pressure distribution systems for surface irrigation shows to be able to assess how systems would perform in practice. The procedure utilized to generate the demand hydrographs allows for simulating the demand under different scenarios for the cropping pattern and irrigation practices. This capability provides for assessing the performances of an existing or design system under different operational conditions. The application of the methodology to alternative design solutions makes it is possible to anticipate the performance and benefits of each alternative. Further work is required to fully explore this methodology for decision-making.

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