Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Optimization of on demand pressurized irrigation networks and on-farm constraints

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Abstract

The variability of flow regimes in on demand pressurized irrigation systems induces uncertainty in pressure head at the hydrants affecting the system hydraulic performance. However, the on-farm networks operating downstream are designed for a fixed upstream pressure head that usually corresponds to their best achievable performance. Based on these considerations, an on demand irrigation system was optimized using the Reliability based model accounting for the variability of flow regimes, the minimization of cost and the maximization of the reliability, and the interaction between the variability at hydrant level and the uniformity of on farm sprinkler systems operating downstream was analyzed. The analysis shows that on farm uniformity strongly varies in space and time and low uniformity levels were achieved despite the consideration of the reliability of the on demand distribution network during the optimization process, which may have drastic effects on crop yield. This study clearly shows that accounting for the interaction between the distribution system and the on farm irrigation network is a must in the modernization/rehabilitation processes, often promoted as tools to produce more agriculture goods with less water input at moderate investments and operational costs.

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1. Introduction

During the past decades, pressurized distribution systems have been developed with considerable advantages over open canals as they guarantee better services to the users and higher distribution efficiency. In order to meet farmers’ requirements, designers and managers are often oriented to on-demand delivery schedules allowing a greater freedom in users’ decisions. Pressurized irrigation systems operating on-demand allow farmers to decide when and how much water to withdraw from the distribution network without informing the system manager, and thus a great flexibility is ensured for carrying out the irrigation calendar. Actually every farm (or group of farms) served with a hydrant can be irrigated according to the climatic conditions, the soil moisture content, the crop type, the adopted on-farm irrigation method and the farmer own organization of work [1]. Indeed, the number and the location of the hydrants operating simultaneously in on demand irrigation systems are impossible to guess a priori, making the computation of the design discharges flowing in each section of the network one of the most important uncertainties.

Therefore, the nominal discharge of each hydrant is oversized allowing the farmer to irrigate for a duration shorter than twenty-four hours per day. Under this condition, the event of finding all the hydrants simultaneously operating has a very low probability of occurrence. This justifies the use of probabilistic approaches [2;3] for computing the peak discharge at every section of the distribution network. The probabilistic model proposed by Clément for the discharge computation is the most used in the Mediterranean countries where many on-demand pressurized irrigation systems have been developed.

Moreover, the pipe-size optimization of water distribution systems has attracted many researchers who, very often, formulated an objective function leading to minimize its capital and/or operating cost [4;5;6;7;8;9]. However, the optimal design of distribution systems is a process involving not only the cost but also the performance [10;11;12]. To a greater extent, accounting for the performance in the optimization process is important when dealing with on demand schedule. Actually, the temporal and spatial variability of the hydrants operating simultaneously leads to a variability of flow regimes in on demand pressurized irrigation systems, inducing uncertainty in pressure head at the hydrants and thus affecting the system hydraulic performance [13].

In this context, Lamaddalena et al. (2012) [14] presented an optimization model which combines the minimization of cost with the maximization of the hydraulic reliability, accounting for the stochastic variability of the flows in the different sections of an on demand network. However, the on-farm networks operating downstream are designed for a fixed upstream pressure head that usually corresponds to their best achievable performance. Therefore, the effect of the variability at the hydrant on the on farm system behavior should be considered in a modernization/rehabilitation process, especially that modernization and optimization have often been promoted as tools to improve irrigation efficiency, producing more agriculture goods with less water input at moderate investments and operational costs.

To this aim, an on demand pressurized irrigation network was optimized following the reliability based approach [14] and using Labye iterative discontinuous optimization algorithm [3]. For each generated configuration of hydrants operating simultaneously, the relative pressure deficit and consequently the pressure at hydrant level was calculated as well, using AKLA model [15]. In a second step, an iterative model was applied to generate the characteristic curve of the on-farm sprinkler irrigation network operating downstream each hydrant [1]. The intersection of the on farm curve with the hydrant characteristic curve, defined the actual operating discharge and pressure of the on farm sprinkler network and consequently, uniformity at farm level was calculated through the coefficient of uniformity [16] providing a new perspective on the modernization strategies.
2. Materials and Methods

2.1. Reliability based optimization model

2.1.1. Pipe size computation

As previously explained, the discharges flowing at the different sections of the irrigation network operating on-demand may strongly vary over time and space. In order to account for such variability, a number of possible operation conditions of the network (configurations) are obtained by generating using AKLA model [13] simultaneous openings of m hydrants out of the total number N (with m < N) using a random number generator. The adopted generation model assumes that the events follow a uniform probability of distribution. Each generated configuration of hydrants corresponds to a discharges configuration. In fact, the discharges flowing into the different sections of the network are calculated by considering the sum of discharges delivered by the open downstream hydrants. The generation methodology of configurations adopted in this study assumes that the upstream demand hydrograph is known or previously estimated. After generating C configurations (r1, r2, ……, rC), the Labye’s Iterative Discontinuous Method extended for multiple discharges configurations is used to compute the optimal pipe-size diameters [17]. The process is repeated for each generated configuration, therefore, C independent optimal solutions are obtained, one for each configuration, each one having a different cost.

2.1.2. On demand irrigation networks analysis

AKLA analyzes the performance at hydrant level considering two indicators: relative pressure deficit and reliability. It describes the water system operational status as either satisfactory or unsatisfactory, where unsatisfactory (failure) corresponds to a drop in pressure head (and/or discharge) at the hydrant below the minimum required for on-farm irrigation.

2.1.2.1. Relative pressure deficit

Within each generated configuration (r), a hydrant (j) is considered satisfied when the following relationship is verified:

\[ H_{j,r} \geq H_{min} \]  

where \( H_{j,r} \) represents the head of the hydrant \( j \) within the configuration \( r \), and \( H_{min} \) is the minimum required head for the appropriate operation of the on-farm system. Both are expressed in meters.

The relative pressure deficit at each hydrant is defined as:

\[ \Delta H_{j,r} = \frac{H_{j,r} - H_{min}}{H_{min}} \]  

Once the upstream available piezometric elevation, \( Z_0 \) [m a.s.l], is established, the set of discharges to be tested, \( Q \), and the number of configurations, \( C \), to be investigated are selected, the following procedure is adopted for the computation:

Two options are actually available in the computer software for the calculation of the head losses. Using the Darcy-Weisbach formulation, the head losses, \( Y \) [m], are:

\[ Y = \lambda \frac{L}{D} \frac{v^2}{2g} L \]  

where \( D \) [m] is the pipe diameter, \( L \) [m] is the length of the section, \( v \) [m s\(^{-1}\)] is the flow velocity, \( g \) [m s\(^{-2}\)] is the acceleration of gravity and \( \lambda \) is the adimensional coefficient of resistance. This coefficient is calculated using the Colebrook equation:
\[
\frac{L}{\sqrt{\lambda}} = 2.0 \log \left( \frac{2.51}{R_e \sqrt{\lambda_h}} + \frac{\varepsilon}{D} \right)
\]

(4)

where \( R_e \) is the number of Reynolds and \( \varepsilon \) is the absolute roughness [m] of the pipe. In a second option the head losses, \( Y \) [m], are computed from:

\[
Y = 0.000857 \left( 1 + 2\gamma / \sqrt{D} \right)^2 \frac{Q^2}{D} = bQ^2L
\]

(5)

where \( \gamma \) is the roughness parameter of Bazin \([m^{0.5}]\), \( Q \) \([m^3 s^{-1}]\) is the discharge flowing in the pipe and \( b \) \([m^{-1} s^2]\) is the dimensional coefficient of resistance. The other variables are the same as above. Hydrants having a pressure head lower than the minimum pre-established \( H_{min} \) are identified. Once the analysis is completed, it is possible to identify the range of variation of the head at each hydrant for each configuration, and the relative pressure deficit \( \Delta H_{j,r} \).

2.1.2.2. Reliability

Let \( H_t \) be the random variable denoting the state of the system at a time \( t \) (where \( t \) assumes the values 1, 2, ..., \( n_t \)). Then, \( H_t \) is identified as the pressure head at the hydrant level. At each instant \( t \), the possible values of \( H_t \) fall into the category \( S \), which is the set of all satisfactory outputs (the pressure heads at the hydrants are satisfactory when \( H_{j,r} \geq H_{min} \)), or the category \( F \), which is the set of all unsatisfactory outputs (failure state: \( H_{j,r} < H_{min} \)). The reliability of the system could be described as the probability \( R_e \), that the system has a satisfactory state:

\[
R_e = \text{Prob} [H_t \in S]
\]

(6)

Therefore the hydrant reliability can be defined as follows[11]:

\[
R_{e,j} = \frac{\sum_{r=1}^{C} I_{h,j,r} I_{p,j,r}}{\sum_{r=1}^{C} I_{h,j,r}}
\]

(7)

where \( R_{e,j} \) is the reliability of the hydrant \( j \); \( I_{h,j,r} \) is a hydrant index equal to 1 if the hydrant \( j \) is open in a configuration \( r \) and to 0 if closed; \( I_{p,j,r} \) is a pressure head index equal to 1 at the hydrant \( j \), open in the configuration \( r \), if its pressure head is higher than \( H_{min} \) and to 0 if lower than \( H_{min} \); \( C \) is the total number of generated configurations. For each discharge configuration the analysis performed with AKLA gives the available pressure head [m] at each operating hydrant. Indeed, the indexes \( I_{h,j,r} \) and \( I_{p,j,r} \) may be easily calculated and the relationship 7 may be applied for calculating the hydrant reliability.

2.1.2.3. Optimal network

Following the above definition of reliability, this indicator can be defined at system level as follows:

\[
R_{e,sys} = \frac{\sum R_{e,j}}{N}
\]

(8)

Combining the cost minimization with the reliability maximization, a Pareto-front optimal set of solutions can be produced and the trade-off between cost and reliability shown. A non-dominated set of solutions is obtained and consequently, moving from one solution to another would improve reliability and degrade cost or vice versa. An indicator \( I \) maximizing the ratio \( R_{e,sys} \) to \( \text{Cost}_{sys} \):

\[
I = \max \left( \frac{R_{e,sys}}{\text{Cost}_{sys}} \right)
\]

(9)
allows for the selection of one solution in the Pareto-front: the selected configuration among all the identified optimal solutions is the one with the maximum amount of reliability per euro employed or, with the minimum average cost per unit of reliability.

2.2. On farm sprinkler network characteristic curve

The iterative model (Sprinknet) [18;19] generates the characteristic curve of a sprinkler irrigation network according to the following steps:

2.2.1. Lateral characteristic curve

The parameters $H_{k,i}$ and $q_{k,i}$ denote the pressure head and discharge of the sprinkler $k$ within the on-farm network corresponding to the iteration $i$, while $Y_{k,i}$ represents the head loss in the reach upstream to that sprinkler. The sprinkler numbering always starts from the downstream end of the network and the lateral.

Step 1: The initial pressure head ($H_{k,0}$) at the downstream end of the network is arbitrarily fixed and the sprinkler discharge $q_{1,0}$ corresponding to pressure head $H_{1,0}$ is then calculated using the equation:

$$ q = K H^x $$

where parameter $K$ depends primarily on the nozzle diameter but it also varies with sprinkler design and manufacturing.

The discharge $q_{1,0}$ of the sprinkler represents the discharge flowing in the first section length $R_1$ of lateral 1 and it is used to calculate the head loss $Y_{1,0}$ in m, in that section.

Step 2: The pressure head at the junction point of sections 1 and 2 corresponds to the pressure head at the second sprinkler:

$$ Y_{1,0} = Y_{1,0} + S $$

Step 3: A new iteration is carried out, where a new value $H_{1,1}$ of the pressure head is used at sprinkler 1:

$$ H_{1,1} = H_{1,0} + \Delta H $$

$\Delta H$ of 0.5m is used. Steps 1 and 2 are repeated with the new initial pressure head $H_{1,1}$ and consequently, the second point (B) of the lateral 1 characteristic curve is obtained. The procedure continues until sufficient points are available to define the characteristic curve of lateral 1. The same procedure is used to calculate the characteristic curves of all the other laterals of the network.

2.2.2. Aggregation of the laterals up to the hydrant

Step 1: The calculation of the network characteristic curve starts from the downstream end of the main line where the characteristic curve of each lateral is considered as input data. An initial pressure head $H_{m1,0}$ is arbitrarily selected from the characteristic curve of lateral 1 and the corresponding discharge $q_{m1,0}$ flowing in the main section length $m_1$ is obtained. The head loss $Y_{m1,0}$ in the main line section $m_1$ is then
calculated and consequently the pressure head $H_{m2,0}$ at the junction between sections $m_1$ and $m_2$ is obtained from equation 13 and used to determine the discharge $q_{L,2,0}$ in lateral 2. The sum $(q_{L,1,0} + q_{L,2,0})$ corresponds to the discharge flowing in section $m_2$.

$$H_{m2,0} = H_{m1,0} + Y_{m1,0} + \Delta S$$

(13)

This procedure is repeated up to the upstream end of the on-farm network and the first point (A0) of the characteristic curve of the on-farm network is thus obtained.

Step 2: The initial pressure head is then increased by $\Delta H$ and the previous procedure is repeated ($\Delta H = 0.5m$ is recommended).

$$H_{m1,1} = H_{m1,0} + Y_{m1,0} + \Delta H$$

(14)

The second point (B') of the characteristic curve of the network is therefore determined. The iterations continue until obtaining a sufficient number of points to fit the characteristic curve of the on-farm network. The intersection of the characteristic curves of the hydrant with the on-farm sprinkler network operating downstream, defines the actual operating conditions of the on-farm network allowing for its performance analysis.

2.3. On farm sprinkler network analysis

Irrigation uniformity can be used as indicator to describe the performance of the on-farm sprinkler irrigation network. Irrigation uniformity [20] is usually characterised by:

(i) the distribution uniformity $D_U$, which indicates the uniformity of application throughout the field:

$$D_U = 100 \frac{Z_{1q}}{Z_{av}}$$

(15)

where: $D_U$ is the distribution uniformity in %; $Z_{1q}$ is the average of the lowest one-quarter of the measured values in m$^3$ m$^{-2}$ and $Z_{av}$ is the average applied depth in the entire field in m$^3$ m$^{-2}$.

(ii) the coefficient of uniformity $C_U$, developed by Christiansen [16]:

$$C_U = 100 \left( 1 - \frac{1}{n} \sum \frac{|Z - n|}{Z} \right)$$

(16)

where $C_U$ is the coefficient of uniformity in %; $Z$ is the individual depth of catch observations from uniformity test in cm$^3$ cm$^{-2}$; $|Z - n|$ is the absolute deviation of the individual observations from the mean in cm$^3$ cm$^{-2}$; and $n$ is the mean depth of observations in cm$^3$ cm$^{-2}$. In this study $C_U$ was considered for the analysis of the sprinkler networks given the territorial scale and objective of the approach [21].

2.4. The case study

District 4 of the ‘Sinistra Ofanto’ irrigation scheme (Fig. 1), managed by the Consorzio di Capitanata [22], covers a topographic area of 3256 ha in the province of Foggia (Southern Italy). District 4 is supplied by a daily storage and compensation reservoir with a capacity of 28 000 m$^3$, where the maximum and minimum water levels are 143 and 139 m a.s.l., respectively. The district 4 network starts from the reservoir with a steel pipe of 1200 mm in diameter. It crosses the whole district and serves 32 sectors. The analysis carried out in this paper refers to sector 25 which covers an area of about 50 ha [23]. The upstream pipe network is connected to the mainline pressurized pipe through a control head unit equipped with a gate, a flow-meter and a discharge regulator having a nominal discharge equals to 60 l s$^{-1}$. The
network has 24 nodes from which 19 are hydrants with a nominal discharge of 10 l s\(^{-1}\) each. The minimum design pressure head at the hydrants was assumed equal to 20 m, considering the low pressure on farm equipments used in the area. The piezometric elevation at the upstream end of the network is 128 m a.s.l. and the land elevation ranges between 95 m a.s.l. and 104 m a.s.l. The layout of the network is reported in Fig. 2. Each hydrant serves an on-farm network with a very simple layout on a flat area, and a very commonly used nozzle type sprinkler (Rainbird_5000 (4.0RC)), which represents the actual situation in most of the sprinkler irrigated plots in the study area. The on-farm sprinkler network consists of a main line with seven laterals carrying seven sprinklers each, with a 15m by 15m sprinkler spacing (Fig. 3). Pipes are in poly vinyl chloride with diameters of 108.7mm for the manifold and 44.6mm for the laterals. Water distribution patterns of the Rainbird_5000 (4.0RC) were indoor tested at different working pressures (7, 14, 21, 28 and 24 m) under no-wind conditions and the results are summarised in Fig. 4 while parameter \( K \) (eq. 10) was found equal to 0.154.
3. Application and Results

3.1. Optimization of sector 25 distribution network

Using AKLA model, 100 different random discharge configurations were generated, corresponding to a peak discharge of 60 l s\(^{-1}\) each, and 100 different optimal solutions with different costs and reliability \(R_{\text{Sys}}\) were computed. In Fig. 5, the cost of the networks versus the configurations are represented classified in a decreasing order. An important cost reduction is observed after few configurations are generated. In particular, the maximum registered cost of 1.05x10^5 € decreases and reaches the value of 0.99x10^5 € and 0.94x10^5 € when 5% and 10% of the most unfavorable configurations are respectively eliminated, while the overall reliability of the network \(R_{\text{Sys}}\) (eq 8) is respectively 0.99, 0.92 and 0.90. Figure 6 shows \(R_{\text{Sys}}\) as function of the generated configurations, while in Fig. 7 \(R_{\text{Sys}}\) is represented as function of the cost where, the cloud of points defines a non linear relation Cost-\(R_{\text{Sys}}\). The Pareto-optimal set of solutions shows the trade off between reliability and cost where the indicator \(I\) (eq. 9) allowed for the selection among the identified optimal solutions of the configuration which gives the maximum amount of \(R_{\text{Sys}}\) per Euro employed (Fig. 8); The cost and the reliability for the selected optimal network being:

\[
\text{Cost}_{\text{Sys}} = 0.84x10^5 \text{ €} \quad \text{and} \quad \text{Re}_{\text{Sys}} = 0.95
\]

3.2. Relative pressure deficit calculated at hydrant level

The analysis of the optimized network was carried out randomly generating 100 configurations corresponding to a discharge of 60 l s\(^{-1}\) each and calculating at the level of each hydrant within each configuration the relative pressure deficit as explained in section 2.1.2.1. The configurations of hydrants being subject to a strong space and time variability, the pressure deficit at the hydrant (and consequently the pressure head) and consequently the pressure head can only be expressed in terms of probability of occurrence [15]. The envelope curve of Fig. 9 corresponds to the 90% probability of occurrence of the deficit, eliminating the 10% of the most unfavorable conditions generating the greatest deficits.
3.3. The actual operating conditions of the On-farm sprinkler network: intersection of hydrant and on farm network Characteristic curves

Following the approach described in section 2.2, the characteristic curve of each on farm sprinkler network operating downstream a hydrant was generated (Fig. 10) and intersected with the characteristic curves of the hydrant at various probabilities of occurrence (Fig. 11). The procedure is repeated for each hydrant (total of 24 hydrants) and configuration (total of 100 configurations). The intersection point provides the actual pressure and discharge available at the upstream end of the on farm network. An example of the interaction hydrant-on farm network is represented in Fig. 11 which shows that when 21.5 m are available at the hydrant (90% probability of occurrence), the on farm network operates with an actual pressure head and discharge of 18 m and 8.7 ls\(^{-1}\) respectively; whereas 27 m of pressure at hydrant provide the on farm network with actual pressure and discharge of 23 m and 10 ls\(^{-1}\) respectively. This example highlights how the on farm network is influenced by its characteristic curve; in fact, pressure heads at hydrant greater than 27 m would have no effect on the operation of the on farm system but would only produce great localized head losses inside the flow regulator.

3.4. Performance analysis of the on-farm networks under various operating conditions

Once the pressure and the discharge at the upstream end of the on-farm network are obtained (for each configuration), by calculating the head losses down to the on-farm network, it is possible to obtain the pressure head and, consequently, the discharge at each sprinkler in the network. The on-farm network performance is expressed through irrigation uniformity as reported in section 2.3. The wetted patterns at various pressure heads and the corresponding radii were measured for a sprinkler type Rainbird 5000 (4.0 RC) (Fig. 4). Furthermore, a linear model was used to assess—the basis of the wetted patterns measured indoor—the wetted pattern of each sprinkler in the network depending on its actual operating pressure. Then, the performance indicator was computed by using equation 16. Figure 12 shows a cloud of points corresponding to the \(C_U\) achieved by the on farm sprinkler network downstream each hydrant inside each generated configuration. These points can be contained between two envelope curves. The upper envelope would represent the maximum \(C_U\) achieved while the lower envelope would represent the minimum \(C_U\) for all the investigated configurations. The number of tested configurations being large, \(C_U\) can be assigned to different probabilities of occurrence.

Analyzing the 90% curve, where 10% of the most unfavorable conditions are eliminated, one can notice that despite the optimization approach which accounted for the reliability of the distribution system, the distribution uniformity achieved downstream the hydrants at on farm level is scarce in most of the cases. A \(C_U\) ranging between 75 and 85% is achieved downstream the hydrants 1 to 5, but this
uniformity drastically decreases and reaches 22% at hydrant 16 with values lower than 50% starting hydrant 9. This trend is inverted and $C_U$ tends to increase slightly overcoming the value of 50% at hydrant 19 and reaches 65% at hydrant 21 but decreases again below 50% at hydrant 22 and keeps registering low values at hydrants 23 and 24.

Fig. 8 The Pareto-front and the optimal solution selected applying indicator I

Fig. 9 Relative pressure deficit at hydrant level within 100 configurations and 90% envelope curve

Fig. 10 Characteristic curve of a representative on farm sprinkler network of the study area with the first, second and third generated points $A'$, $B'$ and $C'$
4. Conclusions

The design of collective pressurized water distribution networks has been the subject of a number of research works, due to the relevance of its economic, environmental and social aspects [4;7;24;25], the ultimate objective being to design networks which are flexible enough to permit efficient on-farm irrigation, leading to high crop yields at moderate investment and operational costs [28]. In this context, Lamaddalena et al. (2012) [14] presented an optimization model which combines the minimization of cost with the maximization of the hydraulic reliability, accounting for the stochastic variability of the flows in the different sections of an on demand network. However, the reliability based approach did not account for the effect of the variability at the hydrant on the on farm system behavior operating downstream and designed for a fixed upstream pressure head that usually corresponds to its best achievable performance. Moreover, relations between irrigation uniformity and crop yields show that attaining high uniformity is a pre-condition to achieve high application efficiencies, and to consequently match the crop use requirements. Therefore, uniformity is an indicator that relates well to the system characteristics that favor water conservation and saving, as well as to higher water productivity [21;26;27;28;29]. Based on the above, a detailed analysis was carried out on an on demand irrigation system optimized through the reliability based approach and the great effect of the variability at the hydrants was demonstrated. The analysis shows that on farm uniformity strongly varies in space and time despite the reliability of the on demand distribution network accounted for in the optimization process. Moreover, low uniformities are achieved downstream the hydrants of the irrigation sector which may have drastic effects on yield. This is well pre-announced in the intersection of the hydrant and the on farm characteristic curves (Fig. 11), where the on farm network results under-sized under the current operating conditions of the on demand distribution system, and would necessitate a pressure head at hydrant of 27 m to operate satisfactorily.

![Fig. 11 Interaction between the on farm sprinkler network and one hydrant of sector 25 characteristic curves at various probabilities of occurrence](image-url)
Fig. 12 CU achieved at on farm level downstream each hydrant in 100 generated configurations with different probabilities of occurrence

References


