HYDRAULIC RELIABILITY AS A TOOL FOR PERFORMANCES EVALUATION AND DESIGN OF PRESSURE IRRIGATION NETWORKS WITH DEMAND SERVICE

L'AFFIDABILITÀ IDRAULICA COME STRUMENTO PER LA VALUTAZIONE DELLE PRESTAZIONI E PER LA PROGETTAZIONE DELLE RETI DI IRRIGAZIONE IN PRESSIONE CON SERVIZIO A DOMANDA

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Abstract esteso

La progettazione delle reti di distribuzione irrigua in pressione del tipo "a domanda" pone interessanti sfide sia per quanto riguarda il dimensionamento dei singoli elementi della rete (tipicamente, i diametri interni delle condotte e, in alcuni casi, le potenze da assegnare alle pompe degli impianti di sollevamento posizionati in testa alla rete), sia per quanto riguarda la successiva fase di verifica della loro funzionalità dal punto di vista idraulico. Nel presente lavoro viene pertanto presentata una metodologia finalizzata alla progettazione interattiva, su base probabilistica, delle reti di irrigazione in pressione con servizio "a domanda". La metodologia si basa, da un lato, su un primo dimensionamento dei diametri da assegnare ai vari tratti della rete, che utilizza un approccio probabilistico molto diffuso in letteratura tecnica, reso facilmente fruibile attraverso la proposta di impiego di un qualsivoglia solutore idraulico, anche di "Vecchio" tipo, atto a condurre analisi del tipo DDA (Demand Driven Analysis); dall'altro, su approccio probabilistico che accoppia la capacità di generare un numero S particolarmente elevato di "scenari di richiesta" da parte degli utenti, tutti ugualmente possibili, all'uso di un simulatore idraulico, in grado di effettuare analisi del tipo PDA (Pressure Driven Analysis) e, quindi, in grado di portare in debito conto, se debitamente implementato, gli effettivi legami esistenti tra le portate erogate dai vari idranti e i carichi esistenti in corrispondenza degli stessi idranti. La definizione di specifici "indicatori di performance", locali e globali, costituenti delle vere e proprie variabili aleatorie da analizzare, "a posteriori", su base statistica, unitamente: i) all'individuazione di specifici "valori-soglia" di tali "proxy"; ii) alla stima della probabilità di superamento o meno di tali valori soglia (a seconda dello specifico proxy considerato); iii) alla conoscenza dei nodi (e/o dei tratti) in cui i valori di tali indicatori risultano inadeguati, consente non solo una valutazione oggettiva dell'affidabilità, sotto l'aspetto idraulico, della rete oggetto di progettazione, ma anche l'individuazione degli interventi che possono essere attuati per incrementarla.

ABSTRACT

The design of “on demand” pressurized irrigation distribution networks raises interesting challenges, both in terms of sizing individual network elements (typically, the internal diameters of the pipes and, in some cases, the power ratings assigned to the pumping systems located at the beginning of the network) and in terms of the subsequent verification of their hydraulic functionality. This paper therefore presents a methodology aimed at the interactive, probabilistic design of “on demand” pressurized irrigation networks.

The methodology is based on the one hand, on an initial sizing of the diameters to be assigned to the various sections of the network, which uses a probabilistic approach widely used in technical literature, made easily usable through the proposal to use any hydraulic solver, even an old type, capable of conducting DDA (*Demand Driven Analysis*) type analyses; on the other hand, on a probabilistic approach that couples the ability to generate a particularly high number S of "request scenarios" from users, all equally possible, with the use of a hydraulic simulator, capable of carrying out PDA (*Pressure Driven Analysis*) type analyses and, therefore, capable of taking into account, if duly implemented, the actual relationships existing between the discharges supplied by the various sprinklers and the existing piezometric heads at the sprinkler itself.

The definition of specific local and global "*performance indicators*" constituting actual random variables to be analysed, "a posteriori", on a statistical basis, together with: *i)* the identification of specific "threshold values" of these "proxies"; *ii)* the estimation of the probability of exceeding or not these threshold values (depending on the specific proxy considered); and *iii)* the knowledge of the nodes (and/or sections) in which the values of these indicators are inadequate allows not only an objective assessment of the reliability, from a hydraulic perspective, of the network being designed, but also the identification of the interventions that can be implemented to improve it.

1. Introduction

The ongoing climate changes, resulting from the progressive global warming that began and became increasingly evident starting from the second half of the 19th century, induce, on the one hand, a greater intra-annual variability of precipitation, with showers of limited duration and increasingly stronger intensity (Avino et al, 2023) followed by increasingly longer periods of complete absence of precipitation (Wilby and Wigley, 2002; Trenberth, 2011); on the other hand, a progressive desertification of the territories, especially in the subtropical areas (Tabari, 2020).

Both issues make it increasingly necessary to make the most of the limited water resources available and, therefore, require the use of increasingly efficient irrigation systems, capable of both avoiding water waste and improving soil productivity.

From this perspective, pressurized irrigation techniques are increasingly being adopted. While they minimize losses within the supply-distribution chain, they also make the supply of water resources more effective and efficient. This not only allows for better rationing of the resource's distribution but also allows farmers to completely free themselves from the need to irrigate according to a "shift and timetable" scheme, typical of supply-distribution systems built with irrigation systems based on the use of "free-surface" canal networks.

The total budget for the Common Agricultural Policy (CAP) for the 2021-27 Multiannual Financial Framework (MFF) is € 386.6 billion (Source: European Commission, https://agriculture.ec.europa.eu/common-agricultural-policy/financing-cap/cap-funds_en#managementofcapfunds). The CAP strategic plans are based on nine specific objectives (SOs), three of which specifically address:

- SO4: Contribute to climate change mitigation and adaptation, as well as sustainable energy
- SO5: Promote sustainable development and efficient management of natural resources such as water, soil, and air
- SO9: Improve the response of EU agriculture to societal needs for food and health, including safe, nutritious, and sustainable food, as well as animal welfare.

To these three, a "cross-cutting objective" must be added, aiming to promote knowledge, innovation, and digitalization in agriculture.

In particular, the European Commission launched, in 2023, a five-year support plan for farmers in the form of a new Common Agricultural Policy (CAP). This has received € 307 billion in funding and includes stronger incentives to help our farmers adopt more sustainable and resilient practices.

In turn, the European Investment Bank (EIB) announced, in December 2024, a € 3 billion financing package for agriculture, forestry and fisheries across Europe, along with initiatives to strengthen agricultural insurance (Source: European Commission, https://ec.europa.eu/commission/presscorner/detail/it/ip_24_6322).

In Italy, the National Recovery and Resilience Plan (PNRR), financed with European funds from Next Generation EU, envisages massive "Investments in the resilience of the irrigation agro-system for better management of water resources", for a total amount of € 880 x 10^6 (Source: Openpolis, https://openpnrr.it/misure/129/), with the aim of improving the water resources available to the agricultural system and "...*making the availability of water for irrigation more constant, increasing the resilience of the agroecosystem to climate change and droughts. By converting one-third of current irrigation systems to other, more efficient systems that use innovative technologies, it is expected not only to improve water resource management and reduce losses, but also to combat illegal water abstraction in rural areas. …*"

As a result of the problems mentioned above and the significant financial resources available to address them, it now appears essential to propose and use appropriate design methodologies.

Given the above, this paper proposes and illustrates, with the aid of some practical examples, a new approach for the interactive design of pressurized, “on demand” irrigation systems. The approach presented is physically based, using hydraulic simulators that appropriately capture the physics of the phenomenon of pressurized irrigation using sprinklers to feed rain wings systems for agriculture irrigation. At the same time, it is statistically based, using concepts from Probability and Statistics, as well as probabilistic models, both in the initial design phase and in the subsequent verification phase, to adequately describe the random process of sprinkler opening/closing.

2. Design methods commonly adopted in the technical field

The methodologies proposed and/or used for a rapid design of “on demand” irrigation networks are numerous and are mainly based on probabilistic approaches. According to Gallizio (1945), if we indicate by n the number of sprinklers located downstream of a given section of a branched irrigation network, the number m of sprinklers that can be opened simultaneously (with $m \leq n$) can be evaluated through the expression

$$\frac{A^{m-1}}{B\, C_m^n} = P \qquad (1)$$

where the symbols used have, respectively, the following meaning (Fig.1):

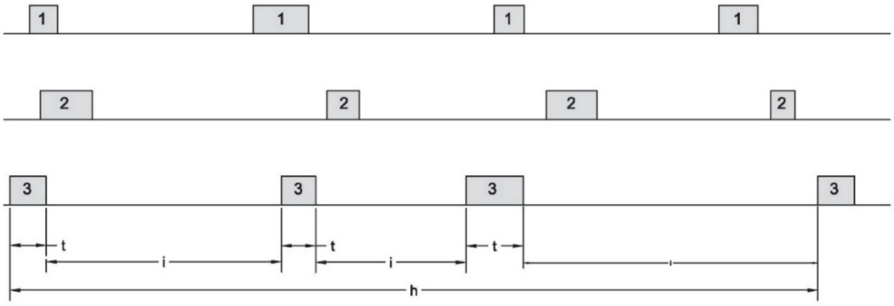

Figure 1 - Definition sketch of the probabilistic approach used for the sizing of the diameter of the pipes of a pressurized irrigation network with "on demand" service.

Fig. 1 - *Schema di definizione dell'approccio probabilistico utilizzato per il dimensionamento del diametro delle tubazioni di una rete di irrigazione pressurizzata con servizio "on demand".*

- $A = \frac{i}{t}$ is the ratio that occurs, during the peak period, between the average duration i of the time interval between two deliveries and the duration t of a delivery.
- $B = \frac{h}{i}$ is the ratio between the average duration of the peak period, h, that occurs, and the average duration i of the time interval between two deliveries during the peak period
- $C_m^n = \binom{n}{m} = \frac{n!}{m!\,(n-m)!}$ is the binomial coefficient, equal to the number of possible combinations of

m elements that can be extracted from the n.

- P is the probable time between the overlapping of m sprinkler openings and the subsequent overlapping, also of m sprinklers simultaneously open on the n that could be opened, which Gallizio proposes to set equal to 1.

In turn, Clément (Clément, 1966; Clément and Galand, 1979), taking as a reference only the cases (in truth, very close to reality) in which the sprinklers present in the network can be considered either completely open (with elementary probability of opening equal to p) or completely closed (with elementary probability of closing $q=1-p$) evaluates the probability $p_{M_n}(m) = P[M_n = m]$ that out of n sprinklers placed downstream of a generic section of the network only m can be open at the same time through the *binomial distribution* (which, as well known in Probability, represents the one suitable for allowing the perfect evaluation of the probability that, out of n experiments of the type "success or failure" or, equivalently, of the type "sprinkler completely closed or sprinkler completely open", there will be a failure in the m-th experiment). Consequently, Clément evaluates this probability as

$$p_{M_n}(m) = P[M_n = m] = C_m^n \, p^m q^{n-m} \tag{2}$$

in which the elementary probability of opening p of a single sprinkler can be evaluated starting from the duration t of a single opening of the sprinkler and the time T' actually available for irrigation through the expression:

$$p = \frac{nt}{T'} \tag{3}$$

The probability that, out of n potentially open sprinklers, the number of simultaneously open sprinklers does not exceed m is given, because of Eq. (2), by the expression

$$P_{M_n}(m) = P[M_n \leq m] = \sum_{j=0}^{m} \{C_j^n \, p^j q^{n-j}\} \tag{4}$$

Note that (1) and (2) coincide if we set

$$P = \frac{1}{p_{M_n}(m)} \frac{h \, q^{n+1}}{i} \tag{5}$$

In turn, the probability that, out of n potentially open sprinklers, the number of actually open sprinklers exceeds m is given by:

$$P[M_n > m] = 1 - P[M_n \leq m] = 1 - \sum_{j=0}^{m} \{C_j^n \, p^j q^{n-j}\} = \sum_{j=m+1}^{n} \{C_j^n \, p^j q^{n-j}\} \tag{6}$$

Based on (6), once the probability of exceeding $P[M_n > m]$ has been assigned, it is easily possible, by trial and error, to identify the number m of sprinklers for which the difference between the first and second member is minimal.

3. Probabilistic sizing of the various sections of the irrigation network

3.1 Evaluation of the elementary probability of opening one of the sprinklers present in the network

To use (6), it is necessary to evaluate:

- On the one hand, the number n of sprinklers existing downstream of each of the sections being sized
- On the other hand, the elementary probability p of each of these sprinklers is open.

The two problems are addressed and resolved, respectively, in the following two paragraphs.

3.1.1 Automatic identification of the number n of sprinklers present downstream of each section of the network

To identify, for each section of the network, the number n of sprinklers existing downstream of each section, various approaches can be used, possibly based on the use of GIS systems. In the authors' opinion, in order to quickly yet reliably identify the number n of sprinklers present downstream of each section, and to be able to perform the sizing calculations for any "demand-based" distribution network just as easily and reliably, it may be advisable to immediately implement, right from the start of the design process, the entire hydraulic scheme of the network within the calculation code that will then be used for the hydraulic checks (for example, the EPANET release 2.2 software, produced and maintained by the U.S. Environmental Protection Agency, available free online).

In fact, at this preliminary stage of the design, both the internal diameters of the pipes positioned along the various sections and their roughness parameters can be completely "invented," as they have no influence on the results obtained at this stage. Similarly, both the actual positioning heights of the sprinklers and the actual planimetric and altimetric positioning of the tanks, as well as their free surface topographic altitude, can be completely invented.

Once everything is set up, each sprinkler is "switched" to the "open" position, considering the value q_0 = 1 l/s as the "required" discharge for a potential hypothetical user present at the sprinkler. At this point, the hydraulic simulation software used is run in DDA (Demand Driven Analysis) mode, so the discharge delivered at each sprinkler coincides with that requested by the potential user, regardless of the value of the piezometric head actually existing both at the supplying node and in all other parts of the network. This behaviour, far from being physically based and consistent with what is, on the contrary, well known from hydraulics and experimental evidence, is made possible only because, in this analysis mode, the software simultaneously solves only the mass balance equations at the network nodes and the energy transformation equations within the various sections. Because of this analysis mode, the software used will be able to provide, because of the analyses, in addition to the piezometric heads at the nodes (or, equivalently, the pressures), also the discharges passing through the various sections (or, equivalently, the flow velocities within the sections).

Consequently, since the networks under examination are of the "exclusively branched" type, since the water cannot flow to the nodes located downstream of a given section if not within the section itself, by continuity (mass balance), the discharge circulating in the section can only be absolutely equal to the sum of the discharges effluent from the sprinklers located downstream of the sections themselves and, therefore, having set for each sprinkler a discharge q_0 constantly equal to 1 l/s, characterised by an absolute value equal to n l/s, where n is the number of sprinklers present downstream of each section.

3.1.2 Evaluation of the elementary probability of opening one of the sprinklers present in the network

To evaluate the elementary opening probability p for each sprinkler, we used Clément's classic approach, adapted to consider the introduction of a "*degree of elasticity*" and the system's response to demand. The "*degree of elasticity*" (or "*degree of freedom*") refers to the ratio $e = t''/t'$ between the time t'' that one wishes to keep available for irrigation compared to the time t' strictly necessary to perform it.

Based on this approach, the elementary opening probability p for each sprinkler can be calculated using the expression

$$p = \frac{e\,D}{r\,n\,q^*} \tag{7}$$

which coincides with that of Clement for *e=1.*

3.1.3 probabilistic sizing of pipes

Once the total number n of sprinklers present downstream of the same section is known for each section of the irrigation network, and once the elementary probability p of each of these sprinklers opening has been fixed, based on Eq. 7, it is possible, having fixed the risk $P[M_n > m]$ that the number of sprinklers actually opened is higher than the value m taken as a reference for the sizing, to identify, based on Eq. (6), the number m of sprinklers for which the second member is, for the sake of safety, just lower than the first member.

The maximum discharge Q_{max}^{l} which, unless there is a risk of exceeding the limit equal to $P[M_n > m]$, should circulate in the l-th section of the network (with l =1,2,….,L, where L is the total number of pipes present in the distribution network) is obtained by multiplying the maximum number m of sprinklers probabilistically open at the same time downstream of that section by the “nominal discharge of the sprinkler” (i.e., the discharge that the sprinkler should deliver with the pre-established residual load), q^*.

$$Q_{max}^{l} = m\, q^{*} \tag{8}$$

Once a maximum flow velocity equal to V_{max} has been established based on the mechanical and hydraulic characteristics of the pipes to be used and the type of joints, the minimum internal diameter of the *l*-th pipe, $D_{i,min}^{l}$,, can be identified based on the equation defining the average velocity:

$$D_{i,min}^{l} = \sqrt{\frac{4\, Q_{max}^{l}}{V_{ax}}} \tag{9}$$

The actual internal diameter of the *l*-th pipe, D_{i}^{l}, can in turn be easily identified, in an easily automated manner, starting from the Table of values of the internal diameters D_{i}^{j} previously prepared by the designer (with *j* = 0,1,2,…,*N*), first identifying in which range of values $\left[D_{i}^{j}, D_{i}^{j+1}\right]$ the diameter $D_{i,min}^{l}$ falls, and then using, for safety reasons, the valueD_{i}^{j+1} as the value of D_{i}^{l}.

4. Evaluation of the hydraulic reliability of the network

The reliability of a system is defined as the probability that the system itself, inserted in a given context, for a given number of years, with the aim of achieving a given objective, will be able to achieve it.

In the case in question, the reference system consists of a pressurized irrigation network, designed to satisfy, for a pre-assigned number of years, the demands, at least partially random, arising from a pre-assigned number of users inserted in a pre-assigned territorial context, characterized by a given climate and pre-assigned soil characteristics, and intended to host a pre-assigned type of crop.

In order to be able to irrigate the land owned by him/her at a time interval *T* appropriate to the climatic characteristics of the area, the agronomic characteristics of the land and the type of product to be obtained, each individual user requests to be able to use, within a pre-assigned period of time *T* (a certain volume of water V_T), in order to satisfy the water needs for irrigation use.

This volume of water V_T is distributed through a sprinkler which, in turn, supplies the single field through the use of a connecting pipe with diameter d_c and length l_c and, then, through a rain wing with diameter d_p and length l_p, in turn characterized by the presence of n_p equally spaced nozzles capable of delivering a unit discharge (theoretically independent of the specific position of the nozzle inside the rain wing) $q_p = q^{*}/n_p$, q^{*}being the discharge desired by the user, and which can be delivered by the sprinkler when the pressure height at the sprinkler itself is equal to the value $h_{spr.}^{*}$ (or, equivalently, the pressure height at the sprinkler is equal to $H_{spr.}^{*} - z$, z being the altitude of the centre of gravity of the sprinkler, measured starting from an assigned horizontal reference plane, and $H_{spr.}^{*}$ is the piezometric head at which the sprinkler is able to perfectly deliver the discharge q^{*}).

The discharge q that the sprinkler is actually able to deliver when the pressure height at the sprinkler is equal to h_r and the piezometric head is equal to H can be calculated starting from the pressure-discharge law obtained by taking into account, on the one hand, the pressure drop that, when the discharge q passes, occurs in the connecting pipe to the rain wing, given by the expression

$$\Delta H_c = \beta_c \frac{q^2}{d_c^5}\, l_c \tag{10}$$

and, on the other hand, taking into account the pressure losses, which gradually decrease due to the progressive reduction in discharge, which occur along the rain wing, which can be calculated, as a first approximation, by assuming the discharge delivered by the individual nozzles to be constant and equal to $1/n_p$ of the discharge q, as

$$\Delta H_p = \beta_p \frac{q^2}{d_p^5}\frac{l_p}{n} + \beta_p \frac{\left(q - 1\frac{q}{n}\right)^2}{d_p^5}\frac{l_p}{n} + \beta_p \frac{\left(q - 2\frac{q}{n}\right)^2}{d_p^5}\frac{l_p}{n} + \beta_p \frac{\left(q - 3\frac{q}{n}\right)^2}{d_p^5}\frac{l_p}{n} + \cdots + \beta_p \frac{\left(q - (n-1)\frac{q}{n}\right)^2}{d_p^5}\frac{l_p}{n} \tag{11}$$

and, therefore, as

$$\Delta H_p = \beta_p \frac{q^2}{d_p^5} l_p \left[1 + \frac{\left(1 - \frac{1}{N}\right)^2}{N} + \frac{\left(1 - \frac{2}{N}\right)^2}{N} + \frac{\left(1 - \frac{3}{N}\right)^2}{N} + \cdots + \frac{\left(1 - \frac{N-1}{N}\right)^2}{N}\right] = \beta_p \frac{q^2}{d_p^5} l_p F \tag{12}$$

where the coefficient F can be evaluated through the expression

$$F = \frac{1}{N} \sum_{i=1}^{N} \left\{ \left[1 - \frac{(i-1)}{N} \right]^2 \right\} \tag{13}$$

Consequently, the overall head loss ΔH_t which occurs along the connecting pipe and the rain wing because of the flow of the generic discharge q can be evaluated, approximately, through the expression

$$\Delta H_t = \Delta H_c + \Delta H_p = \beta_c \frac{q^2}{d_c^5} l_c + \beta_p \frac{q^2}{d_p^5} l_p F = \left(\beta_c \frac{l_c}{d_c^5} + \beta_p \frac{l_p F}{d_p^5} \right) q^2 = c' \, q^2 \tag{14}$$

Therefore, if q^* indicates the discharge delivered by the sprinkler with the pre-established residual piezometric head $h^*_{spr.}$ measured at the sprinkler itself, ΔH_t^* indicates the value of ΔH_t deduced from Eq. 14 substituting, in place of the generic discharge q, the discharge q^*, and with $h_r^* = c^* \left(\frac{q^*}{N} \right)^2 = \frac{c^*}{N^2} \, q^{*2} = c" \, q^{*2}$ the residual pressure head that one would like to maintain on the last of the nozzles constituting the rain wing in order to facilitate irrigation, it will be necessary that, in correspondence with the sprinkler, the corresponding values $h^*_{spr.}$ of the piezometric height $h_{spr.}$ and $H^*_{spr.}$ of the piezometric level $H_{spr.}$ are equal, respectively, to

$$h^*_{spr.} = \Delta H_t^* + h_r^* = c' q^{*2} + c" \, q^{*2} = (c' + c") \, q^{*2} \tag{15}$$

$$H^*_{spr.} = z_{spr.} + h_r^* + \Delta H_t^* = z_{spr.} + (c' + c") \, q^{*2} \tag{16}$$

from which

$$q^* = \frac{1}{\sqrt{c' + c"}} \left[h^*_{spr.} \right]^{0.5} = c \left[h^*_{spr.} \right]^{0.5} \tag{17}$$

$$q^* = \frac{1}{\sqrt{c' + c"}} \left[H^*_{spr.} - z_{spr.} \right]^{0.5} = c \left[H^*_{spr.} - z_{spr.} \right]^{0.5} \tag{18}$$

being $c = \frac{1}{\sqrt{c' + c"}}$

Clearly, if $h_{spr.} < h^*_{spr.}$ (and, therefore, $H_{spr.} < H^*_{spr.}$), the discharge delivered by the sprinkler will be $q < q^*$ and the residual piezometric head will be $h_r < h_r^*$. Conversely, if $h_{spr.} > h^*_{spr.}$ (and, therefore, $H_{spr.} > H^*_{spr.}$), they will be $q > q^*$ and $h_r > h_r^*$.

By carrying out, with the aid of the EPANET rel. 2.2 calculation code or similar software, a PDA (Pressure Driven Analysis) type analysis, once all the characteristics of the network have been assigned (topology; internal diameters, lengths and roughness parameters of all sides; tank heights; characteristics of the sprinklers and the height of the centre of gravity of their outlets, it is easily possible, for each set of sprinklers considered open, to evaluate: *i)* the discharge delivered by each sprinkler; *ii)* the residual load h_r; *iii)* the discharges flowing in all sections q_{link}, and *iv)* the relative flow velocities, V_{link}.

To evaluate the hydraulic reliability of the system, one can proceed as follows:

i) Using the Monte Carlo technique, a sufficiently large number S of scenarios is generated (for example: S = 10,000);

ii) Taking the s-th scenario as a reference (with s = 1, 2,…, S), the number n_s of sprinklers to be considered simultaneously open is generated using the *binomial distribution* (with $0 \leq n_s \leq n_{net.}$, where $n_{net.}$ is the number of nodes in the network containing a sprinkler capable of delivering a discharge for irrigation purposes);

iii) Using the uniform probability distribution, $n_{net.}$ values are generated uniformly distributed between 0 and 1, assigning the first generated value to the first sprinkler in the network, the second generated value to the second sprinkler in the network, and so on

iv) The n_s sprinklers characterized by presenting the assigned values closest to the value 1 are identified, and these sprinklers are considered open, while all others are considered closed.

v) Using specific software capable of adequately conducting a "Pressure Driven Analysis" type analysis, the following are evaluated: i) for each of the n_s open nodes, the discharge q_s^{node}, the pressure h_s^{node} existing at that node, the piezometric head H_s^{node}, and the residual pressure head $h_{r_s}^{node}$; ii) for each of the L sections of the network, the discharges q_s^l flowing in each section (l = 1, 2,…., L) and the related flow velocities, V_s^l.

vi) For each of the open nodes, the following are evaluated (Cozzolino et al., 2005):

1) The Local Performance Index relative to the Discharge Delivered at node j in the s-th operational scenario, $LPI\_DDN_j^s$, defined as

$$LPI\_DDN_j^s = \begin{cases} \frac{q_j^s}{q_j^*} & if\ 0 \leq h_j^s \leq h_j^* \\ 1 & if\ h_j^s > h_j^* \end{cases} \tag{19}$$

2) The Local Performance Index relative to the Covered Area at node j in the s-th operational scenario, $LPI\_CAN_j^s$, defined as

$$LPI\_DDN_j^s = \begin{cases} \frac{A_j^s}{A_j^*} \equiv \left(\frac{{h_r}_j^s}{{h_r}_j^*}\right)^2 & if\ \ 0 \leq h_j^s \leq h_j^* \\ 1 & if\ \ h_j^s > h_j^* \end{cases} \tag{20}$$

3) The Global Performance Index relative to the Overall Discharge Provided by the Network in the s-th operational scenario, GPI_OPDN^s, defined as

$$GPI\_OPDN^s = \frac{\sum_{j=1}^{N_s}(\delta_j^s\, q_j^s)}{\sum_{j=1}^{N_s} q_j^*} \tag{21}$$

in which

$$\delta_j^s = \begin{cases} 1 & if\ \ 0 \leq h_j^s \leq h_j^* \\ \frac{q_j^*}{q_j^s} & if\ \ h_j^s > h_j^* \end{cases} \tag{22}$$

4) The Global Performance Index relative to the Overall Area Served by the Network in the s-th operational scenario, GPI_OASN^s, defined as

$$GPI\_OASN^s = \frac{\sum_{j=1}^{N_s} A_j^s}{\sum_{j=1}^{N_s} A_j^*} = \frac{\sum_{j=1}^{N_s}\left({h_r}_j^s\right)^2}{\sum_{j=1}^{N_s}\left({h_r}_j^*\right)^2} \tag{23}$$

vii) Indicated with the symbol PI^s any of the four performance indices defined above, these values are sorted in ascending order, such that

$$PI_1 \leq PI_2 \leq \cdots \leq PI_{s-1} \leq PI_s \leq PI_{s+1} \leq \cdots \leq PI_{S-1} \leq PI_S \tag{24}$$

viii) To each of these values, the estimates $\hat{P}[PI_1 \leq pi]$ of the relative probabilities $P[PI_1 \leq pi]$ of not exceeding are attributed, obtained as

$$\hat{P}[PI_s \leq pi] = \frac{s-0.5}{S} \tag{25}$$

6. Case Study

To demonstrate how the proposed approach can easily lead to the accurate design of a demand pressurized irrigation network, this section presents its application to a specific case study.

The area of interest is in the Basilicata region (Italy) and covers approximately 653 hectares (Fig. 2). The percentage of unused areas (roads, rivers, etc.) is estimated at 13%, resulting in an effective irrigable area of approximately 568 hectares. Because of the practice of considering only a part of the surface conceptually served by the network as the actual surface to be irrigated ("partialisation"), only 60% of this area is effectively irrigated, resulting in a net topographical area effectively irrigated of 341 hectares. The area to be irrigated has elevations ranging from 271.93 to 415.23 m above sea level. Due to the climatic characteristics of the area, the irrigation period is expected to be 6 months (from April 1st to September 30th of each year). The total expected water requirement over the 6 months, based on agronomic studies, is equal to 1.33 × 10^6 m^3. Therefore, the continuous D endowment, evaluated considering that irrigation takes place 7 days a week and 24 hours a day (for which T = 24 × 7 = 168 hours), is equal to 0.260 l/(s ha). However, if the irrigation is carried out only 6 days a week out of 7 (and, therefore, with a full day of rest for users), and excluding the night hours (8 hours out of 24), irrigation is carried out only over a period T'= 16 × 6 = 96 hours, so $r = \frac{T'}{T}$ = 0.57143. For reasons related to the irrigation method used (sprinkler system), the discharge q^* to be delivered through the sprinkler is assumed to be 10 l/s. The sprinkler system used as a reference has a length of 100 m and has 10 sprinklers, placed at a constant Δx distance of 10 m, each capable of delivering a discharge of at least 1 l/s with a residual load value (evaluated on the final sprinkler) h_r^*=20 m. Regarding the connecting pipe between the sprinkler and the sprinkler system, a HDPE pipe with a diameter d_c =125.3 mm and a length l_c =250 m was designed. Consequently, based on Eqs. (12), (13), (14) and (15), the load required, at the sprinkler, to deliver the desired discharge q^*= 10 l/s, is $h^*_{spr.}$ = 36.75 m. The number of sprinklers present in the network is equal to 616 (corresponding to a density slightly less than 1 sprinkler per hectare of gross surface area to be irrigated). The degree of elasticity granted to users, to allow them a sufficiently long time to irrigate, is equal to 2. Therefore, because of Eq. (7), p=0.0503357.

The distribution system is made up, depending on the configuration examined in the analyses performed and described below, of 770 (Configuration 1, Fig. 2a) or 769 pipes (Configuration 2, Fig. 2b), with an internal diameter between 166.2 mm and 1017.4 mm. Depending on the configuration examined, the system is divided into two distinct branched distribution networks, each of which is served by a compensation tank (Configuration 1) or into three distinct branched distribution networks, each of which in turn is served by a compensation tank (Configuration 2). The overall length of the network is equal to 63,560.47 m (Configuration 1) or 63,529.68 m (Configuration 2).

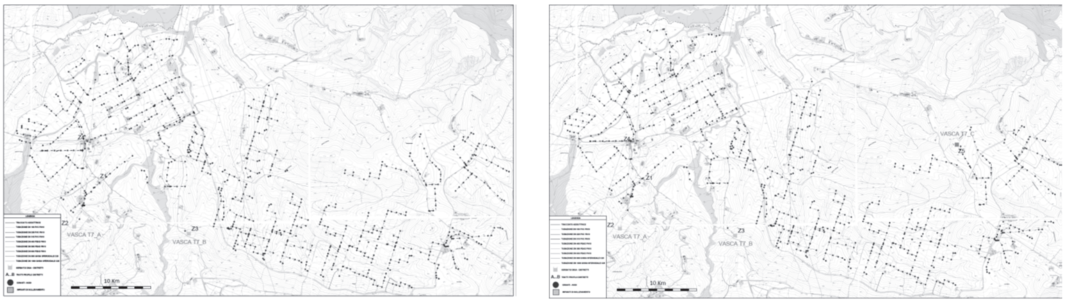

Figure 2a,b - Irrigation network definition schemes used to illustrate the proposed approach: a) Configuration 1; and b) Configuration 2.

Fig. 2a,b - *Schemi di definizione della rete di irrigazione utilizzati per illustrare l'approccio proposto: a) Configurazione 1; e b) Configurazione 2.*

In the case of Configuration 2, the construction of an additional underground compensation tank was planned, located at an altitude of 393.90 m above sea level, near which a piezometric tower is located capable, through an adequate lifting system with a socket located in the tank itself, of guaranteeing an additional load of at least 20.00 m above ground level, so that the third sub-network serving the district will, in fact, be served by a load tank located at an altitude of no less than 413.90 m above sea level. The third compensation tank is connected to the external supply system by a HDPE PN10 pipeline with a nominal diameter of DN 315 mm and an internal diameter D_i=290.8 mm, with a total length of 5398.15 m.

The probability of failure of the irrigation system was set equal to $P[M_n > m]$=0.01. Using the EPANET calculation code (rel. 2.2) in DDA (Demand Driven Analysis) mode, using the approach described in paragraph 3.1.1., the number n_l of sprinklers located downstream of the l-th link were identified, side by side. Consequently, using Eq. (6), the number m_l of sprinklers simultaneously located downstream of the l-th was identified, side by side, which is not exceeded except in 1%. By multiplying this value by the discharge q^*, using Eq. (8), the maximum discharge Q^l_{max} flowing on the l-th side was obtained which, if the network functioned perfectly (i.e. giving rise, in correspondence with each of the open sprinklers, to a load equal to $h^*_{spr.}$), should not be exceeded except in 1% of cases. Furthermore, given the very considerable extension of the district to be irrigated and the presence, within it, of distant areas located at relatively high altitudes, whose irrigation would be possible only by imposing small pressure losses per unit length of the pipes, a maximum speed value V_{max}=0.60 m/s was assumed. These hypotheses allowed the preliminary sizing of the network.

Once the sizing had been carried out (see the additional material presented separately), the reliability of the initially designed system was then evaluated.

To this end, to have sufficiently significant statistics on the behaviour of the irrigation network, S=10,000 simulations were carried out. The time required for these simulations, performed with the aid of software implemented in the VB.net language, using (intentionally) an old-generation PC (equipped with a WINDOWS 10 Pro 64-bit system and an Intel(R) Core(TM) i5-4460 CPU @ 3.20GHz processor, with 12.0 GB of RAM and an old type of hard disk formatted with the NTFS format) was approximately 32 hours, and is therefore compatible with normal use by operators and technicians working in this sector. Each of the S scenarios taken as reference for the estimation of the network reliability was created using the procedure set out in points *i)* to *iv)* of chapter 4.

The simulations were carried out using, especially due to its diffusion in the application field, the EPANET code (Rossmann et al, 2020). However, in order to avoid the errors that can be produced by the current version of this software when the "emitter" option is selected for the sprinklers, the technique adopted was to use the expression of Wagner et al. (1988) used by the EPANET code to take into account the possible reduction of the discharge actually delivered q, with respect to the maximum potentially deliverable q^{**} when the piezometric height on the sprinkler was the maximum compatible with the network under examination, $h_{spr.}^{**}$: In particular, the expression used to simulate the delivery of the generic discharge q at the sprinkler was:

$$q = \left[\frac{H_{spr.} - z_{spr.}}{H_{spr.}^{**} - z_{spr.}}\right]^{0.5} q^{**} \qquad (26)$$

in which, for ease of representation, it was assumed: i) that the minimum pressure was $H_{spr.}^{min} - z_{spr.} = 0$; ii) that, in correspondence with a value $H_{spr.}^{*} - z_{spr.} = 36.75$ m, the discharge was, according to Eqs. (18) and (26), q^{*} =10 l/s; iii) that the required pressure was $H_{spr.}^{**} - z_{spr.}$=100 m, so that, in correspondence with this pressure, the discharge delivered (required discharge) was, according to Eqs. (18) and (26), q^{**} =16.495721977 l/s.

The results of the analyses performed for the two configurations are briefly reported in the following Figures 3a,b,c (Configuration 1) and Figure 4a,b,c (Configuration 2).

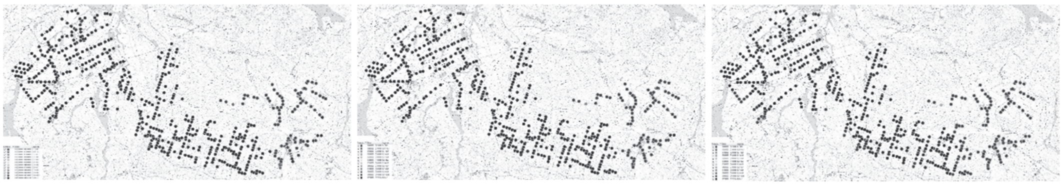

Figure 3a,b,c - Configuration 1: Spatial distribution of the local performance index related to the discharge delivered to the node, defined by equation (19), considering a threshold value lpi_ddn=0.6, lpi_ddn =0.8 and lpi_ddn=1.0, respectively.

Fig. 3a,b,c - *Configurazione 1: Distribuzione spaziale dell'indice di prestazione locale relativo alla portata erogata al nodo, definito dall'equazione (19), considerando rispettivamente un valore di soglia lpi_ddn=0,6, lpi_ddn =0,8 e lpi_ddn=1,0.*

In both figures, the values of the estimates $\hat{P}\left[LPI\_DDN_j > lpi\_ddn\right]$ of the probability with which the performance index $LPI\_DDN_j^s$ defined by Eq. (19) exceeds the pre-assigned lpi_ddn value are reported, with different colors and shades. Three threshold values are considered: lpi_ddn = 0.6 (i.e., the discharge supplied to users served by the sprinkler is equal to 60% of that required); lpi_{ddn}= 0.8 (i.e., the discharge supplied to the users served by the sprinkler is 80% of the required discharge) and lpi_ddn = 1 (i.e., the discharge supplied to the users served by the sprinkler is 100% of that required). From an examination of the first Figures 3a, 3b, and 3c, we observe, first, that even a seemingly optimized size of a "demand-based" pressurized irrigation distribution system does not necessarily automatically result in the system being able to fully satisfy user demand. In particular, as one would certainly expect, we observe that the probability of satisfying the demand tends to increase as the reference level of satisfaction decreases (i.e., "...he who is content, is happy!"). Consequently, the representation shown in Fig. 3 also provides quick indications on the type of crop to be applied in the various zones of the same irrigation district, distinguishing between areas where it is possible to plant the most water-intensive crops from those where, "*ob torto collo*" it is possible to plant only less water-intensive crops. At the same time, the representation shown in Fig. 2b also helps the designer immediately understand the type of intervention to be implemented, and the changes to be made to the design, to improve the effectiveness of the distribution system.

In the case in question, having already taken steps, during the dimensioning phase of the distribution network, to reduce to a minimum both the probability of exceeding the discharge of the individual sections (assumed to be equal to 1%), and the speed that can be achieved, in the various sections, in correspondence with the flow of such significant values of discharge (and, consequently, the pressure drops per unit of weight of the liquid flowing in the pipeline and per unit of path, I), there was no other possibility than to locate, in an area at a sufficiently high altitude located closer to the area characterized by a lower level of service (area characterized, for the same value of the lpi_ddn performance index, by the presence of a greater number of red, yellow and shaded green dots compared to the others), a third compensation tank, buried, near which is located a piezometric tower capable, through an adequate lifting system with a socket located in the tank itself, of guaranteeing an additional load of at least 20.00 m above the ground level. countryside.
After having carried out: i) the complete resizing, always on the same probabilistic basis and always considering the same value of the maximum flow velocities, of the three resulting sub-networks; ii) the execution of the same S=10,000 checks with the PDA technique, the procedure described in chapter 4 was carried out again, arriving at identifying, through Eq. (19), for each node j and for each scenario s, the values $LPI\_DDN_j^s$. Then, for each of the three pre-established threshold values (lpi_{ddn} = 0.6, 0.8 and 1.0) the values of the estimates $\hat{P}\left[LPI\_DDN_j > lpi\_ddn\right]$ of the probability with which the performance index $LPI\_DDN_j^s$ exceeds the pre-assigned lpi_ddn value were again identified. These values have been reported, in turn, in the following Fig. 4a,b,c.

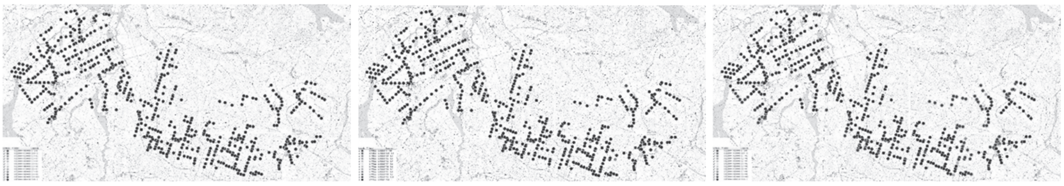

Figure 4a,b,c - Configuration 2: Spatial distribution of the local performance index related to the discharge delivered to the node, defined by equation (19), considering a threshold value lpi_ddn=0.6, lpi_ddn=0.8 and lpi_ddn=1.0, respectively.

Fig. 4a,b,c - *Configurazione 2: Distribuzione spaziale dell'indice di prestazione locale relativo alla scarica erogata al nodo, definito dall'equazione (19), considerando rispettivamente un valore di soglia lpi_ddn=0,6, lpi_ddn=0,8 e lpi_ddn=1,0.*

From their examination, it emerges, once again, that it is impossible, in the case in question, that all the potential users served by the irrigation system considered here are completely satisfied, while their number increases, progressively, if they are satisfied with receiving less water than required for optimal irrigation (see how, going from a value of lpi_ddn from 1.0 to 0.6. In particular, if the users of the system were satisfied with receiving only 80% of the quantity of water considered optimal, they would be satisfied in 100% of the cases. In turn, from the comparison between Fig. 4 and 5 it emerges that, with the same value of lpi_ddn, the number of users who would be completely satisfied with the implementation of the interventions envisaged in Configuration 2 would be much greater (especially if we refer to values of lpi_ddn less than or equal to 0.8) than that envisaged in Configuration 1. All this, obviously, with slight differences. increased costs both in terms of construction costs (due to the presence of an additional section of external aqueduct, an additional compensation capacity, an additional loading tower and an additional lifting system, not foreseen in Configuration 1), and in terms of management costs (due to the operation of the lifting system, the presence of an electromechanical system and the greater number of works to be maintained).

7. Conclusions

Demand-controlled pressurized irrigation is an irrigation system that, although already widespread in the more socially advanced and, for this reason, water-efficient areas of the world, will tend to become increasingly popular in the future. This is due to the need to minimize the waste of available water resources in a given area, to implement increasingly profitable crops, and to simultaneously enable the social evolution of the population engaged in agricultural activities. This not only guarantees increased income but also freedom from the need to operate according to rigid schedules that require the imposition of "shifts" and "times," and possibly even the need to irrigate at night and seven days a week. However, the design of such systems, even when carried out in a modern manner on a solid probabilistic basis, does not always guarantee the reliability necessary to ensure proper water distribution to the various users. This is also due to the random nature of the request, the need to ensure sufficient hydraulic loads at the sprinklers and the need to serve users who are very often far from the power sources.

Given the above, it seemed essential to develop a strategy, consisting of a set of various methodological approaches to be used "in cascade", designed to allow, on the one hand, a probabilistic assessment of the actual capacity of the previously designed irrigation system to meet the demands of all users it serves and, on the other, to allow for the rapid identification of the measures to be implemented, and the modifications to be made to the original project, to respond truly effectively to user requests.

The approach proposed here appears to fully meet this need, also providing the possibility of identifying areas of the territory which, although served by the irrigation network, are able to supply, especially for "structural" reasons (i.e., distance from water sources and altitude of the land to be irrigated), quantities of water that are much lower than the originally expressed needs and which, therefore, from the perspective of correct land use planning (i.e., choice of crop types to be planted) and management of the water resources available in a given territory, it appears absolutely necessary to identify.

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