RELIABILITY AS TOOL FOR HYDRAULIC NETWORK PLANNING

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ABSTRACT: This paper presents a methodology to evaluate the reliability of water distribution systems that can be used in the design phase and for identifying repair works to be carried out on existing systems. The methodology is based on the statistical analysis of dimensionless performance indices (hydraulic performance indices) derived from a large number of simulations of various water system demand scenarios and/or operating conditions. The hydraulic reliability index is assumed as the probability that, under a given operating condition, the hydraulic performance index will be above a certain threshold. Finally, the system's overall reliability (mechanical + hydraulic) is estimated using the overall reliability index, which is defined by the weighted mean of the hydraulic performance indices obtained for the various operating conditions. A case study using this methodology shows the concrete possibilities of applying this approach to a wide spectrum of cases, and the small influence on overall system reliability normally exerted by such events as the failure of links, pipes, and valves.

INTRODUCTION

It is common engineering practice to design water distribution systems (WDSs) using heuristic criteria. In general, engineers begin by assigning a system topology (nodes and links) and considering one or more scenarios for consumer demand and system working conditions. They then attempt to identify, possibly with the aid of optimization methods, the set of pipe diameters that generally respect the criteria of economical construction and management and that can, above all, guarantee a high degree of flexibility for system operation.

In recent years, the ever-growing need to find economical and efficient design solutions, together with the use of high-powered computers, has made it possible to carry out not only a cost-benefit analysis for WDSs but also a reliability analysis. The latter analysis aims to provide a statistical evaluation of system performance in the various consumer demand and/or operating conditions in which the system may be required to work.

Obviously, the correct operation and design of a WDS depend on a large number of factors. They include consumer demand, which varies in a random way both temporally and spatially; the possible failure or removal from service of one or more electromechanical components in the system (pipes, pumps, valves, joints, etc.); the quantity of water actually available in the tanks to make up any increase in demand arising on a daily or weekly basis; and the quality of water delivered to consumers, etc.

Consequently, assessment of the reliability of a WDS requires a series of complex considerations on the weight attributable to each of these factors and, generally, a very high number of simulations of the system. These simulations provide numerous samples of the indices by which system reliability can be evaluated and allow for the performance of a suitable statistical analysis.

This paper introduces a methodology for determining WDS reliability. In particular, the proposed approach can simultaneously take into account both failures due to the removal from service of one or more electromechanical components in the system and those stemming from the variability of demand and the emptying of tanks supplying the system. Consequently, we have to analyze at the same time two quite different random variables. On one hand, we should consider the random variability of the flow rate demand, which varies in a continuous way in time and space with values belonging to an unbounded interval $[0, +\infty[$. On the other hand, we should consider the random variable of the WDS working condition, which, on the contrary, belongs to a discrete and finite set. If all working conditions of each electromechanical component are set as on/off status only, the overall number of WDS's working conditions is 2^R.

The reliability considered in this paper, hereafter called overall reliability, is defined as the overall ability of the WDS to deliver the random quantity of water required by the consumers in the case of perfect and imperfect working conditions of the various system components. It is measured as the weighted mean of the probability that a dimensionless index, assumed to characterize the ability to satisfy user demand in a given operating condition, will assume values greater than a threshold value.

In particular, this paper illustrates a method, already partly developed in previous papers (Pianese and Villani 1994a; Pianese 1995), which aims to provide an objective assessment of the reliability of a WDS considering most of the various random factors affecting WDS performance. In this way, it is possible to provide criteria to ensure an adequate design of these types of systems and also to identify the repair works to be carried out on existing systems.

BACKGROUND

WDS reliability assessments were originally based on notions and models developed in the industrial field. WDSs were generally considered as complex systems composed of mechanical, electrical, or electronic components arranged in series and/or in parallel and fitted in a given environment for a certain period of time. Therefore, the reliability of a WDS was initially associated with its mechanical reliability, as the correct operation of the water system was made to depend solely on the working condition of the system's electromechanical components.

For instance, Billinton and Allan (1983) and Wagner et al. (1988a), in referring to a WDS as a system of elements in series and in parallel, claim that to satisfy the demand in a node, it is merely necessary to have a connection between the subject node and a source node. In other words, these authors use topological analysis to identify reliability in terms of reachability and connectivity. This approach is also used as an initial approximation by Goulter and Coals (1986). By proposing two different models for the optimized design of WDSs, they define the condition by which the demand in a node remains unsatisfied when there is a failure in all the links leading to the node in question. However, they acknowledge that the concept of reachability/connectivity provides an over-

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simplified and optimistic interpretation of WDS operation. The existence of a route linking the source node to the distribution node is a necessary but not generally sufficient condition to fully satisfy the demand of the users supplied by the node.

Su et al. (1987) proposed an interesting model for reliability assessment called the minimum cut set model. It was highly innovative with respect to the methods previously adopted as it introduced a mechanical reliability criterion based on the direct simulation of the WDS's operation by means of mathematical modeling. The authors took into account random breaking of pipes and defined the WDS's reliability as the overall probability that the system would be able to deliver the flow rates required with the minimum required piezometric head values.

A simplification of the minimum cut set method is laid out by Jacobs and Goulter (1991). To reduce the overall processing workload, they take into account the probability that a given number of pipes will simultaneously fail along with the probability that the removal of a given number of pipes will cause a system failure to occur.

However, none of the noted works accounts for the possibility that the system may not be fully efficient because of demand conditions other than those considered during the sizing phase. That is, no approach takes into account the random variability of demand. Consequently, the type of reliability they investigate is the one that Su et al. (1987) define as the WDS mechanical reliability.

Unlike previous authors, Bao and Mays (1990) look into the question of hydraulic reliability. In fact, they take into account only failures resulting from hydraulic causes, such as high values of water demand and/or pipe roughness due to their own random nature. To this end, they use the Monte Carlo (MC) method to generate these variables and then simulate system behavior using a hydraulic model. However, they do not take into account that the flow demand in each node varies in time (e.g., over 24 h).

With reference to a study model aiming to identify optimal design solutions, Cullinane et al. (1992) and Gupta and Bhave (1994) combined hydraulic and mechanical availability into a single assessment of reliability. However, they do not take into account the stochastic variability of water demand.

Pianese and Villani (1994b) define a series of nodal reliability indices and distribution system reliability indices that can help to identify the distribution system's weak points and the hydraulic operating conditions that may, with the passing of time, give rise to a poor performance in some WDS components, such as joints. More precisely, they define two indices capable of taking into consideration the negative effect on the reliability of the WDSs under those hydraulic working conditions marked by pronounced and frequent oscillations of the piezometric head and/or excessive values of the flow velocity in the pipes.

These two indices define the reliability of a WDS as a function of those hydraulic working conditions that when producing cyclical vibrations and variations in pressure, can cause large-scale water losses from the joints. The introduction of these indices points out that, although mechanical reliability is conceptually different from hydraulic reliability, in actuality, it is not easy to distinguish the true causes of poor performance in a WDS.

Further contributions designed to bring about improvements were provided by Gupta and Bhave (1994) and Pianese (1995). These contributions evaluate the reliability by using a hydraulic simulator capable of taking into consideration the relationship between the piezometric head and the effective water demand for each node.

PROPOSED APPROACH

The random nature of the factors on which WDS performance depends has led to the development of an approach that fundamentally consists of seven successive steps (Fig. 1). This approach constitutes a modification and a generalization of the approaches already used in the past by a number of authors, including Bao and Mays (1990) and Pianese and Villani (1994a).

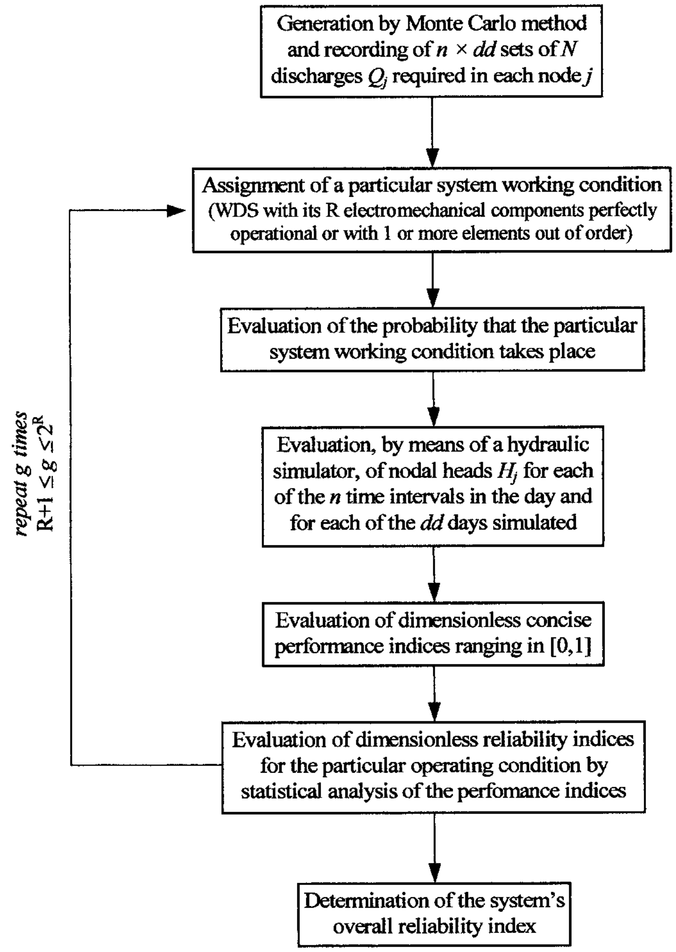

FIG. 1. Methodology Proposed to Evaluate Overall Reliability of WDS

It differs from the one proposed by the latter authors in that it can take into account the possibility of one or more electromechanical components being removed from service and the time variability of water demand. This system reliability is assessed not by using the mean of the specific performance index considered, but by making reference to the probability that the considered performance index will be higher than a preassigned minimum value.

The procedure proposed for assessing the system's overall reliability initially consists of using an MC generator to obtain the flow rates Q_j ($j = 1, 2, \ldots, N$) required by the users in each of the N demand nodes (see Fig. 1). The number of sets of N flow values generated is $n \times dd$, where n represents the number of time intervals into which the day is assumed to be divided, and dd is the number of "typical days" held to be sufficient for the subsequent statistical analysis of the results obtained through simulation.

For each of the $n \times dd$ demand sets generated, a hydraulic simulator is employed to assess the link flows and the piezometric heads in the WDS nodes. This analysis is repeated g times, g being the number of system conditions analyzed. The number of conditions analyzed depends on the state (working/not working) of the single electromechanical components.

This procedure makes it possible to estimate, for each operating condition considered and for each of the demand days generated, the daily volumes of water distributed overall in each individual node and for the whole WDS, as well as the ratios between these volumes and user demand.

The ratios between volumes actually supplied and daily user demand are adopted as system performance indices in the specific operating condition considered. They are held to be random variables to estimate, according to the sample *dd* data made available, the probability distribution and the probability that preassigned minimum values will be exceeded. The probability that the minimum value will be exceeded is taken as the system's hydraulic reliability index (HRI) in the specific operating condition considered.

Once these reliability indices have been estimated for each operating condition, we have only to assess the system's overall reliability using a weighted mean of the HRIs obtained. The weighting is established as the probability that the distribution system will end up operating in the reference condition.

As the number of working conditions that can theoretically arise in a WDS made up of R electromechanical components is 2^R and if we wanted to estimate the reliability index with reference to all possible working conditions using the proposed procedure, the computing effort required would make this unthinkable for even moderately sized WDSs. It is even more important for the approach proposed in this paper, as each working condition examined would entail considering $n \times dd$ different demand sets.

However, as other authors [e.g., Su et al. (1987) and Cullinane et al. (1989)] have already pointed out, the operating condition of a WDS with more than one electromechanical element removed from service at the same time is, in itself, an improbable event. Therefore, to assess the system's overall reliability, it would normally be adequate to consider only the operating conditions that envision a single removal from service at a time in addition to the condition in which all the electromechanical components are fully operational (often the most likely condition).

If, on one hand, this situation implies some slight approximations, at least for fairly small distribution systems as will be more fully illustrated below, on the other hand, it has the considerable advantage of bringing about a major reduction in the number of working conditions to be analyzed.

More specifically, if it were possible (considering the size of the distribution system and the type of electromechanical components in it) to refer only to the case of removal of a single electromechanical component at a time, the number of operating conditions to be examined would fall to just $R + 1$.

HYDRAULIC PERFORMANCE INDEX (HPI)

The reliability of the WDS, in preassigned operating conditions for its electromechanical components, is evaluated through statistical analysis of the performance indices. These performance indices are defined in such a way as to be representative of the system's ability to meet the demand of some users served by one or more nodes (local indices) and of all the users (global indices).

To this end, significant performance indices would be the ones that attempt to quantify the extent to which demand is satisfied in terms of volume supplied to the users compared to demand.

A local HPI for day d and in node j (HPI_j^d) is defined [e.g., Wagner et al. (1988b) and Gupta and Bhave (1996)] by

$$\mathrm{HPI}_j^d = \frac{\sum_{k=1}^{n} \alpha_{k,j}^d \cdot Q_{k,j}^d \cdot \Delta t}{\sum_{k=1}^{n} Q_{k,j}^d \cdot \Delta t} \quad (1)$$

where n = number of intervals into which the day is divided; k = generic interval of the day (k = 1, 2, . . . , n); Δt = time step for which a flow value is considered to be constant; $Q_{k,j}^d$ = flow rate demand in node j during the kth Δt on day d; $\alpha_{k,j}^d$ = piezometric head availability coefficient for node j in the kth time interval on day d, defined in the present paper as

$$\alpha_{k,j}^d = 1 \quad \text{if} \quad H_{k,j}^d > \overline{H}_j$$
$$\alpha_{k,j}^d = \left(\frac{H_{k,j}^d - \underline{H}_j}{\overline{H}_j - \underline{H}_j}\right)^{1/2} \quad \text{if} \quad \overline{H}_j \geq H_{k,j}^d \geq \underline{H}_j \quad (2)$$
$$\alpha_{k,j}^d = 0 \quad \text{if} \quad \underline{H}_j > H_{k,j}^d$$

where $H_{k,j}^d$ = head in node j during the kth Δt on day d; $\overline{H}_j$ = minimum head needed to fully satisfy demand at the node j; $\underline{H}_j$ = elevation of the user in the lowest site out of all those served by node j.

The global performance index corresponding to HPI_j^d is the network HPI (HPI_{net}^d) and, with reference to day d, is defined here as

$$\mathrm{HPI}_{net}^d = \sum_{j=1}^{N} \mathrm{HPI}_j^d \cdot \frac{\hat{Q}_j}{\sum_{j=1}^{N} \hat{Q}_j} \quad (3)$$

This represents a weighted mean of the HPI_j^d values, where the weighting function is given by the ratio between the daily mean flow required by the users at node j ($\hat{Q}_j$) and the daily mean of the whole flow required by all the users served by the water distribution system $\Sigma_{j1}^N \hat{Q}_j$. Therefore, the weighting function can also be regarded as the ratio between the number of equivalent inhabitants served by node j and the whole number of equivalent inhabitants served by the distribution system.

HRI

After calculating the distribution system (HPI_{net}^d) and nodal (HPI_j^d) HPIs for each of the *dd* flow demand sets generated, we get data samples that, for each WDS working condition, are made up of a number of indices equal to the number of typical days taken for reference in the simulations.

In the majority of cases, reliability is assessed using the mean (arithmetic, weighted, geometric, etc.) of the performance indices introduced. In actuality, it is much more meaningful to refer to the probability (the HRI) that the considered index is greater than a certain minimum assigned value hpi^*. Therefore, the HRI of a system in a given operating condition is represented by the probability

$$\mathrm{HRI} = P[\mathrm{HPI} > hpi^*] = 1 - F_{\mathrm{HPI}}(hpi^*) \quad (4)$$

where $F_{\mathrm{HPI}}(hpi^*)$ = HPI's cumulative distribution function.

The value hpi^* is assigned according to the meaning of the index and on the basis of common professional experience, taking into account the socioeconomic context.

Obviously, (4) can be applied to assess the HRIs for the whole distribution system and for individual nodes.

The choice of the threshold value hpi^* involves a number of considerations that are not only based on a cost-benefit analysis but must typically also take into account socioeconomic aspects. For instance, developed countries with high socioeconomic standards should make reference to very high hpi^* values (close to one), whereas in developing countries the same indices could be temporarily maintained at a lower level while at the same time guaranteeing good performance of the WDS. Moreover, it is worth differentiating between threshold values that refer to the whole distribution system hpi_{net}^* or to the single node hpi_j^*, taking care to ensure that $\forall j$, $hpi_{net}^* > hpi_j^*$. This is because as HPI_{net} is calculated using (3) as the weighted mean of the respective nodal values, it might conceal low HPI_j values at certain points in the distribution system that are compensated by the overly abundant values of the better served nodes in the WDS.

WEIGHTING COEFFICIENTS

To take into consideration the situation in which the distribution system and all of its components are fully operational and the situations in which one or more components have been removed from service, it is worth substituting the HRIs already introduced with another index, the overall reliability index (ORI). The ORI serves to concisely represent all possible distribution system operating conditions.

In this paper, a weighted mean of the HRI values obtained in each of the examined operating conditions is proposed to arrive at a global assessment of reliability, where the incidence of each WDS working condition has to be taken into consideration. To this end, it is first necessary to assign an adequate weighting coefficient to each operating condition.

The weighting coefficient considered is given by the probability that the WDS will be in a certain working condition (WDS with all its electromechanical components fully operational; WDS with one of its R components removed from service, etc.). This initially entails defining, for each electromechanical component, the availability A as the probability that it is available for operation at the moment of need (Dhillon 1988), and the unavailability U as the probability that it is not operational.

For the ith component, when the mean time to failure (MTTF_i) and mean time to repair (MTTR_i) are known, the availability A_i is evaluated as follows:

$$A_i = \frac{\mathrm{MTTF}_i}{\mathrm{MTTF}_i + \mathrm{MTTR}_i} \tag{5}$$

and the unavailability U_i as

$$U_i = 1 - A_i = \frac{\mathrm{MTTR}_i}{\mathrm{MTTR}_i + \mathrm{MTTF}_i} \tag{6}$$

When the elementary probabilities regarding the operation/nonoperation of the single electromechanical components are known, we can determine the probability that the WDS in question will find itself in a certain operating condition. This probability will be evaluated as that of an event composed of the events representing the operating status of the individual components. For the assessment of the composite events probability, the latter will be considered in all subsequent evaluations as stochastically independent events.

For the whole WDS, the probability A_{tot} (total availability) that the system will be fully operational in all its components is given by the complement to one of the overall probability that at least one electromechanical component will be removed from service. More concisely, A_{tot} can also be evaluated as the probability that all the components are working properly. Consequently

$$A_{tot} = 1 - \left[\sum_{i=1}^{R} U_i - \sum_{i=1}^{R-1}\sum_{l=i+1}^{R} U_iU_l + \sum_{i=1}^{R-2}\sum_{l=i+1}^{R-1}\sum_{m=l+1}^{R} U_iU_lU_m - \cdots\right] = \prod_{i=1}^{R} A_i \tag{7}$$

where R = total number of electromechanical components taken into account.

For a fully operational WDS, the weighting factor is given by the probability A_{tot} of simultaneous operation of all the system links, calculated by means of (7). However, the weighting coefficient attributable to the HRI values calculated in the event of a failure in the ith link alone is given [e.g., Fujiwara and De Silva (1990) and Fujiwara and Tung (1991)] by

$$u_i = U_i \cdot A_1 \cdot, \ldots, \cdot A_z \cdot, \ldots, \cdot A_R = A_{tot} \cdot \frac{U_i}{A_i} = A_{tot} \cdot \frac{\mathrm{MTTR}_i}{\mathrm{MTTF}_i}, \quad z \neq i \tag{8}$$

Under the preceding hypotheses of independence of failure events, (8) supplies the probability that the ith component will be removed from service while the remaining electromechanical components are fully functional.

Generally speaking, to obtain the weighting coefficient $\{u_{il}, u_{ilm}, \ldots\}$ for the event of a simultaneous failure of two (e.g., the ith and lth component), three (e.g., the ith, lth, and mth component), or more components, it will be necessary to substitute into (8) the terms A of the components presumed to be affected by the failure with the corresponding terms U.

ORI

The assessments of the ORIs could be carried out very accurately, although this would be at the expense of a large number of simulations. Given the weighting coefficients (A_{tot}, u_i, u_{il}, u_{ilm}, . . .) and having determined the HRIs relative to the jth node, the ORI for the single node (ORI_j) for all combinations of failures is defined by

$$\mathrm{ORI}_j = \mathrm{HRI}_j^{(0)} \cdot A_{tot} + \sum_{i=1}^{R} \mathrm{HRI}_j^{(i)} \cdot u_i + \sum_{i=1}^{R-1}\sum_{l=i+1}^{R} \mathrm{HRI}_j^{(il)} \cdot u_{il} + \sum_{i=1}^{R-2}\sum_{l=1+1}^{R-1}\sum_{m=l+1}^{R} \mathrm{HRI}_j^{(ilm)} \cdot u_{ilm} + \cdots = A_{tot}\,\mathrm{HRI}_j^{(0)} \cdot \left[1 + \sum_{i=1}^{R} \frac{\mathrm{HRI}_j^{(i)}}{\mathrm{HRI}_j^{(0)}} \frac{U_i}{A_i} + \sum_{i=1}^{R-1}\sum_{l=i+1}^{R} \frac{\mathrm{HRI}_j^{(il)}}{\mathrm{HRI}_j^{(0)}} \frac{U_iU_l}{A_iA_l} + \sum_{i=1}^{R-2}\sum_{l=i+1}^{R-1}\sum_{m=l+1}^{R} \frac{\mathrm{HRI}_j^{(ilm)}}{\mathrm{HRI}_j^{(0)}} \frac{U_iU_lU_m}{A_iA_lA_m} + \cdots\right] \tag{9a}$$

where the HRIs in node j are evaluated with reference to the various operating conditions, such as $\mathrm{HRI}_j^{(0)}$ when all the electromechanical components in the distribution system are fully operational, $\mathrm{HRI}_j^{(i)}$ when only the ith component is removed from service and the remainder are all working normally, $\mathrm{HRI}_j^{(il)}$ when only the ith and the lth components are removed and the remainder are all working normally, etc.

More concisely, (9a) can also be written as follows:

$$\mathrm{ORI}_j = A_{tot}\,\mathrm{HRI}_j^{(0)} \cdot \left[1 + \sum_{i=1}^{R} \frac{\mathrm{HRI}_j^{(i)}}{\mathrm{HRI}_j^{(0)}} \frac{U_i}{A_i} + \Delta\right] \tag{9b}$$

The term Δ represents the contribution of the operating conditions of the WDS with a failure in more than one component to the assessment of the reliability of node j using the ORI_j index. The order of magnitude of this term is not only a function of the HRIs but also depends on the rates of failure of the electromechanical components and the overall number of elements making up the WDS in question.

In connection with this, it is worth noting that for the values normally assumed for the rates of failure of the electromechanical components that generally make up the WDSs, the term Δ is typically negligible even for very large WDSs composed of several hundreds of links and about 10 weak points (pumps, valves, etc.). This can be easily deduced from (9a,b) using the data and the equations for failure and repair rates available in the technical literature [e.g., O'Day (1982), Walski and Pelliccia (1982), and Guercio et al. (1995)] and also by taking into account that the ratios with maximum values of 1, $\mathrm{HRI}_j^{(i)}/\mathrm{HRI}_j^{(0)}$, $\mathrm{HRI}_j^{(il)}/\mathrm{HRI}_j^{(0)}$, etc., are lower and gradually become smaller.

Generally, to reduce the number of computations without a significant loss of accuracy, the contributions of the terms deriving from the consideration of a simultaneous failure of two or more electromechanical components can be ignored.

With reference to these hypotheses, (9*a*) becomes

$$\mathrm{ORI}_j \cong \mathrm{HRI}_j^{(0)} \cdot A_{tot} + \sum_{i=1}^{R} \mathrm{HRI}_j^{(i)} \cdot u_i = A_{tot}\, \mathrm{HRI}_j^{(0)} \cdot \left[1 + \sum_{i=1}^{R} \frac{\mathrm{HRI}_j^{(i)}}{\mathrm{HRI}_j^{(0)}} \frac{U_i}{A_i} \right] \quad (10)$$

Note that (10) leads to an underestimation of the system's overall reliability. Using the same reasoning, the ORI for the whole system (ORI_{net}) is given by

$$\mathrm{ORI}_{net} = A_{tot}\mathrm{HRI}_{net}^{(0)} \cdot \left[1 + \sum_{i=1}^{R} \frac{\mathrm{HRI}_{net}^{(i)}}{\mathrm{HRI}_{net}^{(0)}} \frac{U_i}{A_i} + \sum_{i=1}^{R-1} \sum_{l=i+1}^{R} \frac{\mathrm{HRI}_{net}^{(il)}}{\mathrm{HRI}_{net}^{(0)}} \frac{U_i U_l}{A_i A_l} + \sum_{i=1}^{R-2} \sum_{l=1+1}^{R-1} \sum_{m=l+1}^{R} \frac{\mathrm{HRI}_{net}^{(ilm)}}{\mathrm{HRI}_{net}^{(0)}} \frac{U_i U_l U_m}{A_i A_l A_m} + \cdots \right] \quad (11)$$

Using the same hypotheses as for a node, we can assume the following approximate equation:

$$\mathrm{ORI}_{net} \cong \mathrm{HRI}_{net}^{(0)} \cdot A_{tot} + \sum_{i=1}^{R} \mathrm{HRI}_{net}^{(i)} \cdot u_i = A_{tot}\mathrm{HRI}_{net}^{(0)} \cdot \left[1 + \sum_{i=1}^{R} \frac{\mathrm{HRI}_{net}^{(i)}}{\mathrm{HRI}_{net}^{(0)}} \frac{U_i}{A_i} \right] \quad (12)$$

Note that the approximations introduced by (10) and (12) to evaluate the ORIs could turn out to no longer be acceptable if one or more of the following scenarios arises: (1) Systems in an advanced state of decay (as a result of the materials used and/or the advanced age of the components); (2) systems served by several pumping stations with no backup pumps or energy supply backup and are, therefore, subject to frequent interruptions of service (MTTF values, on average, lower than those regarding the pipes) and/or long repair times (high MTTR values); (3) WDSs built in extremely unfavorable environments, such as climatic areas characterized by winter temperatures falling well below zero and/or saturated soils.

APPLICATION OF PROPOSED METHODOLOGY TO CASE STUDY

To provide a more effective description of the proposed methodology, an analysis was conducted on the distribution network presented in Fig. 2, whose geometric and hydraulic characteristics are listed in Tables 1 and 2.

The only electromechanical components considered in the example are the $R = 12$ pipes making up the water distribution network whose MTTF_i and MTTR_i values are reported in Table 2 along with the values of U_i and A_i for each side of the WDS in question. These were deduced using (5) and (6), once their respective MTTF_i and MTTR_i were known.

Determining the MTTF_i initially required an estimation of the breaking rate b_D (here reported as breaks/km · year). To this end, we used as an example the equation taken from the 1985 St. Louis ''main break report'' (Su et al. 1987)

$$b_D = \frac{16{,}192.194}{D^{3.26}} + \frac{118.015}{D^{1.3131}} + \frac{183{,}558.095}{D^{3.5792}} + 0.0261 \quad (13)$$

where D = pipe diameter expressed in millimeters.

The reciprocal of b_D supplies the corresponding MTTF_i for the unit length of the ith pipe. Thus, the MTTF_i for a pipe of length L_i is given by

$$\mathrm{MTTF}_i = 365 \cdot \frac{1}{(b_{D_i} \cdot L_i)} \quad (14)$$

with MTTF_i expressed in days and L_i in kilometers.

Pipe diameter also seems to be the most significant parameter in pipe repair and hence for determining the MTTR_i. Walski and Pelliccia (1982) state that the MTTR_i increases with the diameter of the ith pipe according to a power function. For the pipes most frequently used in water distribution networks, the MTTR_i thus calculated ranges from several hours to just over 1 day.

For simplicity's sake, the analyses conducted in this paper have assumed that the MTTR of a pipe is constant and equal to 1 day. It has also been assumed that any break in a pipe always occurs at the beginning of the day ($t = 0^h.00$) so that the typical demand situation that can be taken for reference is the one evolving in the following 24 h. Considering the long term analysis to be carried out, it can be presumed that little or nothing would happen if, instead of deterministically assuming the time 0:00 as the start of the 24-h reference period, the instant in which the failure occurs was also considered as a random variable and was generated using the MC method.

Note that achieving an evaluation of WDS reliability that can accurately take into account the random events represented by failures in the single pipes would require stochastic analysis considering the frequency and the probability of these events as time-dependent variables. Because the aim of the present paper is to conduct an analysis of the system's long-term behavior, the proposed approach considers (Duan and Mays

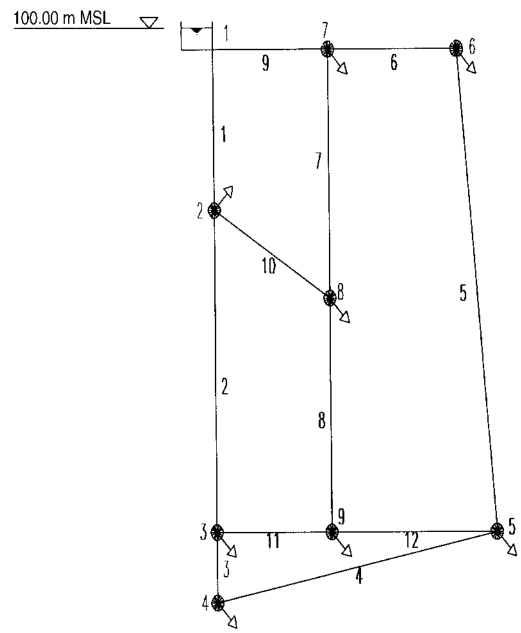

FIG. 2. Schematic Representation of WDS Taken for Reference

TABLE 1. Main Characteristics of WDN's Nodes

Node (1)	$\underline{H}_j$ (m MSL) (2)	$\overline{H}_j$ (m MSL) (3)	P_j (4)	$\hat{Q}_j$ (L/s) (5)
1	82	100	—	—
2	80	98	4,500	23.44
3	75	93	5,300	27.60
4	69	87	4,700	24.48
5	70	88	6,300	32.81
6	76	94	5,300	27.60
7	79	97	3,900	20.31
8	76	94	5,900	30.73
9	72	90	4,100	21.35

Note: Lower $\underline{H}_j$ and upper $\overline{H}_j$ = limits of required pressure head; P_j = equivalent inhabitants; and $\hat{Q}_j$ = daily averaged flow rate required in the nodes of the WDS.

TABLE 2. Main Characteristics of WDS's Links

Link (1)	D_i (mm) (2)	L_i (m) (3)	b_{Di} (breaks/ km·year) (4)	$MTTF_1$ (days) (5)	$MTTR_i$ (days) (6)	U_i (7)	A_i (8)	u_i (9)
1	450	400	6.492E-2	14,055.56	1	7.114E-5	0.9999289	7.101E-5
2	400	800	7.145E-2	6,385.94	1	1.566E-4	0.9998434	1.563E-4
3	200	175	1.400E-1	14,898.36	1	6.712E-5	0.9999329	6.700E-5
4	200	932	1.400E-1	2,797.44	1	3.573E-4	0.9996247	3.568E-4
5	300	1,206	9.244E-2	3,274.12	1	3.053E-4	0.9996947	3.048E-4
6	300	420	9.244E-2	9,401.40	1	1.064E-4	0.9998936	1.062E-4
7	400	620	7.145E-2	8.239.92	1	1.213E-4	0.9998787	1.211E-4
8	200	580	1.400E-1	4,495.19	1	2.224E-4	0.9997776	2.220E-4
9	450	375	6.492E-2	14,992.60	1	6.670E-5	0.9999333	6.657E-5
10	200	435	1.400E-1	5,993.59	1	1.668E-4	0.9998332	1.665E-4
11	300	375	9.244E-2	10,529.56	1	9.496E-5	0.9999050	9.479E-5
12	300	540	9.244E-2	7,312.20	1	1.367E-4	0.9998633	1.364E-4

1990) situations of stationary availability and unavailability that yield failure and repair ratesthat are constant over time (Billinton and Allan 1983).

The last column in Table 2 reports the probabilities u_i, evaluated using (8), that the WDS in question will operate with only the ith pipe withdrawn. For this network, the total availability deduced from (7) is $A_{tot} = 0.998129$.

Again for simplicity's sake, the roughness coefficients were assumed to be constant. In particular, the distributed head losses in pipes were calculated using the Darcy resistance formula for cast-iron pipes, increasing the energy losses by 40% to take into account the increase in roughness over time.

DEMAND MODEL

Variability of User Demand

Demand is extremely variable in time and space, and varies, at least, in a partially random way. Thus it is unrealistic to study a WDS with a deterministic approach that verifies whether the system is functioning properly only with reference to a few, purely conventional working conditions that are thought to represent situations that the system may be required to operate in its lifetime.

A probabilistic approach that allows a WDS to be studied under a wide variety of different load conditions provides a more complete description of WDS behavior and constitutes the necessary approach for an objective evaluation of the system's hydraulic reliability.

To carry out a suitable approach, it is first important to take into account that the flow rate required by the users generally varies in time. Within a stochastic process linking the required flow rate to time, we can identify the four typical components of a historical series. Specifically these are (1) the trend describing the underlying evolution of demand over several years; (2) the seasonal component due to the oscillation of demand during the year; (3) the cyclical component, which is predominantly represented by the variation of the flow rate demand in the space of 1 week and/or 1 day; and (4) the random component, which has a zero mean and constant variance and where the single terms are uncorrelated.

As the first two components are highly dependent on the specific characteristics of the users in question, to define demand in this example we consider only the daily cyclical and the random components and neglect any interannual, seasonal, and weekly cyclical component that may be present. In particular, the averaged daily variation of the demand is considered here to be represented by a graph, characterized by one peak in the morning and two lesser peaks in the afternoon and evening.

The daily trend considered in this example must not be assumed to represent real situations in general but must, rather, be regarded merely as how one of the cases would probably behave in practical applications. Therefore, the use, in this context, of a likely demand model has the sole aim of making it possible to obtain results of interest to practical application.

The daily cyclical component of demand is formally considered to be the same for all demand nodes, although it is slightly staggered to take into account the different lifestyles of the users served by the various nodes. Moreover, the peak coefficients vary for each demand node as a function of the user number supplied. The random component of nodal demand, on the other hand, is assumed node by node as a variable that is statistically independent of the remainder.

Let k ($k = 1, 2, \ldots, n$) indicate any one of the n time intervals into which the day can be subdivided. The ratio

$$DC_{k,j} = \frac{V_{k,j}}{E\left[\sum_{k=1}^{n} V_{k,j}/n\right]} = \frac{Q_{k,j}\Delta t}{E\left[\sum_{k=1}^{n} Q_{k,j}\Delta t/n\right]} = \frac{Q_{k,j}}{E\left[\sum_{k=1}^{n} Q_{k,j}/n\right]} \quad (15)$$

between the volume of water $V_{k,j}$ required by the users in the kth time interval in the node j and the daily averaged volume required $E[\sum_{k=1}^{n} V_{k,j}/n]$ during the time interval Δt represents the users' demand coefficient for the kth time interval for the jth node (Fig. 3 reports the reference trend of the mean demand coefficient throughout the day, i.e., the trend of the demand for a hypothetical node with $P_{\mathrm{reference}} = 5{,}000$ equivalent users).

Evaluation of Demand Coefficients

The maximum DC_j^* among the $DC_{k,j}$ values represents a sort of peak demand coefficient for the jth node (not instantaneous but averaged throughout the time interval of length $\Delta t = 24$ h/n). This coefficient is normally evaluated on the basis of the correlation between maximum flow rates required by the users served by a given network and the number of users. For instance, to determine the peak demand coefficient, the expression (Babbitt 1928)

$$DC^* = 5\cdot\left(\frac{P}{1{,}000}\right)^{-0.2} \cong 20P^{-0.20} \quad (16)$$

is sometimes used, although actually proposed for sewer systems, where P = population served, expressed as the number of equivalent users.

Assigning DC^* as a random variable, this expression can be considered as a derivation of a linear regression performed between the common logarithms of DC^* and the common logarithms of the number P of users served.

In particular, it is hypothesized that:

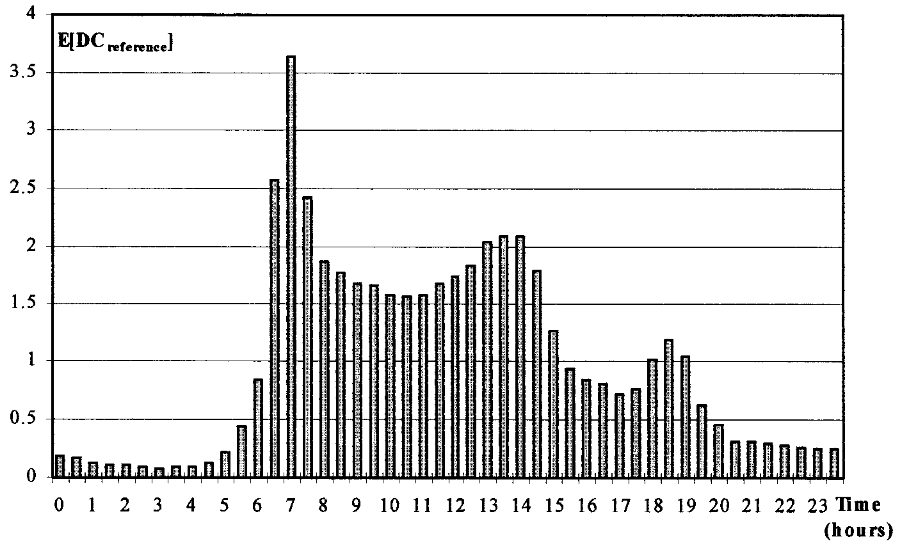

FIG. 3. Mean Trend throughout Day of Demand Coefficient Relative to 5,000 Equivalent Users Supplied by Demand Node (Reference Trend)

- The value of DC^* on the left-hand side of (16) represents the inverse of the common logarithm of the conditional mean $E[\log DC^*|P = p]$.
- The cumulative distribution function of the peak coefficient DC^* is distributed lognormal (i.e., the random variable $\log DC^*$ is normally distributed).
- The variance of $\log DC^*$ is constant and, thus, independent of P (thus, the coefficient of variation of the variable DC^*, $\mathrm{COV}[DC^*]$, can also be assumed to be constant).

On the basis of these hypotheses, the value of DC^* corresponding to a preassigned value $F = F_{DC^*}(dc^*)$ of the cumulative probability can be calculated from the expression

$$DC_F^* = 10^{\mu_{\log DC^*} + u_F \sigma_{\log DC^*}} \tag{17}$$

where $F = \Pr[\log(DC^*) \le \log(dc^*)] = \Pr[DC^* \le dc^*]$ is the probability that the variable DC^* will not exceed the value dc^*; $\mu_{\log DC^*}$ and $\sigma_{\log DC^*}$ are the mean and the standard deviation of the common logarithms of the peak coefficient, respectively; and u_F = standard unit normal random variable, which can be generated using the MC method [Box and Muller's method (1958)].

Within a given distribution network, the means $\mu_{\log DC^*}$ vary according to (16) in relation to the number of equivalent users present downstream from the branch in question. We must also consider that peak demand values do not normally arise simultaneously at all points in the network mainly because of the variability of the users' daily habits and the random nature of the demand.

In light of the above, the mean values of $DC_{k,j}$ were assigned node by node and time interval by time interval and ensuring the condition under which the expression $\sum_{k=1}^{n} E[DC_{k,j}] = n$ must hold for each node in the system. In particular, with reference to the utilization law presented in Fig. 3, the following procedure was used:

1. The mean value of the peak coefficient relative to the node j was calculated on the basis of the simplified equation

$$E[DC_j^*] = E[DC_{\text{reference}}^*] \cdot \left(\frac{P_j}{P_{\text{reference}}}\right)^{-0.20} \tag{18}$$

2. For each node j, the values of $E[DC_{k,j}]$ were calculated on the basis of the expression of proportionality

$$\frac{E[DC_{k,j}] - 1}{E[DC_{k,\text{reference}}] - 1} = \frac{E[DC_j^*] - 1}{E[DC_{\text{reference}}^*] - 1} \tag{19}$$

In applying (19), the values of $E[DC_{k,j}]$ did not turn out to have values lower than a minimum (positive) value $DC_{\min,j}$.

3. The distributions $E[DC_{k,j}] = E[DC_{k,j}(k, j)]$ thus obtained were shifted and slightly modified so that during moments of greater global demand, (16), referring to all users served by the WDS, was also satisfied.

Note that, consistent with the need to refer to a "likely" demand law, the proposed procedure made it possible to create a set of mean values of $DC_{k,j}$. These were able, on one hand, to supply the peak coefficients statistically consistent with the number of users served by nodes immediately downstream of preassigned sections and, on the other hand, to yield a good reproduction, at least in qualitative terms, of a possible mean daily variation of user demand.

Fig. 4 points out how the overall mean demand coefficient varies during the day. Comparing this to Fig. 3 shows that the consequence of the above procedure for defining demand is an increase in the time interval when WDS is globally subject to the maximum demand and a flattening of the peaks. This is what actually happens in real life when, instead of referring to the demand of a small number of users, reference is made to all the users in a given WDS.

If we assume that, like the coefficients DC_j^*, the coefficients $DC_{k,j}$ are also random variables and if we extend the lognormal distribution hypothesis to them, we can generally write that

$$(DC_{k,j})_F = 10^{\mu_{\log DC_{k,j}} + u_F \sigma_{\log DC_{k,j}}} \tag{20}$$

The values of $\mu_{\log DC_{k,j}} = E[\log DC_{k,j}]$ can be obtained starting from the values of $E[DC_{k,j}]$ already identified for each node (according to the procedure described above) by means of the equation

$$E[\log DC_{k,j}] = \log(E[DC_{k,j}]) - \frac{1}{2}\log(1 + \mathrm{COV}^2[DC_{k,j}]) \tag{21}$$

The values of $\sigma_{\log DC_{k,j}}$ in turn come to depend on the coefficient of variation $\mathrm{COV}[DC_{k,j}]$ according to the well-known expression

$$\sigma_{\log DC_{k,j}} = \sqrt{\mathrm{var}[\log DC_{k,j}]} = \left[\frac{\log(1 + \mathrm{COV}^2[DC_{k,j}])}{\ln 10}\right]^{1/2} \tag{22}$$

Therefore, to obtain the values of $DC_{k,j}$ for each node and, therefore, the flow rates required, the following expression can be used:

$$(DC_{k,j})_F = 10 \cdot \exp\left\{\log E[DC_{k,j}] - \frac{1}{2}\log(1 + \mathrm{COV}^2[DC_{k,j}]) + u_F\left[\frac{\log(1 + \mathrm{COV}^2[DC_{k,j}])}{\ln 10}\right]^{1/2}\right\} \quad (23)$$

Eq. (23) points out that to generate statistically indistinguishable data samples, we have to know the mean $E[DC_{k,j}]$ and the coefficient of variation $\mathrm{COV}[DC_{k,j}]$.

In the case in question, the values $E[DC_{k,j}]$ were assigned with reference to the demand diagram shown in Fig. 3 and the approach described above (Steps 1–3). Moreover, it is assumed that $\mathrm{COV}[DC_{k,j}] = 0.3$.

Results Obtained

As is shown in Fig. 1, evaluating the HRIs initially entails generating a data sample of the flow rates required by users over a 24-h period for each node. A series of direct comparisons determined that a data sample made up of the daily flow rate demand for 250 different days was adequate to consider the differences between the different samples generated to be statistically negligible.

With reference to (10) and (12) and the hypotheses underlying their formulation, the HRIs were evaluated only for the condition in which all of the WDS's pipes are working and for the conditions with a failure in one link at a time. Despite the simplifications introduced, it was nevertheless necessary to simulate WDS operation $dd \times n \times (R + 1) = 250 \times 48 \times 13 = 156{,}000$ times, where $R = 12$ is the number of investi-

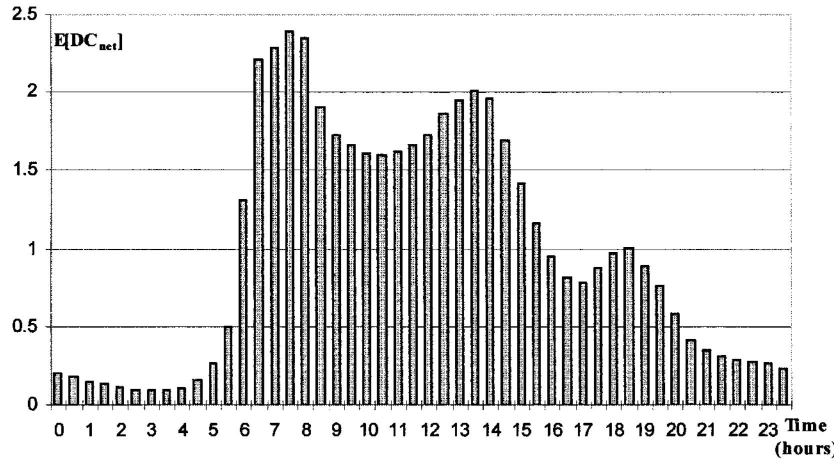

FIG. 4. Daily Evolution of Mean Coefficient of Overall Demand $E[DC_{net}]$ of 40,000 Users

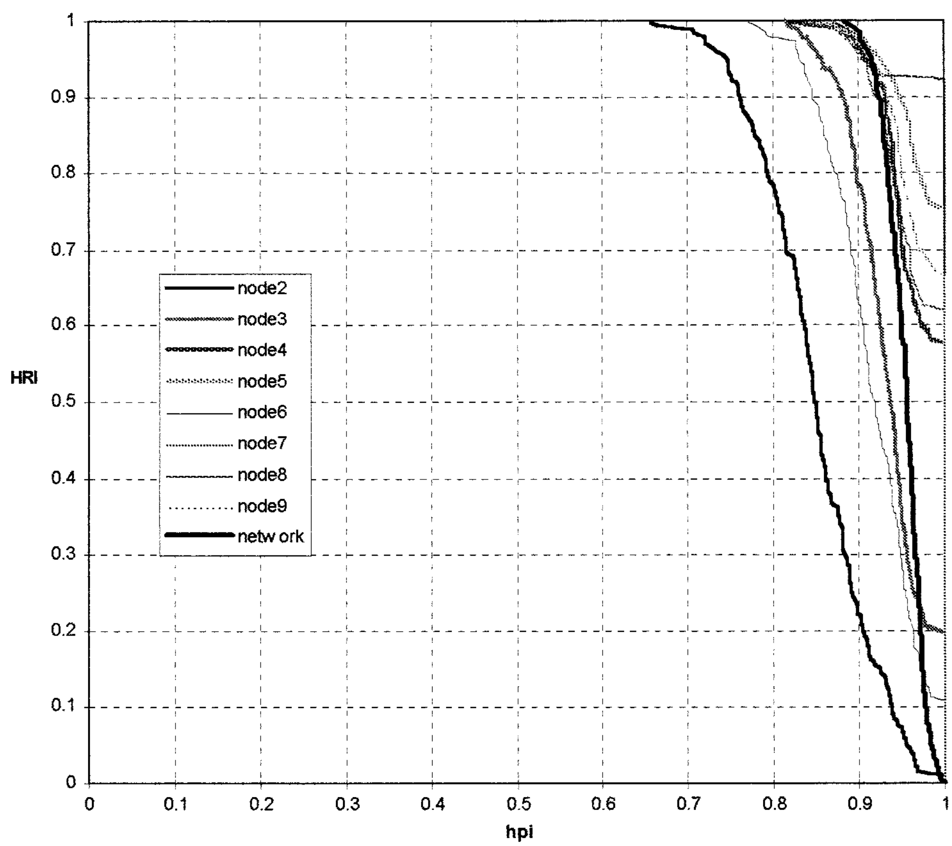

FIG. 5. Network and Nodal Reliability Functions for Fully Operational Network

gated conditions in addition to that of perfect functioning conditions.

The HRI's values were then identified for each of the 13 most probable operating conditions on the basis of (4). In particular, (4) was first applied after arranging the values of the HRIs deduced for each day in increasing order, and then estimating the $\hat{F}_{HRI}(hpi)$ values corresponding to it by means of the equation $\hat{F}_{HRI}(hpi) = (r - 0.5)/dd$, where r is the number of values for which HPI is not greater than *hpi*.

Fig. 5 shows the HRIs for the whole system and the individual nodes of a WDS with all of its various components fully operational. Figs. 6(a and b) show examples of the nodal HRIs for the failure only in pipe 1 or pipe 4, respectively.

The local and global reliability indices (HRI_j and HRI_{net}, respectively) were estimated for the different operating conditions, imposing in (4) a threshold value $hpi^*_{net} = 0.95$ for the whole system and $hpi^*_j = 0.90$ for the single node. The reliability indices thus calculated are shown in Table 3. In particular, the second column shows the HRI values for the case of a WDS with all components fully operational (Case 0). The third, fourth, fifth, and subsequent columns report HRI values calculated for an operating condition in which only pipe 1 (Case 1), only pipe 2 (Case 2), only pipe 3 (Case 3) is interrupted, and so forth. Predictably, given the positions that pipes 1 and 4 occupy in the network, the reliability of the WDS falls significantly when there is a failure in link 1, whereas there is only a slight drop when there is a failure in link 4. Furthermore, the HRIs of Table 3 show that the failure of a component can increase the reliability in some nodes compared to the case of WDS with all components fully operational (e.g., case 2 for node 2, case 3 for node 2, . . .). The component failure imposes a different distribution of pipe flows, with different energy losses for each network links. Thus, the new paths of flow can cause higher piezometric heads in some nodes.

Finally, Table 4 shows the values assumed by the ORIs in the nodes for the whole WDS calculated using (10) and (12), respectively.

A comparison between the system's ORI (Table 4) calculated using (10) and (12) and its hydraulic reliability $HRI^{(0)}$ with its various components fully operational (Table 3, column 2) is extremely interesting. Note that the WDS suffers a considerable loss in reliability when a link breaks, particularly when failures occur in links 1 and 9 (Table 3, columns 3 and 11). However, the relatively small deviations between the values of $HRI^{(0)}$ and those of ORI point out that for relatively small WDSs, mechanical reliability plays an almost negligible role in the system's overall reliability. Therefore, to evaluate the overall reliability of a WDS, the possibility of taking into consideration its hydraulic reliability alone or, at most, the failure of just one component at a time should be considered first.

The incidence of mechanical reliability might turn out to be important only in very specific geotechnical and weather conditions [such as those reported by Goutler and Kazemi (1989)] where much higher failure rates than those considered in the present paper might arise.

In such cases, it would be possible to introduce into (9)–(12) not only the probabilistic weight regarding the times in which electromechanical components are operating normally or are removed from service, but also a penalization function. This penalization function could better measure the inconven-

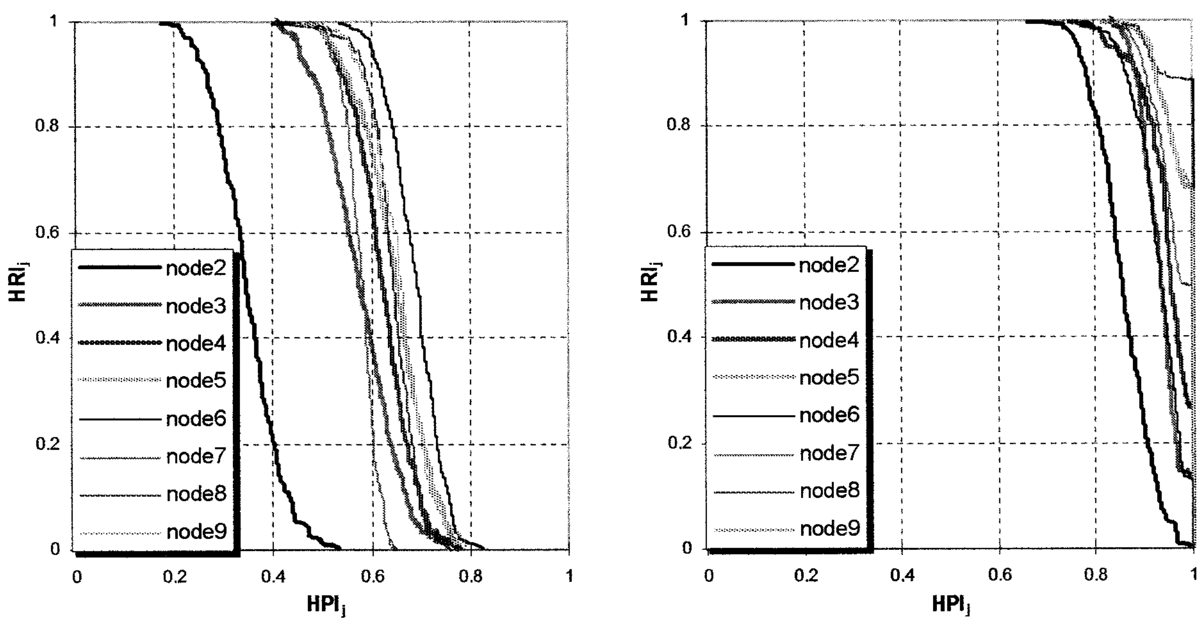

FIG. 6. Reliability Function for (a) Case 1; (b) Case 4

TABLE 3. Values of Nodal and Network Reliability Indices (HRI) for Different WDS Operating Conditions

Index (1)	Case 0 (2)	Case 1 (3)	Case 2 (4)	Case 3 (5)	Case 4 (6)	Case 5 (7)	Case 6 (8)	Case 7 (9)	Case 8 (10)	Case 9 (11)	Case 10 (12)	Case 11 (13)	Case 12 (14)
HRI_2	0.2180	0	0.9740	0.4620	0.2260	0.0060	0	0	0.2060	0	0.1940	0.6100	0.3420
HRI_3	0.7820	0	0	0.8980	0.7940	0.4100	0	0.4060	0.7900	0	0.7780	0.9500	0.8420
HRI_4	0.9620	0	0	0	0.8700	0.7980	0.1260	0.9180	0.9220	0	0.9500	0.9300	0.9340
HRI_5	0.9740	0	0	0.9060	0.9620	0.6340	0.0020	0.8940	0.9540	0	0.9700	0.7300	0.5540
HRI_6	0.6260	0	0	0.3900	0.7740	0.9620	0	0.5380	0.6620	0	0.6140	0.0820	0.1100
HRI_7	0.9540	0	0	0.8860	0.9060	0.9580	0.9900	0.9820	0.9380	0	0.8340	0.7580	0.8580
HRI_8	0.9660	0	0.2740	0.9380	0.9580	0.9620	0.9580	0	0.9580	0	0.9780	0.9540	0.9420
HRI_9	0.9700	0	0	0.9620	0.9700	0.7780	0.0820	0.7980	0.9340	0	0.9740	0.5580	0.9900
HRI_{net}	0.5980	0	0	0.0460	0.5300	0.1020	0	0	0.3000	0	0.4620	0.1780	0.1620

TABLE 4. Values of Nodal and Network ORI

ORI (1)	Value (2)
ORI_2	0.2180
ORI_3	0.7816
ORI_4	0.9615
ORI_5	0.9734
ORI_6	0.6258
ORI_7	0.9536
ORI_8	0.9656
ORI_9	0.9695
ORI_{net}	0.5973

ience to the users during periods of failure, particularly if these tend to last for some time.

The real possibility of applying the proposed procedure to existing or new systems is confirmed by the relatively short processing times for the network considered in this case (approximately 5 days processing on a personal computer based on a PENTIUM 133-MHz processor and using a nonoptimized advanced Basic software program). Although the reliability analysis of larger networks would require longer computing times, this task can obviously be enhanced through the use of more advanced computers and the implementation of optimized computer algorithms written in intrinsically faster languages, such as FORTRAN or C.

CONCLUSIONS

The design of new water distribution networks and the planning of repairs on existing systems must take into consideration the random nature and the spatial-temporal variability of a number of factors that determine system reliability; e.g., user demand, mechanical failures, roughness indices, etc. The paper has proposed a seven-stage methodology that can identify the overall reliability of a WDS. In this methodology, overall reliability is defined as the weighted probability that the network will be able to satisfy user demand when it is fully operational and when it is only partially operational as a result of a failure in one or more system components (pipes, pumps, valves, etc.). Although not shown in the case study presented here, the water level oscillation in the tanks and pump operating state can be considered in this methodology.

The application of this methodology in a specific case study and the ensuing discussion has shown that the poor mechanical performance of one or more network pipes normally has a small influence on the overall system reliability.

Although the number of processing operations increases considerably as the number of the system's electromechanical components increases, the use of optimized algorithms, along with intrinsically faster programming languages and more powerful PCs, now allow an engineer to analyze even complex systems in only a few days using the proposed methodology.

In spite of recent developments in this field of research, serious difficulties are still encountered in setting up demand models capable of taking into consideration the stochastic variability of water demand and its spatial variability. In connection with this, note that the demand model used in the present paper is not intended as a proposed solution to this problem, per se, but rather aims merely to provide a realistic trend.

Finally, despite the above limitations and in view of the computing potential now available in the technical field, the proposed methodology appears to provide a sufficiently objective and exhaustive tool for assessing the reliability of a WDS.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A_i = availability of ith component;
A_{tot} = total availability (probability that all components are efficient);
b_D = pipe failure rate;
COV[*] = coefficient of variation of variable *;
D = pipe diameter;
DC_j^*, DC_{net}^* = peak demand coefficient for node j and for whole network, respectively;
$DC_{k,j}$ = demand coefficient in node j during kth time interval;
dd = number of days assumed to perform simulation concerning full operation days;
$E[*]$ = μ_* = mean of variable *;
F = $F_*(*)$ = value of cumulative distribution function relative to variable *;
g = all possible working conditions of a WDS (or at least those more likely);
$H_{k,j}^d$ = piezometric head in node j during kth Δt on day d;
$\overline{H}_j$ = minimum piezometric head needed to fully satisfy demand at node j;
$\underline{H}_j$ = minimum piezometric head below which no water is delivered at node j;
HPI_j^d, HPI_{net}^d = HPI for node j and day d, and for whole WDS and day d, respectively;
hpi^* = threshold value of HPI;
hpi_j^*, hpi_{net}^* = threshold value of HPI of node j and of whole network, respectively;
$\mathrm{HRI}_j^{(i)}$, $\mathrm{HRI}_{net}^{(i)}$ = HRI with failure in pipe i for node j and for whole WDS, respectively;
$\mathrm{HRI}_j^{(0)}$, $\mathrm{HRI}_{net}^{(0)}$ = HRI with fully operational network for node j and for whole WDS, respectively;
L = pipe length;
N = total number of demand nodes;
n = total number of time intervals into which day is to be subdivided;
ORI_j, ORI_{net} = ORI for node j and for whole WDS, respectively;
P_j = number of equivalent users supplied by node j;
$P_{\mathrm{reference}}$ = 5,000 equivalent users;
$Q_{k,j}^d$, $Q_{k,j}^s$ = flow rate demand and discharge actually supplied in node j during kth Δt on day d;
$\hat{Q}_j$ = mean daily flow rate required by users served by node j;
R = total number of electric-mechanical components taken into account;
r = number of values for which HPI is not greater than hpi;
U_i = unavailability of ith component;
u_F = standard normal random deviate;
u_i, u_{il}, u_{ilm}, . . . = weighting coefficients;
$V_{k,j}$ = volume of water required by users of node j in kth time interval;
var[*] = variance of variable *;
$\alpha_{k,j}^d$ = piezometric head availability coefficient for node j in kth time interval on day d;
Δ = contribution to the reliability assessment of the operating conditions of WDS with a failure in more than one link;
Δt = $24/n$ = time interval for which flow value is considered to be constant;
σ_* = standard deviation of variable *; and
$(*)_F$ = variable * corresponding to preassigned value of cumulative distribution function.