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**A** – study design
**B** – data collection
**C** – statistical analysis
**D** – data interpretation
**E** – manuscript preparation
**F** – literature search

# Reliability based rehabilitation of water distribution networks by means of Bayesian networks

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**Abstract**

Water plays an essential role in the everyday lives of the people. To supply subscribers with good quality of water and to ensure continuity of service, the operators use water distribution networks (WDN). The main elements of water distribution network (WDN) are: pipes and valves. The work developed in this paper focuses on a water distribution network rehabilitation in the short and long term. Priorities for rehabilitation actions were defined and the information system consolidated, as well as decision-making. The reliability data were conjugated in decision making tools on water distribution network rehabilitation in a forecasting context. As the pipes are static elements and the valves are dynamic elements, a Bayesian network (static-dynamic) has been developed, which can help to predict the failure scenario regarding water distribution. A relationship between reliability and prioritization of rehabilitation actions has been investigated. Modelling based on a Static Bayesian Network (SBN) is implemented to analyse qualitatively and quantitatively the availability of water in the different segments of the network. Dynamic Bayesian networks (DBN) are then used to assess the valves reliability as function of time, which allows management of water distribution based on water availability assessment in different segments. Before finishing the paper by giving some conclusions, a case study of a network supplying a city was presented. The results show the importance and effectiveness of the proposed Bayesian approach in the anticipatory management and for prioritizing rehabilitation of water distribution networks.

**Key words:** *dynamic Bayesian networks, predicting reliability, rehabilitation, static Bayesian networks, water distribution network*

## INTRODUCTION

A water distribution networks (WDN) operates as a system of dependent components (valve, pipe, individual and collective water connection) constructed of polyethylene or other equivalent material. The hydraulics of each component is relatively straightforward; however, these components depend directly upon each other and as a result affect each other's performance. The purpose of the Bayesian analysis is to determine how the systems perform under various demands and operating conditions.

The presented study gives a contribution to WDN management by prioritizing rehabilitation on the basis of assessing the reliability of their components (pipes and valves). The availability of water in the WDN depends on the availability of the pumping system, water quality, the mechanical behaviour of network components, and hydraulic parameters. All these parameters contribute to the assessment and the reliability analysis of WDN. OSTFELD [2004] defined the reliability on the basis of the water quality by the fraction of the delivered quality. KANSAL and ARORA [2004] defined the reliability on the basis of the water quality by the proportion of time in which the network was able to provide the desired water quality. The above two parameters are based on the proportion of time during which the network provided high-quality of water. KANSAL and ARORA [2004] proposed a widely accepted methodology for analyzing the reliability of WDN based on the water quality assessment using two parameters: the reliability of hydraulic system and the quality of water. These reliability parameters: hydraulic and water quality described as well the reliability of WDN. The major disadvantage in obtaining these parameters is highly related on the mathematical modelling methodology [GUPTA *et al.* 2012]. Quantitatively, the reliability of a water distribution system can be defined as the complement of the probability that the system fails, a failure is defined as the inability of the system to provide consumers with a drinking water (quality and continuity of service). Two types of events can cause the failure of a water distribution system: the failure of the system components (eg. tubes and/or hydraulic control elements) and/or demand (transportation of the desired quantities of water to the desired pressure at desired appropriate locations and at desired appropriate times). These definitions show that the reliability of WDN can be classified into two main categories: topological and hydraulic reliability [GHEISI *et al.* 2016; OSTFELD 2001].

In the following, we focus on the topological reliability and specifically the mechanical reliability of the components of the WDN, the failure of one of these elements can leave a fraction of the WDN out of service and consequently interrupting the water supply of a population. KARAMOUZ *et al.* [2016] carried out a study in which, the efficiency of the WDN is quantified using a reliability-based indicator and costs and benefits of its performance are also evaluated. Based on the estimated reliability of the WDN and its calculated revenue, the actual remaining operation period of infrastructure is determined. Several authors have based their studies in the field of WDN on the reliability assessment by artificial intelligence methods either in the design phase [BOZORG-HADDAD *et al.* 2017] or the operation phase [KANAKOUDIS, TSITSIFLI 2011].

For water distribution network rehabilitation, TSCHEIKNER-GRATL *et al.* [2016] presented a methodology for the enhancement of the available data of water supply networks and the prognosis of the necessary rehabilitation rates under limited data availability. A key point in rehabilitation planning is data collection and data reconstruction. In this paper, a relationship between reliability and prioritization of rehabilitation actions will be implemented. The methodology presented is based on the assessment of the water availability in the WDN on the basis of the reliability modelling of pipe and valves by using Bayesian network (BN).

## MATERIALS AND METHODS

In causal reasoning each adverse event is related to one or more causes, so in the operation of WDN each failure scenario has a cause and effect structure. For example an interruption in water supply is a direct consequence of water leak, or maintenance work on the water distribution system. In this example, each cause has an individual probability of occurrence, which affects our beliefs and changes the probability of the final consequence. In addition, the causes have a probability of occurrence defined a priori by measurement, or following investigations (expert opinion). The causes and consequences are uncertain or "stochastic" variables. They are discrete but there are belief scenarios where analysis involving continuous variables. In situations of uncertainty where expert knowledge and measurement data is incomplete, the use of posterior observations by a Bayesian approach reduces and eliminates this uncertainty.

Bayesian networks combine two different mathematical theories: graph theory and probability theory. A priori information, the likelihood and a posteriori information are represented by probability distributions. A priori probability represents the probability distribution of knowledge on a variable before that the parameter it represents is observed. The likelihood is a function of parameters of a statistical model reflecting the possibility of observing a variable if these parameters has a value. A posteriori probability is the conditional probability of the data collected by combination of prior probability and likelihood via Bayes' theorem [SCUTARI, DENIS 2014].

In a BN, dependence and causality is represented by edges. An edge between two variables implies a direct dependence between these two variables: one is called the parent, and the other named child. In a Bayesian model, the behaviour of the child variable should be given in view of the behaviour of its parent or parents (if there are several). To do this, each node in the network has a conditional probability table (CPT). A CPT associated with a node allows quantifying the effect of the parent node on that node: it describes the probabilities associated with child nodes according to the different values of the parent nodes. For root nodes (without parents), the probability is unconditional and called "a priori" probability. The BN prohibit child dependencies to parents. Thus, the set of variables and edges will form a directed (edges have a sense) and acyclic graph (no cycle in the graph). Therefore, a BN (Fig. 1) is defined by a directed acyclic graph (DAG) as [NAIM *et al.* 2004]:

$$P(V_1, V_2, ..., ..., V_n) = \prod_{i=1}^{n} P(V_i / C(V_i)) \quad (1)$$

where: $C(V_i)$ = the set of parents (or causes) of $V_i$ in DAG, $V_1$, $V_2$, $V_n$, = child events, $P$ = probability.

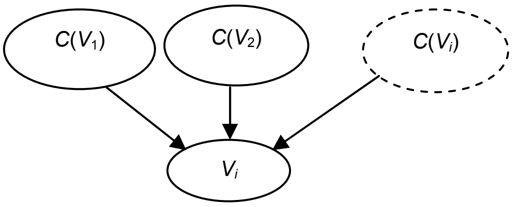



Fig. 1. Bayesian network; source: own elaboration

## BAYESIAN APPROACHES FOR PREDICTING RELIABILITY OF WATER DISTRIBUTION NETWORK

In order to predict the reliability of the water distribution network, one might have to establish a Bayesian model (static and dynamic) that represents the system's performance as a response function of some faults taken as input variables (breaks or leaks of pipe, valve won't open). Having done that, rehabilitation of water distribution network could be accomplished by intervening on some network segments, which change some of the input variables in the Bayesian model. For example, when considering the continuity of water supply, as we have do in this paper, the controllable variables can be the number of faulty valves, the number of water pipe breaks in the distribution network during the year, the preventive maintenance policy and the amount of water lost on each section. However, once the model is built, it's fundamentally easy to update the parameters of the Bayesian model, and consequently the calculation of the prediction values by a simple inference in the Bayesian network. Similarly when new information is available on the individual failure rate, the results will be updated by inference without increasing the calculation time.

## CONSTRUCTION OF STATIC BAYESIAN NETWORK

A Bayesian model can be constructed from peer-reviewed technical literature, census data, and fault statistics reports. When required probability data were unavailable or the sample size was too small, an expert in maintenance engineering can provide subjective estimates of the probabilities. Modelling with BN is similar to that of the fault tree but with more flexibility and advantages. The fault tree is a systematic and comprehensive approach to determine the sequence and combinations of events that could lead to a top event taken as a reference (Fig. 2a). In a BN, the connections between events will be represented by edges that reflect the dependence between these events, and cause-effect relationship. The different types of events will be represented by nodes on the basis that basic events will be the input nodes for the model (Fig. 2b). By implementing this logic in the idea outlined in this paper, the availability of water in a section depends on the reliability of the pipe and that of the valve. A BN models the events with the nodes, while the distinction between the various logic

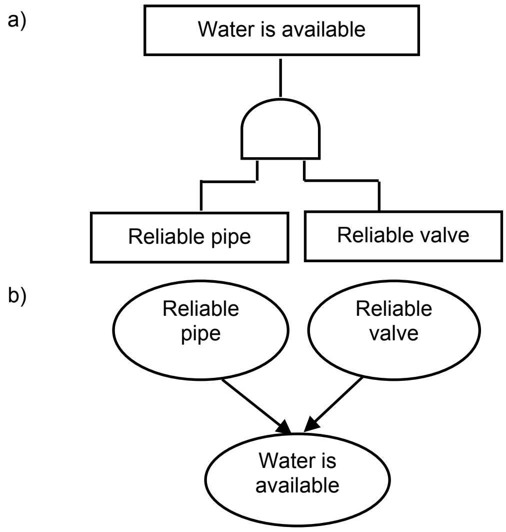



Fig. 2. Mapping of fault tree into basic static Bayesian network; a) "And" logic gate, b) corresponding Bayesian network; source: own elaboration

gates of a fault tree is made by adjusting the CPT [KHAKZAD *et al.* 2011].

## TOPOLOGICAL OF DYNAMIC BAYESIAN NETWORK

In Bayesian modelling, many cases exist where the variables are dynamic and reasoning in time is necessary. Dynamic Bayesian Networks (DBNs) are graphical models allowing to compactly representing the inherent uncertainties in dynamic systems evolving over time. The BNs and DBNs have given a strong contribution in the studies of analysis and assessment of the reliability. As two illustrative examples: BOUDALI and DUGAN [2005] have modelled a reliability of a complex system using BNs, and WEBER and JOUFFE [2006] who have also modelled reliability with dynamic Bayesian networks.

In this study, DBNs are used for assessing the reliability of the valves and therefore predicting the different supply situations of the various sections. In order to master the water supply, it is necessary to control and monitor over time the evolution of variables (water availability)$_t$ for each segment of the WDN. To achieve this objective the idea is to infer, what is the possibility for example that water is available in a WDN fraction based on opening sequences of the valve. In this case the random hidden variable is "water availability" with two state "true" and "false", and the observed variable is "the status of the valve$_t$" and the satisfaction of these suppositions is modelled by the dependencies between all variables in the model that is given by the BDN in Figure 3.

In Figure 3, the fact indicate an edge between the two variables "water availability$_t$" and "the status of the valve$_t$", this means that the availability of water depends on the status and reliability of the valve at time *t* and similarly, the reliability of the valve at time *t* depends on its reliability at time *t*–1. From this DBN

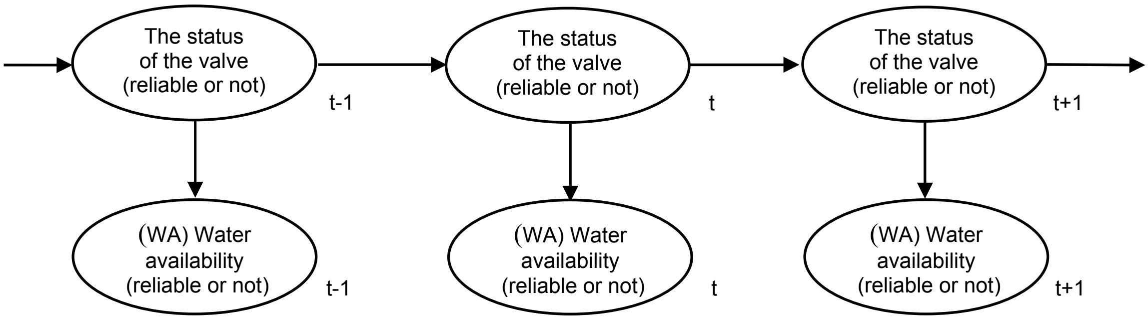



Fig. 3. Dynamic Bayesian network for predicting water availability; source: own elaboration

it is possible to calculate the most recent a posteriori distribution of the variable "water availability$_t$" by filtering, also it is possible to calculate the a posteriori probability of the variable "water availability$_{t+n}$" in a future time, where $n$ the number of time steps, such as:

$$P(V_t / V_{t-1}) = \prod_{i=1}^{N} P(V_{i,t} / C(V_i)_{i,t}) \tag{2}$$

**MODELLING ISSUES**

The modelling of the failure rate (breaks or leaks) by segment requires a significant history of maintenance and failure/repair data. Alternatively, the approach of the entire WDN is insufficient because it does not allow to plan and implement short-term actions. However, the design of reliable models must be adapted with the available data and analysis must be done on a scale segments according to several criteria: material, diameter, when it was laid, flow, pressure, and road. In the case where historical failure data indicate a deteriorating network, a classical reliability assessment of the network can be done using Poisson process for modelling the pipe failures. In this case, the reliability measure is based on individual pipe failure probabilities. Here, the probability of failure of an individual pipe is given by:

$$P = 1 - e^{-\lambda t} \tag{3}$$

where: $P$ = probability of failure, $\lambda$ = failure rate, $t$ = time.

An estimation of $\lambda(t)$ by time slice is determined by the following calculation:

$$\lambda(t_i) = \frac{n_i}{N_i \Delta t_i} \tag{4}$$

where: $n_i$ = the number of failed during $\Delta t_i$, $N_i$ = the number of survivors at the beginning of the slice $t_i$, $\Delta t_i = t_{i+1} - t_i$ = the observed time interval.

By applying the formula (4) to the WDN $\lambda(t)$ is given by:

$$\lambda(t_i) = \frac{\sum_i n_i}{\sum_i \left(\frac{L_i}{100} \Delta t_i\right)} \tag{5}$$

where: $\lambda(t_i)$ = number of failures per 100 m per year, $n_i$ = the number of observed failures on segment $i$, $L_i$ = length corresponds to each segment $i$ (m), $\Delta t_i$ = the observation period for each segment $i$ (year).

The proposed Bayesian approach gives the probability of failure of an individual pipe from the equation (1). For a leak on the pipeline ($LP$), the reliability decreases ($RP$), provided that $P$ (reliability of pipe) ≠ 0:

$$P(LP / RP) = \frac{P(RP / LP) P(LP)}{P(RP)} \tag{6}$$

Bayes' theorem can reverse the probabilities. That is to say, if we know the reliability of the pipe as a consequence of leaking pipe, observing the effects allows estimating the probability of failure.

$$P(RP / LP) = \frac{P(LP / RP) P(RP)}{P(LP)} \tag{7}$$

In the construction step of the model, a priori probabilities definition is not easy. The information provided by the experts and the feedback are two key elements in this step. Also, it requires special attention because the results obviously depend on the available data and on some hypothetical models.

A valve is defined as a dynamic mechanical device by which the flow of fluid may be started, stopped, or regulated by a movable part that opens or obstructs passage. The mission of isolation valves is to isolate a portion of the WDN whenever WDN repair, inspection, or maintenance is required at that segment; in the following we are interested in the isolation valves. The reliability of valves themselves has not been implicitly or explicitly incorporated in reliability assessments to date. Perhaps the main reason for this is that the human factor is the most important factor in determining their reliability. The more frequent the valve exercising programs, the greater the chance that they will operate when needed.

The water availability is governed by the opening of the valve. If the valve does not open after a closure (following maintenance work, for example), there will not be supply for this product. Equation (2) gives figures on the reliability of the valve as a function of the failure (valve won't open).

$$P(RV_t / RV_{t-1}) = \prod_{i=1}^{N} P(RV_{i,t} / VWO_{i,t}) \tag{8}$$

where: $RV_t$ = reliability of the valve at time $t$, $VWO$ = valve won't open, $N$ = number of time steps.

## AN EXAMPLE OF HOW TO MODEL THE RELIABILITY PREDICTION

In the design of WDNs, two architectures can be used.

- Network in a radial arrangement for which the network segment is controlled by one valve, so the availability of water in the framework of this study is mainly dependent on the reliability of the pipe and of the valve (Fig. 4a).
- The meshed network for which the water availability depends essentially on the reliability of piping and block valves (in the example of Figure 4b there are two valves).

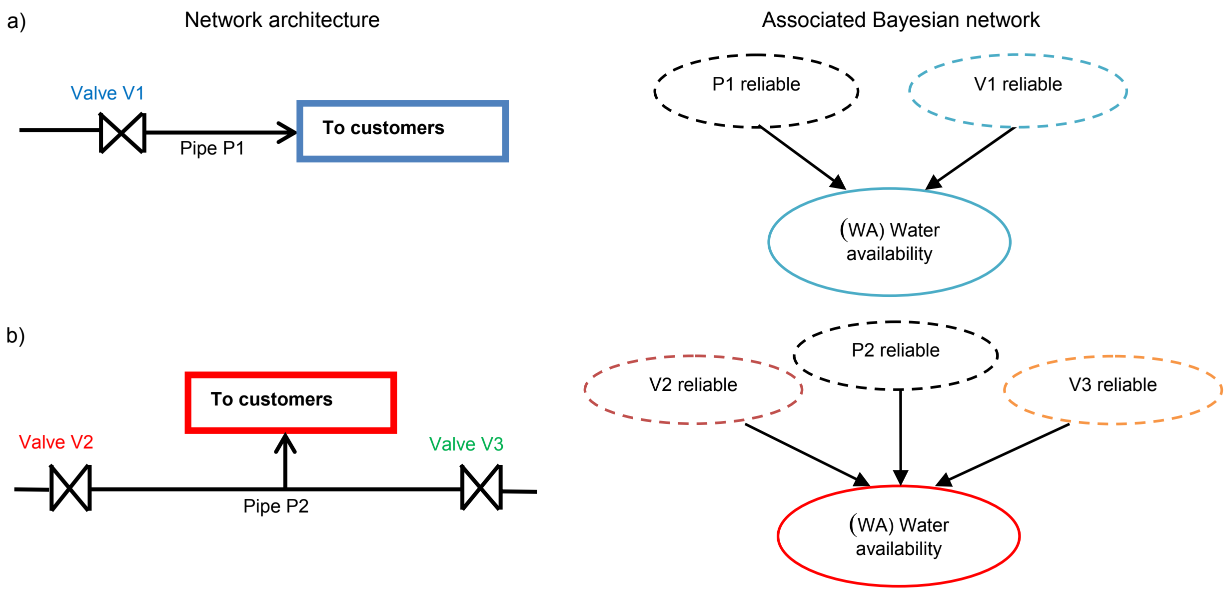



Fig. 4. Bayesian network structures for radial and meshed architectures; a) radial network, b) mesh network; source: own study

The failure rate $\lambda$ represents the probability of having failure in the time intervals constituting the life cycle of the studied WDN. To estimate this failure rate, the historical files and the formula (5) have been used. Table 1 gives the failure rates for pipes P1 and P2 (breaks/leaks pipe), and the valves V1, V2, and V3 (valve won't open).

**Table 1.** A priori probabilities

| Element | Failure | State | Probability |
|---|---|---|---|
| P1 | breaking / leaking pipe (LP1) | true (T) | $\lambda = 0.136$ |
| P2 | breaking / leaking pipe (LP2) | true (T) | $\lambda = 0.213$ |
| V1 | valve won't open (VWO1) | true (T) | $\lambda = 0.057$ |
| V2 | valve won't open (VWO2) | true (T) | $\lambda = 0.026$ |
| V3 | valve won't open (VWO3) | true (T) | $\lambda = 0.033$ |

Source: own study.

DBN encodes the joint probability distribution of a time-evolving set of variables $V(t) = \{V1(t), \ldots, Vi(t)\}$. If $t$ time slices (time step) of variables is considered, the DBN can be considered as a "static" BN with $T \times i$ variables. From equation (8) the temporal probability distributions of the three valves V1, V2, and V3, which have a dynamic behaviour, are shown in Figure 5.

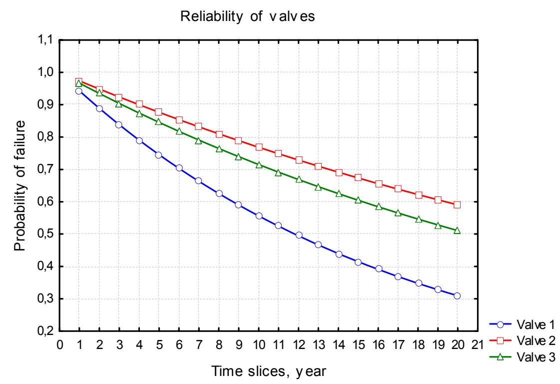



Fig. 5. Temporal probability distributions of the three valves V1, V2, and V3; source: own study

## EXAMPLE I: CASE OF RADIAL NETWORK

The probability of supplying (water availability WA) the subscribers connected to the network of Figure 4a is calculated as follows:

P (WA = T) = P (WA = T / LP1 = T, VWO1 = T) × P (LP1 = T) × P (VWO1 = T) +
P (WA = T / LP1=T, VWO1 = F) × P (LP1 = T) × P (VWO1 = F) +
P (WA = T / LP1 = F, VWO1 = T) × P (LP1 = F) × P (VWO1 = T) +
P (WA = T / LP1 = F, VWO1 = F) × P (LP1 = F) × P (VWO1 = F)

Explanations: T = true, F = false.

Using the data collected in the Table 1 we find:

$$\begin{aligned} P\,(WA = \underline{T}) = {} & 0 \cdot 0.136 \cdot 0.057 + \\ & 0 \cdot 0.136 \cdot 0.943 + \\ & 0 \cdot 0.864 \cdot 0.057 + \\ & 1 \cdot 0.864 \cdot 0.943 \end{aligned}$$

$$P\,(WA = \underline{T}) = 0.814$$

Table 2 gives the conditional probability tables for the radial network architecture.

**Table 2.** CPT for radial network

| Parent variables | VWO1 | T | | F | |
|---|---|---|---|---|---|
| | LP1 | T | F | T | F |
| Water availability (WA) | True (T) | 0 | 0 | 0 | 1 |
| | False (F) | 1 | 1 | 1 | 0 |

Source: own study.

The interpretation of CPTs is as follows: if the valve does not open, water is not available, and also if the pipe is faulty, water is unavailable. One of these two conditions implies that water is not available (OR gat in Fault tree analysis).

Applying formula (2) and on the basis of CPT shown in Table 2, the water availability probabilities as a function of time are obtained. The results are shown in Figure 6. They depend on the reliability data of the valves V1 and the segment of the network P1.

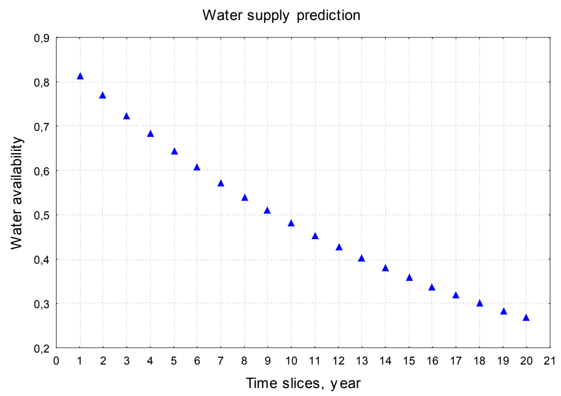



Fig. 6. Water availability as a function of time for radial network; source: own study

**EXAMPLE II: CASE OF MESH NETWORK**

The probability of supplying (water availability WA) the subscribers connected to the network of Figure 4b is calculated in the same way as previously (section 4.1). Table 3 gives the conditional probability tables for the mesh network architecture.

**Table 3.** CPT For Mesh network

| Parent variables | VWO2 | T | | | | F | | | |
|---|---|---|---|---|---|---|---|---|---|
| | VWO3 | T | | F | | T | | F | |
| | LP2 | T | F | T | F | T | F | T | F |
| Water availability (WA) | True (T) | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |
| | False (F) | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |

Source: own study.

For the mesh architecture, water is available, if at least one of the valves opens and pipe is not breaking /leaking (reliable pipe). In this context, by applying formula (2) and on the basis of CPT shown in Tables 3, the water availability probabilities as a function of time are obtained. The results are shown in Figure 7. They depend on the reliability data of the valves V2 and V3, and the segment of the network P2.

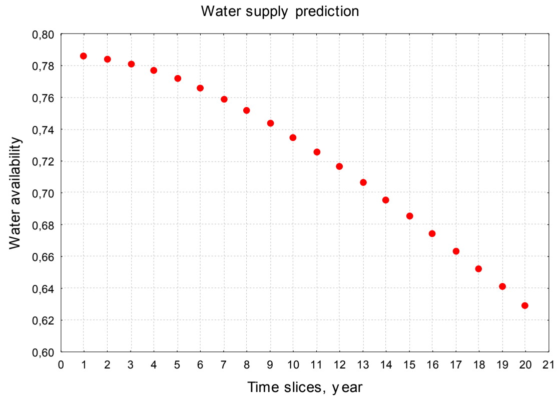



Fig. 7. Water availability as a fonction of time for meshed network; source: own study

**SOME INTERPRETATIONS**

From the results shown in Figures 6 and 7, it is remarkable that despite that there are two water intakes for meshed architecture, but the probability that the mesh network is supplied is 78.63% for the first year. Lower value than that of the radial network (81.74%). This is due mainly to the failure rate $\lambda$(P2) which is higher than $\lambda$(P1). After 10 years of service, the supply from the radial network is found with a probability of 48.04%, low value. After the same period the subscribers connected to the mesh network will have a water supply probability equal to 73.50%, higher value compared with that of the network in a radial arrangement. Now, after 20 years the radial network is at the end of service life, on the other hand, the mesh network is still profitable (a water supply probability greater than 62%).

From these results it is also possible to define a plan of action for the rehabilitation of WDN. For example, if we fix a probability of 60% as the threshold value on the probability of water supply for the rehabilitation of the WDN, it is necessary to provide the rehabilitation for the radial network from the seventh year, whereas for the mesh network rehabilitation is not needed for the 20 years.

## ANALYSIS AND RESULTS

The study area is located in the Azzaba city in the North-East of Algeria, between 36°44' 05.84" to 36°45'10.17" N and 7°05'58.90" to 7°07'42.16" E (Fig. 8). It represents the North-Eastern part of the department of Skikda and is bounded on the North--East by the municipality of Aïn Charchar, on the North-West by the municipality of Ramdane Djamel, on the South-West by the municipality of Essebt, and on the South-East by the municipality of Bekkouche Lakhdar. The water distribution network of the study area (Fig. 9) is inter-connected with branched extensions and serves about 7 000 subscribers. The main network length (main pipes) is nearly 10 km with the pipe diameter varying between 160 and 400 mm (high density polyethylene and cast iron). The water is distributed by gravity using double reservoir with capacity of (2 × 2500) $m^3$.

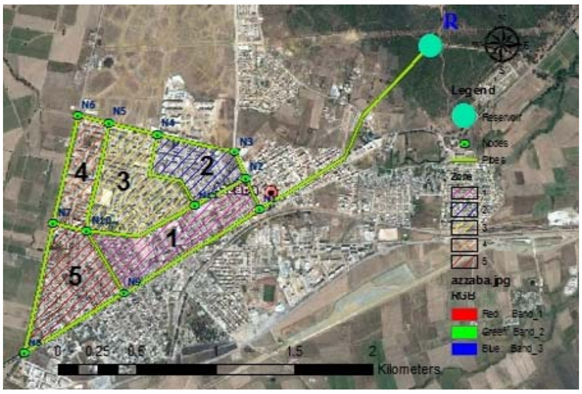



Fig. 8. Study area: 1–5 = zones; source: own elaboration

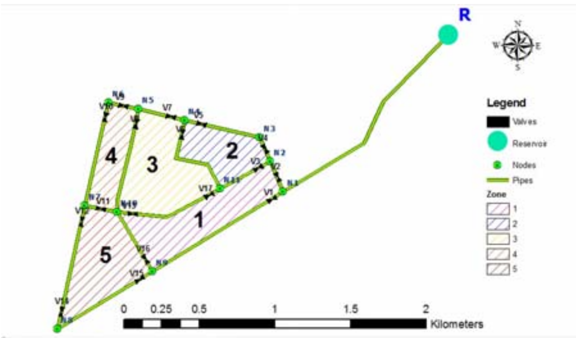



Fig. 9. The water distribution network of the study area; source: own elaboration

In the Bayesian formulations, as soon as the number of variables becomes important, computations become complicated. Similarly, calculations become more difficult to model the dynamic behaviour of valves with DBN. To relax these constraints a program was written in Matlab environment. The profitability of the network can be measured by the probability of guaranteeing water supply to subscribers. Figure 10 gives predicted results on water availability in various pipes of the network.

From Figure 10 it is possible to define priorities in terms of rehabilitation. The rehabilitation plan depends on the objectives of each operation, and especially the availability of financial resources. For example, after 10 years of service, the priorities will be as indicated in Table 4.

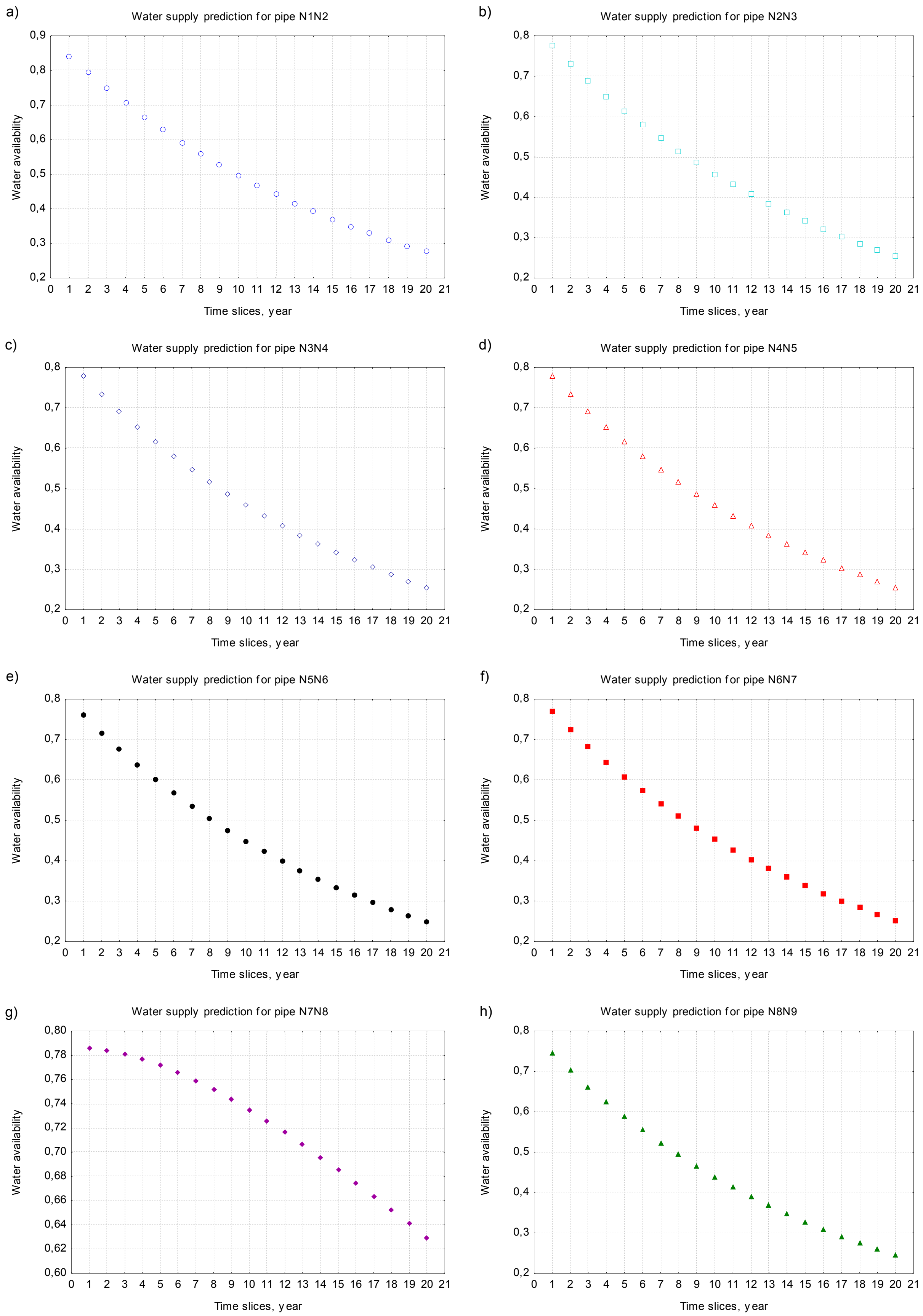
**Table 4.** Rehabilitation priorities of pipes

| Pipe | Probability | Priority |
|---|---|---|
| a. Pipe N1N2 | 0,49622419 | 10 |
| b. Pipe N2N3 | 0,45747909 | 6 |
| c. Pipe N3N4 | 0,45919678 | 8 |
| d. Pipe N4N5 | 0,45872387 | 7 |
| e. Pipe N5N6 | 0,44782391 | 4 |
| f. Pipe N6N7 | 0,45331369 | 5 |
| g. Pipe N7N8 | 0,73504176 | 11 |
| h. Pipe N8N9 | 0,43936517 | 1 |
| i. Pipe N9N10 | 0,44375640 | 3 |
| j. Pipe N9N1 | 0,44012230 | 2 |
| k. Pipe N10N11 | 0,78085682 | 12 |
| l. Pipe N11N2 | 0,46487171 | 9 |

Source: own study.

This section presents predictive results on water supply; results were based on the reliability of the pipes and valves. From the results of the developed model it is possible to easily extract information and transform them into quantitative and qualitative data. This approach allows predicting the behaviour of WDN and gives the possibility to anticipate failures of network elements. On the other hand, it is possible from our approach to simulate the maintenance actions and investment reflections. The proposed Bayesian model has a great interest compared to the Poisson model. It classifies sections with low failure rates, or who have not experienced failures (failure rate equal to 0) with similar sections.

Bayesian networks are a decision-making tool for prioritizing maintenance actions and defining rehabilitation priorities of the water distribution networks. In this context, this paper focused the study on a part of the network, if the study is generalized over the entire network with its multitude of valves; pipe and connections, the results found in our examples are used for the following situations:
– evaluation of WDN reliability;
– WDN performance and operation optimization: prioritize actions and supporting any strategic decisions;
– determination of rehabilitation priorities;
– design of a new WDN: best choice of the network design (radial or mesh network) by considering the reliability as a central element in this design in parallel with the hydraulic elements;
– modification and expansion of an existing WDN: the implantation and the management of the boundary valve in the network is essential in maintaining the integrity of the hydraulic structure;
– preparation for maintenance: optimizing the systematic and predictive maintenance;
– analysis of WDN malfunction: such as water connection breaks, leakage, valve failure.


a)
Water supply prediction for pipe N1N2
Water availability
Time slices, year
b)
Water supply prediction for pipe N2N3
Water availability
Time slices, year
c)
Water supply prediction for pipe N3N4
Water availability
Time slices, year
d)
Water supply prediction for pipe N4N5
Water availability
Time slices, year
e)
Water supply prediction for pipe N5N6
Water availability
Time slices, year
f)
Water supply prediction for pipe N6N7
Water availability
Time slices, year
g)
Water supply prediction for pipe N7N8
Water availability
Time slices, year
h)
Water supply prediction for pipe N8N9
Water availability
Time slices, year

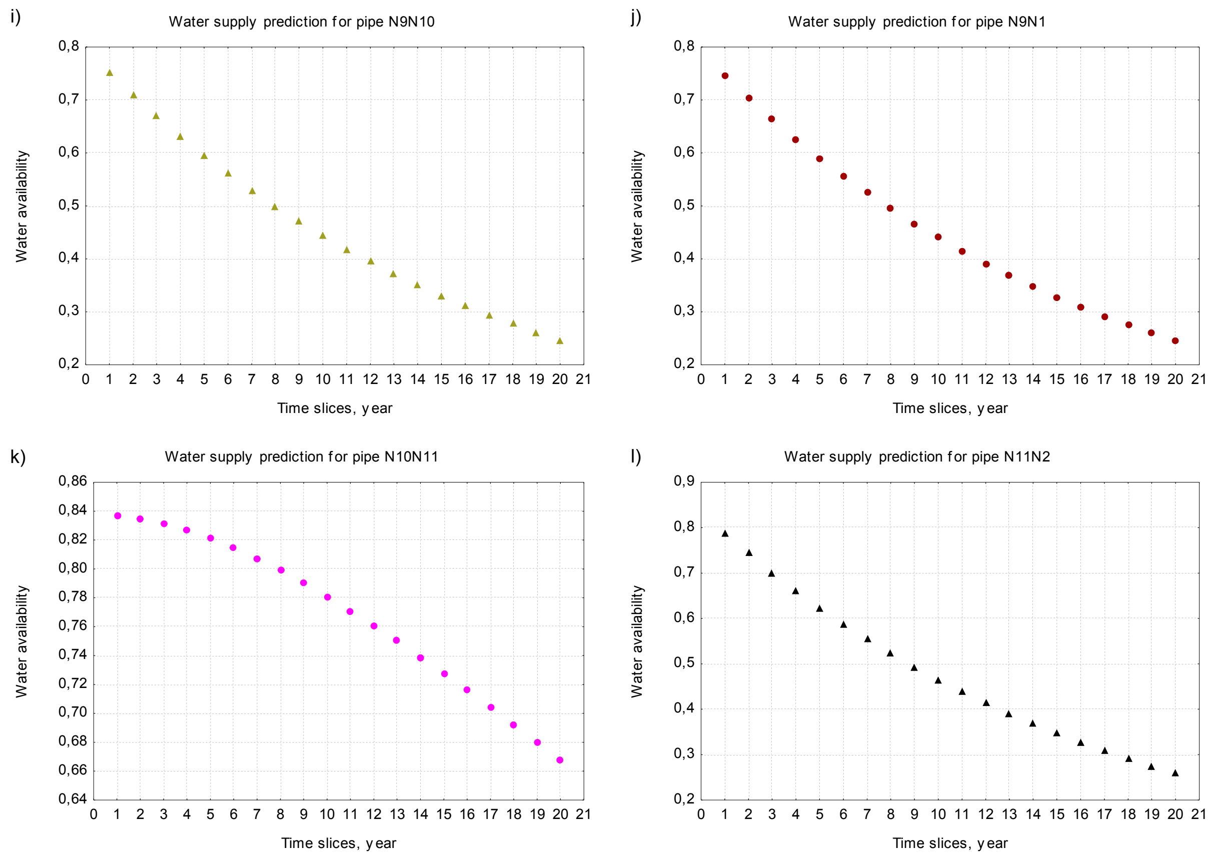



Fig. 10. Water availability as a function of time in each pipes; source: own study

## CONCLUSIONS

A rational and coherent approach to optimizing water distribution network rehabilitation consists of taking reliability data into account. Feedback data are treated as observations and used in statistical inference. The developed Bayesian model is well suited to the evaluation of water supply probabilities. The use of DBN is due to the dynamic character of flow control components which are valves. The Bayesian approach used for modelling the reliability of pipe which has experienced failures, pipes without failures, and valves, represents a new and unique tool for the three cases compared to existing models in the literature. The found results have contributed greatly to estimating in a realistic and practical estimation of foreseeable demand to improve management of the quantities of water and to improve the operational capability of operation and maintenance services. From the case study, realistic results for prioritizing rehabilitation have been defined, and a strategy for the rehabilitation can be developed. Also in the operation of WDN and in general, maintenance and investment actions must be included in the time. To do this, the DBNs are powerful simulation tools of the impact of these actions on the future management of WDN.

In our future work, we will look forward to expand the study by taking into account hydraulic reliability and reliability-based quality (the level of chlorine in the water). From this, it is possible to develop the model by adding the quality and hydraulic parameters as input variables in the model. The same goes with adding new information; add a new variable in Bayesian models is not difficult and the inference process will not take a significant time for calculating the new a posteriori probabilities.

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**Abdelaziz LAKEHAL, Fares LAOUACHERIA**

**Rzetelne odnawianie sieci wodociągowych przy użyciu sieci Bayesowskich**

STRESZCZENIE

Woda odgrywa istotną rolę w codziennym życiu ludzi. Aby zapewnić klientom stałe dostarczanie wody dobrej jakości, operatorzy wykorzystują sieci wodociągowe, ich głównymi elementami są rury i zawory. W pracy opisano odnawianie sieci wodociągowych w krótkim i długim przedziale czasowym. Zdefiniowano priorytety działań renowacyjnych i skonsolidowano system informacyjny oraz system podejmowania decyzji. Dane o wiarygodności zostały sprzężone z narzędziami podejmowania decyzji co do odnowy sieci w kontekście możliwości prognozowania. Ponieważ rury są elementem statycznym, a zawory dynamicznym, zbudowano statyczno-dynamiczną sieć Bayesowską, która pozwala przewidywać niepowodzenia w dostawie wody. Badano zależności między wiarygodnością a ustaleniem priorytetów działań renowacyjnych. Wdrożono modelowanie ilościowej i jakościowej analizy dostępności wody w różnych segmentach sieci wodociągowej oparte na statycznej sieci Bayesowskiej. Następnie użyto dynamicznych sieci Bayesowskich do oceny wiarygodności zaworów w funkcji czasu, co umożliwiło zarządzanie dystrybucją wody bazującą na ocenie jej dostępności w różnych segmentach sieci. Przed wyciągnięciem wniosków przedstawiono przykład sieci zasilającej miasto. Wyniki dowodzą znaczenia i efektywności proponowanego podejścia Bayesowskiego w planowaniu gospodarki wodnej i ustalaniu priorytetów renowacji sieci wodociągowych.

**Słowa kluczowe:** *dynamiczne sieci Bayesowskie, odnowa, sieć wodociągowa, statyczne sieci Bayesowskie, wiarygodność przewidywań*