RELIABILITY OF A WATER SUPPLY SYSTEM IN QUANTITY AND QUALITY TERMS

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ABSTRACT

This work presents an approach focused on the analysis of the Pescara city (Italy) water distribution network reliability.

Through a multicriteria analysis a list of scenario will be ranked in order to obtain the most critical pipes for the reliability of the whole system combining hydraulic and quality performances.

The simulation of the water distribution system has been done with the EPANET software developed by US EPA. The calibration has been done on the basis of experimental data collected during previous works.

The objective of the study was reached defining specific *Reliability Indicators* for both quantity and quality aspects and for combination of them.

This study will contribute to the management of water distribution system like a Decision Support System (DSS) according to the guidelines of the European Project CARE-W.

KEYWORDS
Water supply system, reliability, quality simulation, hydraulic performance, EPANET.

INTRODUCTION

In the last years, there has been considerable emphasis on the state of decay in the nation's infrastructure because of its importance to society's needs. Water distribution systems are one of the many kinds of infrastructure systems amenable to higher levels of serviceability.

The objective of any water distribution system is to make water available to the consumer in proper quantity and pressure, with acceptable quality in terms of flavour, odour, appearance and sanitary security.

A recent Italian law, the called "Legge Galli" (Law 36/94), introduces new concepts in the overall management of water services: integrated water management, optimal area, separation between (public) ownership and (private) management of water distribution networks. Major factors in the fulfillment of the law requirements are the reduction of water losses and the improvement of network reliability; the analysis of breaks in pipes of the network is an essential step towards reliability evaluation.

Because of the existence of design and operation uncertainties, water distribution systems have an associated risk or probability of failure and an associated reliability or probability of not failing. Reliability is a probabilistic phenomenon and depends on the occurrence of random pipe or pump failures. Thus, reliability of water distribution systems should be assessed with probabilistic measures.

The reliability of a component is defined as the probability that the component experiences no failures during the time interval (0, t) from time zero to time t, given that it is a new or repaired at time zero. In other words, the reliability is the probability that the time to failure T exceeds t, or:

$$R(t) = \int_{t}^{\infty} f(t)dt \qquad (1)$$

where $f(t)$ is the probability density function of the time to failure. The probability density maybe developed from equipment failure data, using various statistical methods. In many cases a simple exponential distribution is found appropriate (Mays, 1996; Bizzarri *et al.*, 2002; Ugarelli, 2002):

$$f(t) = \lambda \cdot e^{-\lambda t} \tag{2}$$

where λ is the probability that a component experience a failure per unit of time. The mean time to failure (*MTTF*) is the expected value of the time to failure, stated mathematically as:

$$MTTF = \int_{o}^{\infty} t \cdot f(t)dt \tag{3}$$

so $MTTF = \lambda^{-1}$ and it is expressed in hours.

Our proposal for this work is to present an approach focused on the analysis of the Pescara (Italy) water distribution system reliability.

Through a multicriteria analysis a list of scenario will be ranked in order to obtain the most critical pipes for the reliability of the whole system.

This study will contribute to the management of water distribution system like a DSS according to the guidelines of the European Project CARE-W (*http://care-w.unife.it*).

MODEL FORMULATION

The methodology developed aims to define the optimal network state, in terms of quality and hydraulic reliability, looking at specific boundary conditions.

The analysis of the reliability has been done combining a random generator code, in order to evaluate the probability of failure of the system components with the EPANET engine (Rossman, 1994b).

The simulation program for analyzing system reliability consists of two parts: (1) the simulation section, which generates failure events according to specified probability distributions; and (2) the hydraulic and quality network solution section, which gives the flows and Chlorine concentration throughout the network and the heads at each node for a specified demand in the completely or partially failed system. The probability distribution chosen for pipe breaks and repair times are exponential.

Hydraulic reliability

In the system nodes are targeted to receive a given supply at a given head. If this head is not attainable, supply at the node is reduced. Each node can thus be in a normal, reduced service, or failure mode. The system will be said to be in normal mode if all nodes are receiving normal supply, in failure mode if supply to any node has been shut off, and in reduced mode if some node or nodes are receiving reduced supply but no nodes are completely shut up. Pipes fail randomly, according to failure probability distributions of each component defined using literature parameters (Bizzarri *et al*., 2000).

For each different state simulated the software evaluates the objective function which consider discharge drawn and pressure at each nodes combined with the residual chlorine concentration in the water system.

Data needed for the simulation include:
- Network information: topology; length, diameter, and roughness coefficient of each pipe.
- Demands and boundary conditions: demands at nodes; given head at sources and tanks.
- Failure probability: form and parameters for failure time probability distribution of each component that is subject to failures.
- Total duration of the simulation.

Heads and flows throughout the system, with no failures, has been obtained solving the network with the EPANET engine. The simulation proceeds by randomly generating failures times of the pipes to the specified failure time distributions. When a link fails, it is removed from the system. The new heads at the demand nodes in the reduced network are determined by solving it with EPANET. It is assumed that link failures leave the demand unchanged. The new heads at the demand nodes are used to tell how the system is performing.

We have also to take into account of the following hydraulic constrain:

$$H_m \leq H \leq H_s \tag{4}$$

The vector H represents the heads at specified locations in the system, with H_m and H_s being the lower and upper bounds respectively. The system is said to be performing normally only when, for each node, all the imposed demands can be met with heads above the service limit. If, however, at some node in the reduced system, the head is below the service limit, it is assumed that at that node the system cannot supply the full demand. The actual withdrawals will be then as follows: (1) nodes with heads below the minimum head will be completely shut off; (2) nodes with heads above the minimum head but below the maximum head will be supplied at a reduced level; and (3) nodes with heads above the maximum head will be fully supplied.

Quality reliability

Preserving the water quality throughout the distribution system is, therefore, one of the most challenging technological issues for suppliers. This is not an easily attainable objective, mainly because of the distribution system's complexity and dynamism with respect to building materials, element diversity and other properties variability.

Factors that will influence water quality changes during transmission include:
- Water quality characteristics (chemical, physical, and biological)
- Pipeline characteristics (age, type, tuberculation, corrosion, deposits, etc.)
- Network system characteristics (loops, dead-ends, storage tanks, etc.)
- Network operating characteristics (water demands, velocities, etc.)
- Mixing of waters (different source waters)

When these factors are combined with the kinetics of a network system, it becomes apparent that water quality changes in a distribution system is a complex system that requires computer modeling approaches. For this system to be modeled, both hydraulic characteristics and water quality factors must be linked. The combination of a hydraulic model with a contaminant propagation model, therefore, is needed to predict the water quality changes that are going to occur in a water quality network.

Chlorine inside the system has the effect to prevent the bacterial increase.

There is, however, a problem when water distribution systems have considerable proportions. In a phenomenon known as chlorine concentration decay, chlorine residual concentration disappears along the system. The loss of chlorine residual concentration along the water distribution system is processed in three separated mechanisms (Rossman, 1994a, 1996):
- Chlorine reactions in bulk fluid;
- Chlorine reactions with pipe and other system element's walls;
- Natural evaporation.

The evaluation of the Chlorine concentration for each link connecting node i with node j is based on the mass conservation formula:

$$\frac{\partial (C_{ij})_t}{\partial t} = -\frac{(q_{ij})_t}{A_{ij}} \cdot \frac{(\partial C_{ij})}{\partial x_{ij}} + \theta (C_{ij})_t \; \forall \; n=1,...,N \; \text{e} \; t=1,...,T \tag{5}$$

where, for the link ij, $(C_{ij})_t$ is the chlorine concentration, $(q_{ij})_t$ is the flow at time t, x_{ij} is the distance along the link ij, A_{ij} is the surface of the pipe and $\theta(C_{ij})_t$ is the rate of chlorine concentration decay. We have also to take into account of the following quality constrain:

$$(C_n)_t \geq C_{n,\min} \; \forall \; n=1,...,N \; \text{e} \; t=1,...,T \tag{6}$$

where $(C_n)_t$ is the chlorine concentration at node n at time t and $C_{n,min}$ is a fixed value for the minimum concentration.

Integrated Reliability

The algorithm, developed in our research, analyzes different configurations of the system achieved by considering that, depending on its the mean time to failure, each pipe has a precise probability of being not operating for a period of time. During this period of time the pipes don't give contribution to the system flow. Boundary conditions must be validated for each state simulated.

Linking quality and hydraulic reliability methodology, we can define for each state of pipes operating or not, an integrated reliability.

Our methodology is developed following four steps.

- Fist step:

For each state simulated and for each node it is possible to evaluate:

$$H_{n,k}/H_{nact} \quad \forall \; n = 1,.., N \text{ nodes and } k = 1,...,K \text{ states} \tag{7}$$

Where $H_{n,k}$ is the head value at node n at the k – state of simulation and H_{nact} is the head value in the actual configuration (the configuration calibrated) for the node n.

And:

$$C_{n,k}/C_{nact} \quad \forall \; n = 1,.., N \text{ nodes and } k = 1,...,K \text{ states} \tag{8}$$

Where $C_{n,k}$ is the chlorine concentration at node n at the k – state of simulation and C_{nact} is the concentration in the actual configuration for the node n.

- Second step:

Calculation of hydraulic and quality *Reliability Indicators* (*RI*) for each nodes and state simulated:

$$RI_{hnk}=1 - H_{n,k}/H_{nact} \quad \forall \; n = 1,.., N \text{ nodes and } k = 1,...,K \text{ states} \tag{9}$$

or

$$RI_{cnk} = 1 - C_{n,k}/C_{nact} \quad \forall \; n = 1,.., N \text{ nodes and } k = 1,...,K \text{ states} \tag{10}$$

- Third step:

Definition of four reliability condition classes for each nodes and state simulated:

0,0 → system perfectly reliable: ratio ≤ 0
0,2 → $0 \leq$ ratio $< 0,2$
0,5 → $0,2 \leq$ ratio $< 0,5$
1,0 → system absolutely not reliable: ratio $\geq 0,5$

Subsequently it is possible to draw a table whit ratios result for each state and each node (*Table 1*).

Table 1. Head availability ratio and chlorine concentration ratio for each node and each state simulated

	node 1	node 2	node 3	…	node N
state 1	$1 - H_{1,1} / H_{1natt}$	$1 - H_{2,1} / H_{2natt}$	$1 - H_{3,1} / H_{3natt}$	…	$1 - H_{n,1} / H_{nnatt}$
	$1 - C_{1,1} / C_{1natt}$	$1 - C_{2,1} / C_{2natt}$	$1 - C_{3,1} / C_{3natt}$		$1 - C_{n,1} / C_{nnatt}$
state 2	$1 - H_{1,2} / H_{1natt}$	$1 - H_{2,2} / H_{2natt}$	$1 - H_{3,2} / H_{3natt}$	…	$1 - H_{3n,2} / H_{nnatt}$
	$1 - C_{1,2} / C_{1natt}$	$1 - C_{2,2} / C_{2natt}$	$1 - C_{3,2} / C_{3natt}$		$1 - C_{n,2} / C_{nnatt}$
state 3	$1 - H_{1,3} / H_{1natt}$	$1 - H_{2,3} / H_{2natt}$	$1 - H_{3,3} / H_{3natt}$	…	$1 - H_{n,3} / H_{nnatt}$
	$1 - C_{1,3} / C_{1natt}$	$1 - C_{2,3} / C_{2natt}$	$1 - C_{3,3} / C_{3natt}$		$1 - C_{n,3} / C_{nnatt}$
…					
state k	$1 - H_{1,k} / H_{1natt}$	$1 - H_{2,k} / H_{2natt}$	$1 - H_{3,k} / H_{3natt}$	…	$1 - H_{n,k} / H_{nnatt}$
	$1 - C_{1,k} / C_{1natt}$	$1 - C_{2,k} / C_{2natt}$	$1 - C_{3,k} / C_{3natt}$		$1 - C_{n,k} / C_{nnatt}$

Those ratios results can be translated in condition classes for the system reliability (i.e. *Table 2*):

Table 2. reliability condition classes for each node and each state simulated

	node 1	node 2	node 3	…	node N
state 1	0	0	1	…	0
	0,2	1	1		0
state 2	0	0,5	0,2		1
	0,5	1	1		0,5
state 3	1	0,2	0,5	…	1
	1	0,5	0,5		1
…					
state k	1	0	0,2	…	0
	1	0	1		0,5

- ▪ Fourth step:

As final result, it is possible to evaluate the condition class which represents the reliability of the network for each state simulated. The reliability of the whole system is established as the average value of *Reliability Indicators* calculated for all the nodes during the period T of simulation (i.e. 100 years). It is possible to calculate the Reliability Indicators for the hydraulic (RI_{hk}) or quality (RI_{ck}) aspects, and an integrated value (RI_k) calculated as combination of them. More the parameter is closed to one and much more the network reliability is low.

$$RI_{hk} = (\Sigma_n RI_{hnk})/N \qquad \forall \ k = 1,...,K \text{ states} \qquad (11)$$
$$RI_{ck} = (\Sigma_n RI_{cnk})/N \qquad \forall \ k = 1,...,K \text{ states} \qquad (12)$$
$$RI_k = (RI_{hk} + RI_{ck})/2 \qquad \forall \ k = 1,...,K \text{ states} \qquad (13)$$

CASE STUDY

Following this procedure the computer code was applied to the Pescara - Italy - water distribution network. The network is schematized as a 110 – pipe system, shown schematically in *Figure 1*. The system has 24 km of piping, 30% of which is 700mm in diameter, 85% of it is cast iron and serves about 117.000 inhabitants. No failure data were available for the pipes themselves. It was therefore assumed that the reliability of each pipe may be modeled by an exponential model. In this model the failure rate is evaluated using literature results (Bizzarri *et al.,* 2000) depending on the pipe length, material and diameter.
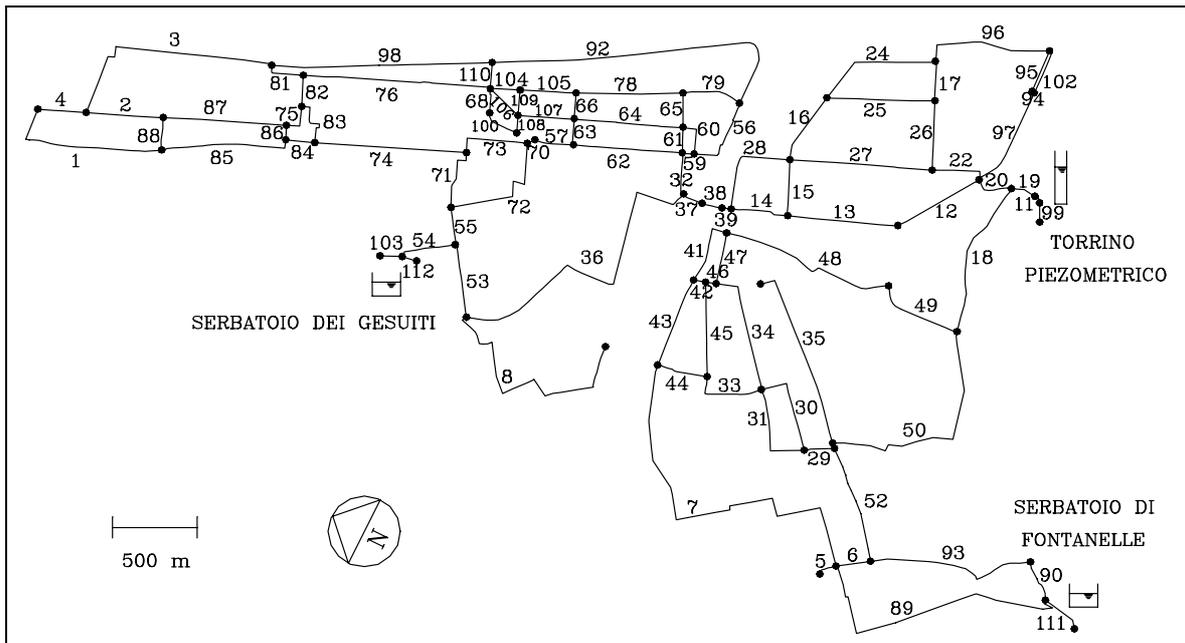
Figure 1. Scheme of the water distribution system of Pescara city (Italy) (Gangai, 1999).
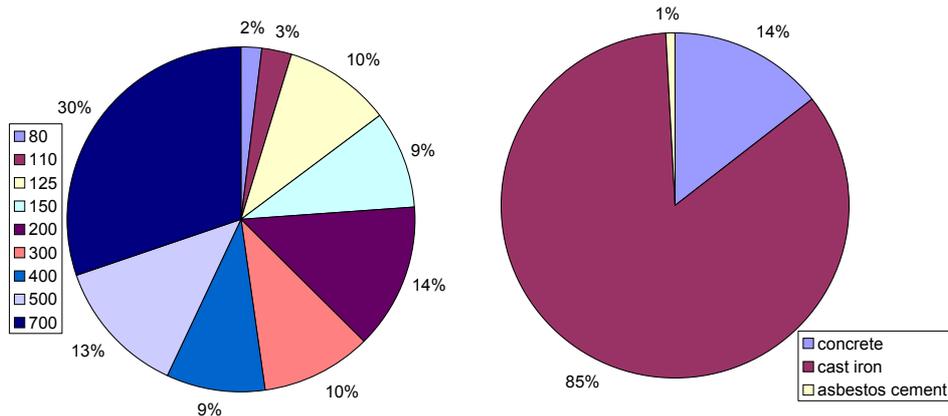

Figure 2. Percentage of diameter and materail pipes present on the water distribution system of Pescara city (Italy) (Gangai, 1999).

For the calibration of the quality model some residual chlorine measurements were available (Del Proposto, 2000): continuous registration at the source node and at the two sinks and measurements done every hour for a day at three fountains located in the city (links 63, 109 and 95). The calibration was focused on the evaluation of the chlorine reaction constant inside the water (bulk reaction) and along the pipe wall (wall reaction), respectively called Kb and Kw. Kb was studied looking at the chlorine decay measured on a sample of 1,5 liters of water spilled at link 63, assuming for Kb a constant value of 1,1 days^{-1} for each link and a value of 1,0 m/day for the constant Kw. Some results of the quantity and quality calibration are shown in *Figure 3* (simulations for 24 hours with a time step of $\Delta t = 0,02$ hours).

RESULTS

Using pipes *MTTF*, depending on materials, lengths and diameters, as defined by literature information (Bizzarri *et al.*, 2000), was possible to run the code finding the pipes broken during the simulation. The failure rate used are shown in *Table 3*.

The failure frequency of each pipes during the simulation period *T* (100 years) was simply calculated as the ratio between *T* and the pipe *MTTF*. Results are shown in *Figure 4a*.

Table 3. Failure rate (Bizzarri et al., 2000)

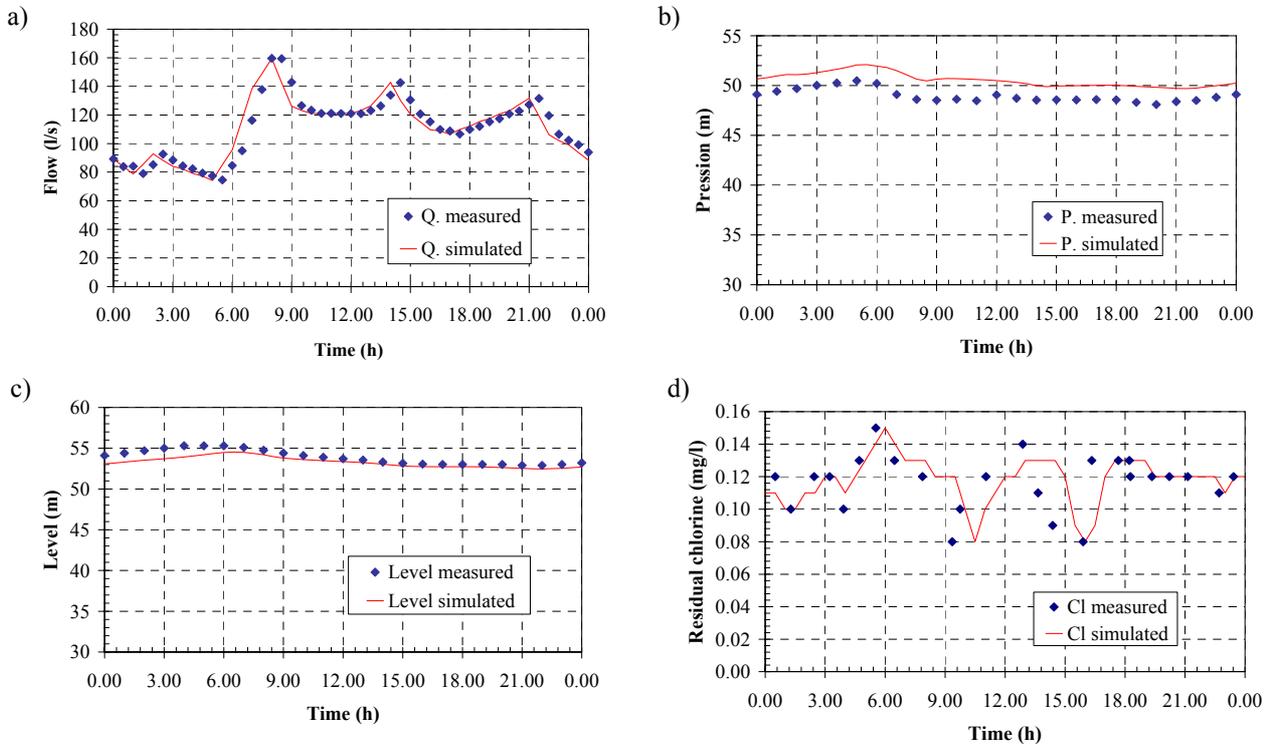| Materials	Failure rate (*break / (length x year*)
Cast Iron	0.060
Concrete	0.168
Asbestos	0.270

Figure 3. Model calibration: (a) Discharge at pipe 18; (b) Pressure at node intersection of pipes 70 and 73; (c) Tank level at "Serbatoio dei Gesuiti"; (d) Residual Chlorine at pipe 63. (Artina et al., 2000).

Solving the hydraulic problem for every new configuration of the network was possible to evaluate the nodal head (H_{nk}) and nodal chlorine concentration (C_{nk}) necessary for the calculation of the *Reliability Indicators* for each pipes during all the simulation period *T*.

The results obtained in terms of *Reliability Indicators* for the whole system are shown in *Figure 4b, 4c, 4d*.

The results highlight the much more critical pipes as the ones linking the reservoir tanks characterised by the greater diameters.

CONCLUSIONS

In this study has been analyzed the Pescara city (Italy) water distribution network in order to evaluate the most critical pipes for the reliability of the whole system combining hydraulic and quality performances. The simulation of the water distribution system has been done with the EPANET software developed by US EPA.

The objective of the study was reached defining specific *Reliability Indicators* for both quantity and quality aspects and for combination of them.

The graphical representation of results allows to see the most critical pipes that require more frequent maintenance. In particular those pipes beyond to be characterized by high failure frequency their no-operating condition produce serious hydraulic and quality consequences to the whole network system.

The procedure adopted can be a first example of approach of combining hydraulic and quality analysis and it will contribute to the management of water distribution system like a DSS according to the guidelines of the European Project CARE-W.
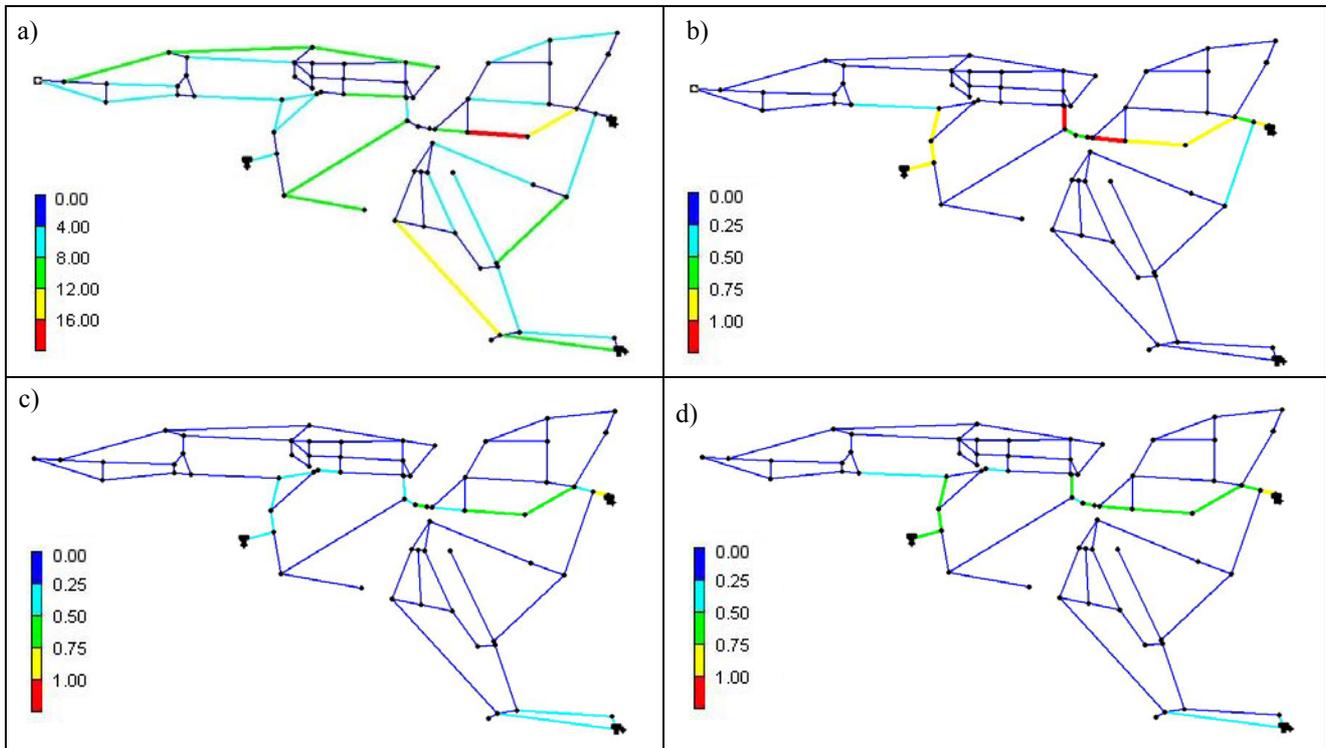

Figure 4. Simulation results: (a) Failure Frequency; (b) Quantity reliability indicator (RI_{hk}); (c) Quality reliability indicator (RI_{ck}); (d) Total reliability indicator (RI_k).

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