CHOICE OF RELIABILITY INDICATOR FOR SERVICE ASSESSMENT OF WATER DISTRIBUTION SYSTEM

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KEY POINTS

- *Choice of the most appropriate reliability index to evaluate two services; hydraulic and water quality, which are divided broadly into water demand, pressure, and available residual chlorine*
- *A weight assignment for each reliability index is achieved through the application of the Analytic Hierarchy Process technique*
- *A measure of the overall system's reliability is estimated after fuzzification, and aggregation of the developed of reliability indexes*

1 INTRODUCTION

Performance assessment of WDS has been extensively reported in the research and practice literature. The use of performance indicators (PIs) can play a key role in the process of measuring the quality of service provided by the water utility, can simplify the comparison between different objectives, and help decision processes involved in the planning and management phases. The use of PIs like reliability, resiliency and vulnerability have been approved by many authors and researchers, and led to the achievement of wide numbers of research studies in multidisciplinary scientific fields (*Hashimoto et al*., 1982; *Fiering,* 1982a; *Merabtene et al.,* 2002). In reality, in WDS, different kinds of failure like that related to pressure, flow and water quality are linked with similar or same parameters. As a results, when one kind of failure occurred it also influences the other type of failure. Therefore, consideration of holistic system performance with regards to various aspects will make the process more complicated but decision makers will potentially gain insights into the performance of the whole system as well as the information on the impacts of each component and aspect on improving the overall performance. The proposed methodology is based on a hierarchical system approach that begins by identifying two aspects namely; hydraulic and water quality aspects, which could be divided broadly into available nodal pressure and available flow, and available free residual chlorine concentration, respectively. Then, based on these services, three complementary reliability estimators (index) are adopted namely; demand-reliability, pressure-reliability, and quality-reliability. To reach the outcome of the proposed approach which is the overall reliability, analytical hierarchy process (AHP) coupled with fuzzy theory is then developed to bring all the reliability estimators into a unique platform and aggregate them into one index. The final model outcome is a single index that depicts the overall reliability which resembles both the hydraulic and water quality performances, and provides a comprehensive evaluation of the system.

2 METHODOLOGY

Traditionally, the concept of the reliability related to WDS rely often on the measurement of the reliability of supply in hydraulic terms separately without considering the quality of water supplied. This paper attempts to synthesize the hydraulic and quality performance of WDS by putting a framework that integrates different measures, each devoted to a specific aspect. The current approach is hierarchical and its development requires the following stepping phases.

2.1 Estimation of the hydraulic and quality services

The estimation of the available flow, pressure and free chlorine concentration at each node is the starting points of the current methodology. In the current study, an approach called Demand Adjusted Epanet Analysis (DAEA) has been applied. *Ermini & Ingeduld* (2005) developed the model based on the standard Epanet hydraulic solver. The model is based on an iterative logical process, starting from a pre-assigning demand allocation (initial condition) and making a series of Demand Driven analysis where demands are calculated and adjusted according to three conditions given in Equation 1 (*Ermini & Ingeduld* 2005; *Bertola*

& Nicolini, 2006).

$$Q_j = \begin{cases} Q_{req} \quad if \quad H_j \geq H_{j,req} \\ Q_{j,req}\sqrt{\dfrac{H_j - H_{\min}}{H_{j,req} - H_{\min}}} \quad if \quad H_{\min} < H_j < H_{j,req} \\ 0 \quad if \quad H_j \leq H_{\min} \end{cases} \tag{1}$$

Where, H_j is the calculated pressure at node *j*, H_{req} and H_{min} are the required and the minimum pressure head of the service, respectively. Q_{req} and the Q_j are the required and the actually delivered flow.

The one dimensional advective reactive transport equation is used to predict the changes in chlorine concentrations along the pipe.

2.2 Reliability index

Reliability of WDS is defined as the ability to deliver water to points of use in the required quantity, pressure, and quality, and when required by the water user at any time (*Kwietniewski*, 1999). Based on the fraction of delivered flow, the head pressure, and the free residual chlorine concentration at each node, three reliability indexes are developed. According to the outflow discharge obtained from the DAEA model (Equation 1), the actual delivered flow at every node is updated at each time step and the comparison between the requested and the delivered flows leads to the calculation of the reliability index related to water demand $R_j(f)$ (Eaqution 2) (*Bertola & Nicoloni*, 2006).

$$R_j(f) = \begin{cases} \dfrac{Q_j}{Q_{req}} \end{cases} \tag{2}$$

Where, R_j (*f*) is the flow reliability index at node j, and the other parameters are defined as previously.

Similarly, reliability index related to pressure at each node is also calculated as shown in Equation 3.

$$R_j(H) = \begin{cases} \dfrac{H_j}{H_{j,req}} \end{cases} \tag{3}$$

Where, R_j (*H*) is the reliability index related to pressure head at node j, and the other parameters are defined as previously.

The water quality reliability R_j (*C*) (Equation 4) at node j, is defined by the ratio of free chlorine concentration available in water supplied to the desired concentration multiplied by the hydraulic reliability.

$$R_j(C) = \begin{cases} \dfrac{C_j}{C_{j,req}} \times R_j(f) \end{cases} \tag{4}$$

Where, R_j (*C*) is the reliability index related to water quality at node j, C_j and $C_{j,req}$ respectively, denote the available and the desired chlorine concentration at node j, and the other parameters are defined as previously.

2.3 Weight assignment using Analytic Hierarchy Process (AHP)

The foundation of the Analytic Hierarchy Process (AHP) is a set axioms that carefully delimits the scope of the problem environment (*Saaty*, 1988). It is based on the well defined mathematical structure of consistent matrices and their associated eigenvector's ability to generate true approximate weights (*Saaty*, 1988). The AHP involves the following three steps (*Ataoui & Ermini*, 2015b).

- Priority setting of the reliability indexes and establishment of the judgment matrix: in AHP, preferences between indexes are determined by making pair-wise comparisons. For each pair of indexes, the experts are required to respond to a question such as "How important is the demand-reliability index compared to pressure-reliability index" using Saaty's intensity scale. At the end of this step, a judgment ratio matrix (size : $n \times n$) results, being based on the decision made on the number of compared elements (*n*) has been established as shown in Table 1. Where, *n=3 (three indicators)* is the dimension of the pairwise comparison judgment matrix.

- Computation of the priority vector: having the comparison matrix, now it's time to compute the priority vector, which is the normalized Eigen vector of the matrix. The calculation of the priority vector is commonly performed by geometric technique.
- Checking the consistency of the judgment matrix: AHP allows some inconsistency in the judgment because human is sometimes inconsistent. The consistency ratio is calculated as per the following: step1; calculate the maximum eigenvalue λ_{max} of the judgment matrix, step 2; compute the consistency index *CI*, and step 3; calculated the consistency ratio *CR*.

Where *RCI* (Random Consistency Index) varies depending upon the order of matrix. For more details on *RCI* selection, see (*Saaty*, 1988).

Size (n)=3×3	*R (f)*	*R (H)*	*R (C)*	Priority Vector	
R (f)	1	3	3	$W_{R(f)}$	59.36 %
R (H)	1/3	1	1/2	$W_{R(H)}$	15.71 %
R (C)	1/3	2	1	$W_{R(C)}$	24.93 %
λ_{max}= 3.054; *CI*= 0.0270; *RCI*= 0.58; *CR*= 4.6%.					Sum = 1

Table 1. Judgment matrix

The standard rule recommended by *Saaty* (1988) indicates that the *CR* should be less than or equal to 10% for decision makers to be consistent in their pairwise judgments. *Saaty* (1988) has also shown that the closer the value of computed λ_{max} is to n, the more consistent the observed values of the matrix are. Once the consistency is checked, the vector of weight (W_i) that reflects the relative importance of each reliability index could be accepted (*Ataoui & Ermini*, 2015b).

2.4 Fuzzification of the reliability indexes

The main objective of this paper is to evaluate the overall reliability of WDS. In literature, different techniques are proposed to harmonize different indicators and bring them into a unique platform. Fuzzy set theory has been applied in this study. Fuzzy set theory was founded by *Zadeh* (1965) to solve the problem of approximate knowledge that cannot be represented by conventional method. The main phases for developing the fuzzy approach (Figure 1) are; definition of the membership functions and fuzzification of the PIs, fuzzy inference (or definition of fuzzy rules) and aggregation, and finally defuzzification of the outputs to obtain the crisp number of the overall reliability (*Ataoui & Ermini*, 2015b).

Figure 1. Fuzzification process

- Definition of membership functions (MFs); a membership function (MF) is what maps the input space to the output space. The most used are triangular and trapezoidal functions and are applied in this study due to their computation simplicity. More detail on the definition of MFs are available in (*Ataoui & Ermini*, 2015a). The membership functions of the three reliability indexes have five levels of granularity which are expressed through five linguistic variables namely; *Poor*, *Fair*, *Satisfactory*, *Good* and *Excellent*.
- Fuzzy inference and aggregation of the reliability indexes: A rules building methodology is employed here which uses weighted average method to combine reliability indexes depending on their weights. The reason behind using this methodology over the traditional methodology of directly soliciting the rules from experts is that the traditional methodology requires the expert to evaluate the performance of a huge number of rules; this process is exhausting and time consuming and the human expert will most probably not carry out this task. The idea is to use the effect of each PI individually together with its weight and then averaged with the other PIs to generate the equivalent effect of the rules. In

this research, the number of different performance combinations needed to cover all the combination possibilities can be found as:

5 levels of *Demand*-Reliability × 5 levels of *Pressure*-Reliability × 5 levels of *Quality*-Reliability = 125 rules

Example: ***IF*** *Demand*-Reliability is good ***AND*** *Pressure*-Reliability is satisfactory ***AND*** *Quality*-Reliability is low ***THEN*** Overall Reliability is?

In order to find the combined effect of the three PIs, a weighted average method is used as shown in Equation 5.

$$Equivalent \quad effect = \sum_{i=1}^{3} impact\ value \quad \times \quad wieght \tag{5}$$

The impact of each reliability index is defined by the most likely value used to represents the MFs. The equivalent effect is matched against another scale called overall performance scale which is divided into five ranges defined by five granularity levels as shown in Figure 2.

Figure 2. Equivalent ranges of the overall reliability

Matching the value of equivalent effect against the scale, then rule is established as below.

IF *Demand*-Reliability is good ***AND*** *Pressure*-Reliability is satisfactory ***AND*** *Quality*-Reliability is low ***THEN*** Overall Reliability is good.

- Defuzzification: This process is the opposite of fuzzification. In this study, Centre of Gravity (COG) called also Centroid method is applied (*Ataoui & Ermini*, 2015a). The crisp value of the overall reliability is then obtained at each node.

The proposed methodology has been implemented and demonstrated through a real WDS of Matera city (Basilicata, Italy). The model is performed for a simulation period of 24 hours under normal operating condition. All the results are plotted on geographic information system (GIS) which has allowed the possibility to locate weak nodes and gives an overview of the spatio-temporal distribution of the overall reliability. It was revealed that under a normal operating condition the WDS of Matera has the capabilities to provide enough water with desirable quality, quantity and adequate pressure during the whole simulation period. It is also observed in almost all nodes the level of overall reliability was always higher than the good level except nodes 10, 22, 42, and 449. The results obtained from the developed models showed that the approach is robust and sound.

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