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Risk assessment of water distribution service

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Abstract

The paper proposes a model that evaluates the risk of a water distribution system looking to three aspects, namely; available pressure, water demand, and water quality. Three failure modes were considered for examining the risk. The risk has been defined imitating the original definition of Hashimoto's vulnerability, and expressed as the failure magnitude with respect to each level of service provided at a certain location and during a certain period of time. When assessing the risk rather than focusing on just one aspect the overwhelming task has been used for better evaluation and mitigation of the overall risk. The model was developed using Analytic Hierarchy Process (AHP) coupled with Fuzzy Set Theory. The first assigns weight for each kind of risk that reflects its relative importance among the other risks. The second is a fuzzy building methodology that employs the assigned weight and others external information to harmonize all risks into a unique platform and allow one to obtain the system's overall risk. The model has been implemented and tested through the real network of Matera city.

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Keywords: Risk assessment; pressure; flow; water quality; analytical hierarchy process; fuzzy set theory

1. Introduction

Water distribution systems (WDS) play a crucial role in supplying sufficient water to users with acceptable volume, pressure, and quality. These infrastructures are usually designed to fulfill base demands with additional capacity for emergency conditions. WDS must satisfy all consumers needs but are vulnerable to a range of failure

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types that can occur during an intentional extreme events and compromise their normal functions. It is important for the utility managers to assess the component of the WDS in order to manage the threat. Normally, one would want to minimize the risk of undesirable consequences. In most cases it is not possible to completely eliminate risk; however, one can mitigate it. Furthermore, an effective risk assessment serves as a guide to the water service by providing a prioritized plan for security upgrades, modifications of operational procedures, and/or policy changes to reduce the utility's critical assets.

Previous studies were conducted to identify threats toward WDS, and more attention has been focused on vulnerability analysis. The most widely used and cited definition of risk of water resource systems may be the one by [1], though a similar concept has been applied earlier to show the sensitivity of a water supply system to drought [2]. [1] defined the risk as vulnerability measures of the probable damage subsequent to a failure. [3] defined risk as the degree of susceptibility and environment to hazards. In the same context [4] defined risk as the notion of susceptibility to a scenario whereas risk focuses on the severity of consequences to a scenario. [5] defined risk as a property associated with a component, a subsystem, or the overall water system to represent the possibility of being influenced by threats with given likelihoods and severities. [6] developed risk to quantify future water supply sustainability based on multiple scenarios. The integrity of any WDS to transport water to consumers depends on a number of factors that are strongly linked to each other, and as a result, when one kind of failure occurred it also influences the other type of failure. However, assessing the risk looking to lonesome service, it is likely to miss possible risk happening to other services.

In this paper, a model has been proposed that evaluates the risk of WDS looking to three aspects, namely; available pressure, water demand, and water quality. Three failure modes were considered for examining the risk of WDS. The risk has been defined imitating the original definition of Hashimoto's vulnerability [1], and is expressed as the failure magnitude with respect to each level of service provided at a certain location and during a certain period of time. For better evaluation and mitigation of the overall risk, the overwhelming task has been used rather than focusing on just one aspect of risk. The model was developed using Analytic Hierarchy Process (AHP) coupled with Fuzzy Set Theory. The first assigns weight for each kind of risk that reflects its relative importance among the other risks. The second is a fuzzy building methodology that employs the assigned weight and others external information to harmonize all risks into a unique platform and allow one to obtain the overall risk. To demonstrate the applicability of the current model, the methodology has been implemented and demonstrated through the WDS of Matera city (Basilicata).

2. Methodology

The development of the overall risk model requires i) estimation of available pressure, available flow and free residual chlorine at each node, ii) risk evaluation with respect to aforementioned aspects, iii) weight assignment through the analytic hierarchy process, iv) fuzzification of the estimated risks, v) aggregation of the risks; and vi) defuzzification and estimation of the overall risk.

2.1. Estimation of the parameters

The estimation of available flow, pressure and water quality is the starting point to initiate the process of the current methodology. An ideal approach is to investigate the quantity of water needed for each individual customer, the period of time they need water for, and the appropriate level of water quality that is suitable for their needs. In the current study, an approach called Demand Adjusted Epanet Analysis (DAEA) has been applied to estimate those parameters. [7] developed the model based on the standard Epanet hydraulic solver. It is a modified hydraulic analysis of Demand Driven but takes into consideration the influence of pressure condition on the allowed demand. 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 as showed in Equation (1) [7,8].

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

Where, H_j is the available 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, respectively.

The previously described model is integrated in the MIKE NET SOFTWARE. This latter is used to simulate the hydraulic and water quality analysis for an extended period simulation. The one dimensional advective reactive transport equation is used to predict the changes in chlorine concentrations along the pipe.

2.2. Risks estimation

Once the parameters have been estimated, now it's time to calculate their related risks. A modified Hashimoto's vulnerability definition is adopted in this study, as it is reported to be simple in implementation and calculation, and can handle different aspects by changing only few parameters. [1] defined the vulnerability as a measure of the magnitude of system failure. In this study risk is measured based on the threshold deviation experienced during a failure event at a particular node. In other word it provides a measure of failure severity for a particular aspect. Three risks are developed.

- Risk related to flow ($R_{Q,j}$), as shown in Equation 2 is determined by the gap between the available flow and required flow.

$$R_{Q,j} = \frac{(Q_{j,req} - Q_j) * Z_j}{Q_{j,req}}; Z_j = \begin{cases} 1 \quad if \quad Q_j < Q_{j,req} \\ 0 \quad if \quad Q_j > Q_{j,req} \end{cases} \tag{2}$$

Where, $R_{Q,j}$ is the flow risk index at particular node j, Z_j is a coefficient which depends on the flow and may take 0 or 1.

- Risk related to pressure ($R_{H,j}$), high water pressure is major cause of leaks, pipe damage, and wasted water. While some might consider high water pressure a good thing, water pressure that is too high can cause annoying and expensive damage. In this research, component is not considered at risk if the available pressure (H_j) is less than the required one ($H_{j,req}$). $R_{H,J}$ is determined by Equation 3.

$$R_{H,j} = \frac{(H_j - H_{j,req}) * K_j}{H_{j,req}}; K_j = \begin{cases} 1 \quad if \quad H_j > H_{j,req} \\ 0 \quad if \quad H_j < H_{j,req} \end{cases} \tag{3}$$

Where, $R_{H,J}$ is the risk index related to pressure at particular node j, and K_j is a coefficient which depends on the pressure and may take 0 or 1.

- Risk related to water quality ($R_{C,j}$), as shown in Equation 4, is defined at each node by the ratio of the available free residual chlorine concentration to the required concentration..

$$R_{C,j} = \frac{C_j - C_{j,req}}{C_{j,req}} \tag{4}$$

Where, $R_{C,j}$ is the risk index related to water quality, C_j and $C_{j,req}$ respectively, denote the available and the desired chlorine concentration at node *j*.

2.3. Weight assignment

Weights assignment is very important step in multicriteria decision analysis (MCDA). In most cases, the relative importance of each kind of risk is subjective, and these subjectivities are usually assigned on the basis of consultation with decision makers and experts. Thus, the weights will be influenced by the knowledge of those consulted and by their preferences and biases. Analyzing the preferences, biases, and their possible treatments is outside the scope of this research. In this research, the analytic hierarchy process (AHP) technique has been applied as it is widely used around the world in a wide variety of decisions situations, and has been reported to be a simple and very effective subjective weighting method [9]. The foundation of the Analytic Hierarchy Process (AHP) is a set axiom that carefully delimits the scope of the problem environment [10]. It is based on the well-defined mathematical structure of consistent matrices and their associated eigenvector's ability to generate true approximate weights [10]. The basic procedure to carry out the AHP consists of three steps.

- Priority setting of the risk 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-risk index compared to pressure-risk 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 risks indexes) 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 mean 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 steps:
  Step1; calculate the maximum eigenvalue λ_{max} of the judgment matrix;
  Step 2; compute the consistency index *CI*:

$$CI = (\lambda_{\max} - n)/(n-1) \quad (5)$$

Step 3; Calculate the consistency ratio CR:

$$CR = (CI)/(RCI) \quad (6)$$

Table 1. Judgment matrix.

n = 3×3	R_Q	R_H	R_C	Priority Vector	
R_Q	1	7	4	W_{RQ}	69.55 %
R_H	1/7	1	1/4	W_{RH}	7.54 %
R_C	1/4	4	1	W_{RC}	22.90 %
λ_{max}=3.076; CI= 0.0380; RCI= 0.58; CR=6.6%.					Sum = 1

Where, *RCI* (Random Consistency Index) varies depending upon the order of matrix. For more details on *RCI* selection, see [10].

The standard rule recommended by Saaty [10] indicates that the *CR* should be less than or equal to 10% for decision makers to be consistent in their pairwise judgments. Saaty [10] 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 risk index could be accepted and plotted [11].

2.4. Fuzzification

The main objective of this paper is to evaluate the overall risk of WDS. In literature, different techniques are proposed to harmonize different aspects and bring them into a unique platform. Fuzzy technique is applied in this study as it is reported to be the most sophisticated aggregation technique and to be easy in the implementation and programming. Fuzzy logic was founded in 1965 by Zadeh to solve the problem of approximate knowledge that cannot be represented by conventional method, especially when the measured data is vague and too imprecise to justify the use of numbers. As a solution, fuzzy technique provides a language with syntax and semantics to translate qualitative knowledge into numerical reasoning. The main phases of fuzzy set theory are: definition of membership functions (MFs), fuzzification of the risks indexes, and construction of the assessment matrix [12].

- Definition of the membership functions (MFs): This is the main step on which all the other subsequent operations are based. A MF is what maps the input space to the output space. There are many forms of MFs, such as triangular, trapezoidal, bell curve, and Gaussian. The most used are triangular and trapezoidal functions and are applied in this study due to their computation simplicity. As shown in Fig. 1, the triangular MF requires only three parameters (*l, m, u*) to be defined. The parameters *l*, *m*, and *u* respectively, denote the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event [13]. Each triangular fuzzy (TFN) number has linear representations on its left and right side whereby its MF is defined as following.

$$\mu_{TFN}(x)=\begin{cases}0 & if \quad x<l\\ \left(\frac{x-l}{m-l}\right) & if \quad l\le x\le m\\ \left(\frac{u-x}{u-m}\right) & if \quad m\le x\le u\\ 0 & if \quad x>u\end{cases};\mu_{ZFN}(x)=\begin{cases}0 & if \quad x<l\\ \left(\frac{x-l}{m-l}\right) & if \quad l\le x\le m\\ 1 & if \quad m<x<m'\\ \left(\frac{u-x}{u-m'}\right) & if \quad m'\le x\le u\\ 0 & if \quad x>u\end{cases} \tag{7}$$

However, the trapezoidal (ZFN) MF (Fig.1) requires four parameters (*l, m, m', u*), where m and m' are the most promising values, and the other parameters are defined as previously. The ZFN is represented by Equation 7.

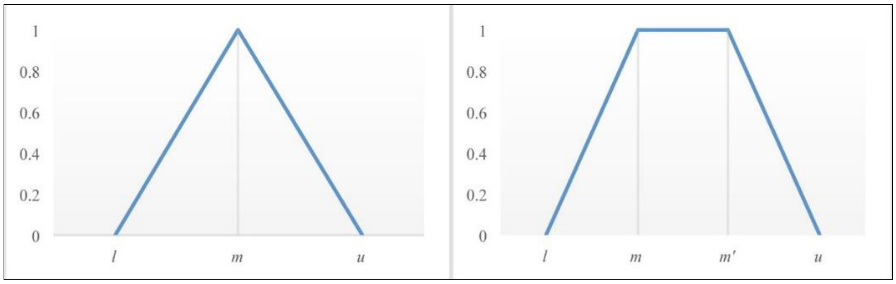

Fig. 1. Triangular (TMF) and trapezoidal (ZMF) membership functions.

- Fuzzification: Usually, any performance scale consists mainly of two parts: numerical scale and linguistic scale. Any linguistic description is a formal representation of systems made through fuzzy set approach. It provides an alternative to describe and use human languages in related analysis system and approximates the reasoning of the decision-making problems [14]. For an absolute judgment, [15] recommended that the number of classes must be restricted to fewer than seven. There are many types of linguistic scales. For example, a five-point scale is widely used in the condition assessment process. In this paper, the MFs used to describe the risks indexes have five levels of granularity that range from zero to one, which are expressed through five linguistic variables, namely, Absent or very low, Low, Medium, High and Very High. The Absent or very low level indicates the minimum level of a system's risk that is already achieved in many of the best-performing cities around the world and is close to zero, the Very high level indicates a system or component of higher risk. Fig. 2 illustrates an example on how to plot the fuzzy numbers with their associated linguistic variables.

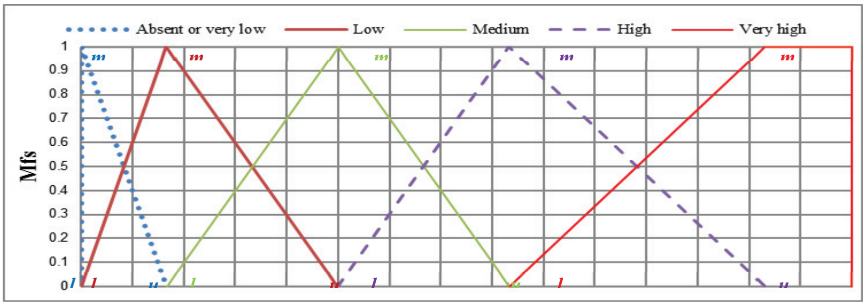

Fig. 2. Fuzzification example

At the end of this step an assessment matrix M_j (Equation 8) is obtained in which are plotted the fuzzy values of risk indexes under five granularity levels.

$$M_j = \begin{bmatrix} \hat{R}_{H,j} \\ \hat{R}_{Q,j} \\ \hat{R}_{C,j} \end{bmatrix} = \begin{bmatrix} \mu^{R_H}_{absent/verylow} & \mu^{R_H}_{low} & \mu^{R_H}_{medium} & \mu^{R_H}_{high} & \mu^{R_H}_{veryhigh} \\ \mu^{R_Q}_{absent/verylow} & \mu^{R_Q}_{low} & \mu^{R_Q}_{medium} & \mu^{R_Q}_{high} & \mu^{R_Q}_{veryhigh} \\ \mu^{R_C}_{absent/verylow} & \mu^{R_C}_{low} & \mu^{R_C}_{medium} & \mu^{R_C}_{high} & \mu^{R_C}_{veryhigh} \end{bmatrix}_j \quad (8)$$

Where, $\hat{R}_H$, $\hat{R}_Q$, and $\hat{R}_C$, respectively, denote the fuzzified risk of pressure, flow, and water quality respectively, under five granularity levels. The global scale that describes the condition of overall risk is also established. This scale has been proposed to help decision maker in water main management to make an informed decision. The scale ranges from zero to one tending from the lowest to the highest component/system risk. Linguistically the overall risk scale was defined by five levels of granularity the same as established prior for the three risks indexes.

- Aggregation: The aggregation consists of synthesizing the three fuzzified risks with their associated weight and thus permit the estimation of the overall risk at each node. The aggregation is performed through the assessment matrix M_j obtained previously by the fuzzification process, together with the vector of weight W_i presented in Table 1. The aggregation is carried as shown in Equations 9.

$$\hat{R}_j = M_j \times \begin{bmatrix} W_{R_H} \\ W_{R_Q} \\ W_{R_C} \end{bmatrix} = \begin{bmatrix} \hat{R}_{j,absent/verylow} & \hat{R}_{low} & \hat{R}_{medium} & \hat{R}_{high} & \hat{R}_{everyhigh} \end{bmatrix}_j \quad (9)$$

Where, $\hat{R}_j$ is the fuzzified overall risk at particular node j under five granularity levels.

- Defuzzification: Is the procedure for determining the crisp value that is considered the most representative of the fuzzy set output. There are many defuzzification techniques, the most commonly used method is the Centroid method (also called Center of Gravity "COG") and it is applied in this research. Applying COG method [16], the crisp value of the overall risk has been retrieved by Equations 10.

$$R_j = \frac{\int_x \mu_{\mathrm{Res}}(x) \quad x \cdot dx}{\int_x \mu_{\mathrm{Res}}(x) \quad dx} \tag{10}$$

Where, R_j is overall risk at node j.

The estimated overall risk obtained from the model provides an overview risk of each single node at a specific time. However, this estimated risk could not provide risk for the whole WDS. For better risk assessment, it is important to consider the entire system in the evaluation process. To do that, Equation 11 has been used to estimate the system's overall risk, where the required nodal demand over a particular time was used as a weighted factor in the aggregation process.

$$R_t^{sys} = \frac{\sum_{j=1}^{n} Q_{j,req} \times R_j}{\sum_{j=1}^{n} Q_{j,req}} \tag{11}$$

Where, R^{sys} is the overall risk of the WDS at a particular time step, and all the other parameters have their usual meaning as defined previously.

3. Application

The current research has been validated through the Matera's WDS (Basilicata, Italy). The distribution network comprises 114 nodes connected by 144 pipes with a total length of 57.71 km. Water is fed by gravity from two elevated tanks (Jazzo Gattini and Serra Venerdì) with the total head of 474 m, and 433 m, respectively. MIKE NET software has been used for the hydraulic and water quality analysis for extended period simulation (24 hours) under normal operating conditions. The one dimensional advective reactive transport equation has been used to predict the changes in chlorine concentration along pipes. Fuzzy set theory and analytical hierarchy process has been performed using MS Excel and Matlab. Outcome results have been plotted on GIS (Fig. 3a), thus allowing to locate the faulty nodes across the network and providing an overview of the spatial and temporal distribution of the overall risk.

Fig. 3a shows the overall risk of Matera's water network. As can be seen by the figure in almost all nodes the risk is absent or low and this could be an indication of high management of the system, and reveals that the system has the abilities to provide the required services without interruption. Only few nodes (red point) show high level of risk (Fig. 3b), these nodes are considered as the most critical nodes in the network. As the model is hierarchical, it reveals that the high risk level is due essentially to the hydraulic parameters where demand has been the unfavourable factor since it has the most important impact. Under normal operating condition, the risk level obtained for the mentioned nodes is not acceptable and requires immediate intervention from system utilities in order to investigate the cause of low performance and take the corrective action to remedy the situation.

4. Conclusion

A global risk model that addresses the influence of hydraulic and water quality aspects on the responses of water distribution system was developed in this research. Three services namely; pressure, flow, and free residual chlorine concentration available at each node were considered. The estimation of those services was performed through a model called Demand-Adjusted Epanet Analysis (DAEA). Then, a model was constructed that begins by evaluating three types of risk index based on the estimated services. In order to bring all the indexes into a unique platform and allow to obtain one index that depict the overall risk at each node, the model integrate the technique of AHP with fuzzy set theory. The first assigns weight for each index that reflects its relative importance among the other indexes. The second is a fuzzy building methodology that uses the assigned weight and others external information to harmonize all indexes into a unique index. The whole approach was demonstrated using the Matera's WDS. From the results, the model was able to detect the faulty node and identify the weak area that may need appropriate strategies for planning and investment.

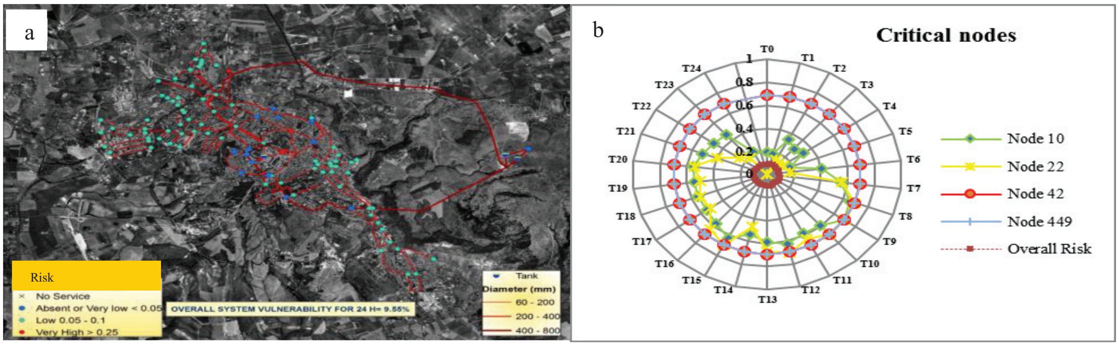

Fig. 3. (a) Overall risk; (b) Critical nodes

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