Water network functional analysis

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Abstract. Water distribution systems should have a high level of reliability and availability. Water distribution system failures should be diagnosed and categorised, according to their consequences, causes, frequency, and other important factors. A failure analysis of the water distribution system is considered in this study, as well as a method for establishing a failure susceptibility index and evaluating the risk of failures within a defined area, based on categories and zonal characteristics. A risk scale, such as tolerable, controlled, and unacceptable, will be used to assess the risk of failure. The methodology is provided to help in the performance and risk assessments of water distribution systems, as well as decision-making.

1. Introduction

In order to support the operators in optimizing the performance of the system, modelling various random failure states is required [1], [2]. The term "failure state" refers to a state in which the system has failed to fulfil one of its assigned functions [3]. Structural failures and performance failures are the two types of failure conditions. Pipe breaking or deformation, for example, is an example of a structural failure, which can cause a function not to be met [4].

All structural failures result in functional failures. Some functional failures can result structural failures, eg. a pump failure can be structural or functional, a pump may fail because of loss of electrical power (a functional failure), also it may also fail because of pump-wall cracking (a structural failure) [5], [6]. The water distribution system's diversity (thousands of kilometres of pipes of various materials and ages), the combination of processes as physical, chemical, biological, and the lack of consistent data sampling make water quality analysis following failure occurrences very difficult [7], [8], [9]. In terms of the special nature of water-pipe network, the maintenance is inextricably linked with the management of network operational reliability, as to provide adequate water quality to the recipients [10].

Economic and social implications are the two types of effects associated with the occurrence of threats in the water distribution system. The costs of restoring the water supply system to proper functioning, as well as the financial implications borne by the waterworks, are linked to the interruptions or lack of water delivery. Social effects are linked to hygienic and sanitary difficulties, as well as the risk of water recipients losing their health or life, hygienic and sanitary difficulties, and ecological impacts [11], [12], [13].

The presented issue is in line with global trends in water safety, that must involve an assessment of environmental threats as well as water supply system analyses in various conditions, particularly during emergency situations [14].

The primary basis for the failure and risk analysis can be found in the WHO recommendations, EU legislation, and current Minister of Health regulations concerning water quality for consumption.
The risk factors linked with the various types of threats emerging in the water distribution system can be found in the stage of system designing, construction and operation [15], [16]. The stage of water supply system designing can include wrong examination of ground conditions, incorrect choice of the trajectory of the water pipeline, badly selected materials, fittings, anticorrosion protection, errors in hydraulic systems [17], [18], [19]. The undesirable events associated with construction of the water supply system are deviation from the design in terms of pipe laying technology, inappropriate corrosion protection (passive and active), and poorly conducted pressure tests and other procedures [20], [21]. At the stage of water supply system operation undesirable events include water pipeline functioning was not monitored, crisis water supply alternatives were not considered, and a water quality protection and warning system was inconsistent, lack of the complex archives of failure data, and lack of program to control the risk associated with the operation of the water supply system [22], [23], [24].

The analysis of hazards study uses data from prior safety analyses, deductions from unwanted occurrences and their causes, and the knowledge of experts on the operation of current water distribution systems are some of the most often used methods of failure and risk assessment [25], [26].

The failure database contains partial circumstantial descriptive data (when, where, and sometimes a description of the failure). It does not identify the failures mode, mechanism, criticality, and causes in technical codified manner. We can identify the failure mode, e.g., transverse crack, longitudinal crack. We can identify the mechanisms sometimes; corrosion or high operating pressure, but it is much more difficult to characterise the failures, the size of the crack or the criticality of the crack (the leakage rate, the local pressure drop, the risk of in-pipe contamination). In case of a pipe corrosion-cracking failure mode, it is complicated to identify the cause, is it: a corrosivity of the ground, a lack of corrosion protection, and a corrosive water [27], [28], [29].

Water-pipe and fitting breakdowns are unpredictable events that can be triggered by mechanisms related to: groundwork (for example, when a water-pipe is mechanically destroyed by an excavator); water-pipe technical and operational issues; design and/or construction errors or sudden temperature changes [30].

The common failures in water distribution systems are due to: conceptual errors, technical design errors (network in open, ring or mixed system), and/or wrong specification hydraulic circumstances in operation (too high working pressure, lack of water hammer-protecting fittings) [31].

Failures in the water distribution network are frequently linked to management processes and to a lack of water monitoring, resulting in a lack of reaction to minor water leakage and a tendency to avoid critical water supply situations [32], [33].

Water distribution system failure risk-based management could be described as the procedure of coordinating the functioning of system components and operators, utilizing reasonable resources, to achieve the acceptable risk level in the productive manner, in terms of technology, finances, and dependability [34]. Failure risk-based management can effectively contribute into eventual water distribution crisis management, as well [35], [36].

As a result, the implementation of an emergency plan drinking water supply is almost mandatory on local and regional levels in many countries, as Germany, France, and Spain [37], [38].

Emergency plans should embrace various critical crisis scenarios, as well as a detailed assessment of risk likelihood, as to create a robust incident response plan for water distribution [39], [40], [41].

Data on pipe failures was gathered from the operation of water network.

The primary aim of the work is to analyse failure events and propose a failure risk assessment methodology.

### 2. Failure and Risk Analysis

Table 1 depicts the number of failures in various types of water delivery networks, with the number of failures proportional to the length of the network.

The presented failure rates $\lambda_m$ for pipes were calculated according to the formula (1) [9]:

$$\lambda_m = \frac{m(t,t + \Delta t)}{L \cdot \Delta t} \quad (1)$$
where:

\( \lambda_m \) – unit failure rate of the \( i \)-th network type, [nos. of failures \( \cdot \) km\(^{-1} \) \( \cdot \) year\(^{-1} \)],

\( m(t,t+\Delta t) \) – the total number of failures in a specific type of network over time interval \( \Delta t \),

\( L \) – the network length (distribution, water supply connections, etc.) in a given time interval, during which the failures took place, [km],

\( n \) – the network type,

\( \Delta t \) – time period, [year].

The method of identifying risk areas (MIRA) is based on the selection of factors influencing the size of the failure risk of failure in the water distribution network. The described method entails categorizing the risk factors regarding water supply network breakdowns and allocating them to ranking point values and point weights, and then calculating the Failure Susceptibility Index (FSI).

Each class is assigned points values as follows: neglected factor (0÷1), unimportant factor (2÷3), average factor (4÷6), important factor (7÷8), very important factor (9÷10). The weight are assumed depending on the so-called the degree of exposure according to the scale, 1 represents low, 2 represents medium, and 3 represents high.

If a given factor is not presented, the values of the \( I_i \) and \( P_i \) indices are assumed equal to 1 [20].

In this way, the value of the FSI vulnerability index is obtained, calculated according to the formula [41]:

\[
FSI = \sum_{i=1}^{k} I_i \cdot P_i
\]  

where:

FSI – Failure Susceptibility Index,

\( I_i \) – rank of \( i \)-th risk factor (level of importance),

\( P_i \) – weight of \( i \)-th factor,

\( k \) – number of factors (classes) taken into account in the FSI method.

Table 1 proposes factor classes for the analysis of identification of water network failure risk areas and for \( I_i \) and \( P_i \) values [27], [28], [41], [42], [43].

Table 1. Factor classes, \( I_i \) and \( P_i \) values for the FSI method.

| The class of the indicator                      | Rank of \( I_i \) | Weight of \( P_i \) factor |
|-----------------------------------------------|-----------------|----------------------------|
| Type of water network - WN\(_T\)              | 10              | 1 - low                    |
| Water network age - WN\(_A\)                 | 9               | 2 - medium                 |
| Water network material - WN\(_M\)            | 6               | 3 - high                   |
| Hydrogeological conditions - HC              | 8               |                            |
| Failure rate - \( \lambda \)                 | 5               |                            |
| Corrosion protection - CP                     | 4               |                            |

|                |                | 1 - low | 2 - medium | 3 - high |
|----------------|----------------|---------|------------|----------|
| Type of water network - WN\(_T\)              | 10              | water supply | distribution | mains |
| Water network age - WN\(_A\)                 | 9               | to 20 years | from 20 to 60 years | above 60 years |
| Water network material - WN\(_M\)            | 6               | plastics | steel | grey cast iron |
| Hydrogeological conditions - HC              | 8               | good | average | poor |
| Failure rate - \( \lambda \)                 | 5               | < 0.5 number of failures \( \cdot \) km\(^{-1} \) \( \cdot \) year\(^{-1} \) | from 0.5 km\(^{-1} \) \( \cdot \) a\(^{-1} \) to 1.0 km\(^{-1} \) \( \cdot \) a\(^{-1} \) | > 1.0 km\(^{-1} \) \( \cdot \) a\(^{-1} \) |
| Corrosion protection - CP                     | 4               | full | standard | none |
The class of the indicator Rank of $I_i$ Weight of $P_i$, factor

| The density of underground infrastructure, dynamic loads, including the difficulty of repairs in the area where the network is situated - DU | 3 | pipeline in the not urbanized areas | pipeline in the pedestrian traffic (pavements) | pipeline in the street |

According to the adopted risk categories assessment in the Table 1, a variety of failure events can be examined, using the following Failure Susceptibility Index scale:

- The tolerable FSI, less than 90 points.
- The controlled FSI, from 90 to 160 points.
- The unacceptable FSI, more than 160 points.

The following category of FSI can be considered:

- Tolerable category indicates that the water network performs its functions effectively.
- Controlled category, some elements' performance should be improved, and some segments of the water pipe network must be repaired.
- Unacceptable category, means that the water network does not perform its functions and has to be modernized or reconstructed.

### 3. Characteristics of the water supply network and Failure Analysis of network

About 33 thousand inhabitants are supplied with tap water in the considered city in the Subcarpathian province. This corresponds to approximately 94.5 percent of the entire population of the city. In 2020, the total length of the active water supply network is 239 km. Water is sent to the recipients via two main lines. Cast iron pipes are used for the 1st main with nominal diameters of 300, 400, and 500 mm. Cast iron, steel, and HDPE pipes (diameters of 500 and 600 mm) were used in the construction of the second main. The distribution network was built in the 1960s and 1970s. The main material was cast iron pipes with nominal diameters ranging from Ø 150 to Ø 200 mm.

The structure material of the pipelines has been modernized and replaced over the years. At the end of 2020, the water company administered water distribution network (179.2 km) and water connections (60.0 km). The following materials are used in the water supply system: steel - 9.2%, grey cast iron pipes - 3.3%, PVC - 24.8%, HDPE - 62.2%, asbestos cement - 0.4%.

After the analysis of the results of monitoring the quality of treated water at the Water Treatment Plant it was observed that none of the parameters determining the quality of water in this period of time was exceeded.

For the five-year period of operation, 370 failures were recorded in the water supply network. About 6.9 kilometres of the water supply network were built in the last year of the study.

The average failure rates for water pipes, according to the analysis, are as follows:

- Failure rate for distribution pipes $\lambda_R = 0.31$ nos. of failures $\cdot$ km$^{-1} \cdot$ year$^{-1}$ in comparison to the limit value $\lambda_{Rlim} = 0.5$ number of failures $\cdot$ km$^{-1} \cdot$ year$^{-1}$,
- Failure rate for water supply connections $\lambda_P = 0.38$ nos. of failures $\cdot$ km$^{-1} \cdot$ year$^{-1}$, against the limit value $\lambda_{Plim} = 1.0$ nos. of failures $\cdot$ km$^{-1} \cdot$ year$^{-1}$.

The detailed analysis show, that the highest number of recorded failures were in the months of the winter-autumn period, emerges as a result of the density of soil and temperature changes, increasing the forces of stress in the wall of the pipe, which can lead to cracks. The most common causes of failures
include damage to connections, which corresponds to almost 30% of all types of failures. Moreover, failures are often caused by failure of valves (about 18%) and failure of hydrant (15% of all failures in the analysed period). The least damages were caused by mechanical damage to the pipeline and leaks on the bands at the point of connection to the network.

4. An Example of the Method Being Applied
A five-kilometer segment of the distribution network that is part of the water delivery distribution network in the considered city, providing water to 33 thousand people was considered. The network characteristics for the purpose of FSI determination, as well as the $I_i$ and $P_i$ values are given in the Table 2 [42], [43].

| The class of the indicator | $I_i$ | $P_i$ |
|-----------------------------|------|------|
| WN_T - distribution         | 10   | 2    |
| WN_A -19 years              | 9    | 1    |
| WN_M - plastics             | 6    | 1    |
| HC - poor (soils with low bearing capacity, e.g. snowstorms) | 8    | 3    |
| $\lambda$ - low (0.45 number of failures $\cdot$ km$^{-1}$$\cdot$ year$^{-1}$) | 5    | 1    |
| CP - not applicable         | 1    | 1    |
| DU - along the main street  | 3    | 3    |

The result of FSI reached 74, that belongs to the group of tolerable failure risk level. Tolerable category indicates that the water network performs its functions effectively.

5. Conclusions
The methodology considers three risk-acceptability levels (tolerable, controlled and unacceptable). These are the most frequent responses that water distribution system decision-maker used to use for risks evaluation. Along with its complexity, the risks involved with the functioning of the water distribution system cannot be avoided, however, it can be decreased to a tolerable degree.

Risk analysis related to water distribution system operation should be a key component of multifaceted water distribution system risk management. System and subsystems failure analyses should be considered from the water distribution system design, through construction and during operating phases. It should constitute a basis for estimating the system and the subsystems reliability. Another major issue is determining the criteria values for failure and risk levels, that should be done by collaborative teams of specialists in risk methodologies and engineers using the research and engineering information. In the processes of failure and risk analysis, the operators’ and specialists’ viewpoints and assessments are significant.

A very important point in failure analysis activities is to contribute in building up failure advanced databases, integrating the operational technical assessments, the experts judgements and users’ satisfaction expressions.

The failure analysis and assessment approach chosen should be adjusted to the systems examined in the database, as well as the knowledge and experience of the professionals conducting the analysis. In addition to the aforementioned concerns, the criteria to be used for all failure metrics and assessment are crucial. These criteria should take into account the kind of municipal infrastructure as well as the characteristics of the particular urban agglomeration. It is critical to emphasize the method's universality and the potential of applying it in practice to a variety of water supply systems with various extents of local specificity.
The approach for determining the level of failure risk given here can be used applied to identify network parts for modernisation, as many water distribution system failures show that significant modernizations and repairs are required. Applying operational data, field research, geographic information system and professional evaluations, a risk map can also be structured on a water-pipe network layout in a straightforward method, allowing specific areas of tolerated, controllable, and intolerable risk to be identified.

Risk analysis experience in the context of water supply system operation has already been developed at the scientific scale and disseminated in guidelines. This has taken the place of personal trial and error as a method of investigation.

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