

## Model of Failure Risk Analysis in the Water Pipe Network

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**Abstract:** A water distribution system (WDS) ought to be high reliable continuous operating system. Failure factors in WDS should be identified and prioritised, for example, the causing factors in the most frequent failures in water-pipe network. In this paper, the failure risk analysis of the WDS is presented, and accordingly, a new method consisting the failures index (FI) and the evaluation of risk of failure within the relevant area, based on the assumed categories (tolerable, controlled and unacceptable risk). It is expecting that the methodology for the WDS performance risk analysis would provide the city leadership for decision making support.

**Keywords:** *Water pipe network, failure, risk analysis*

### 1. Introduction

An essential element of drinking water distribution system (WDS) is water supply network. Each damage (failure) of this network may cause disruption in the supply of water to customers in terms of quantity or quality (the so-called secondary water pollution in water supply network). The aim of the network is to supply consumers a required amount of water, with a specific pressure and a specific quality, according to the valid standards, and with the acceptable price [20]. Nowadays, the water-pipe companies try to get quality management certificates, according to the international standard ISO 9001:2000, that requires the procedures to estimate widely understood risk.

The management of risk connected with the WDS can be defined as a process of coordination of the operation of the WDS elements and its operators, using available means, in order to obtain the tolerable risk level in the most efficient way, as far as technology, economic and reliability are concerned [5]. Also the WDS itself can cause a crisis situation when various scenarios of undesirable events, which can cause system operating unreliability, and in consequence, the loss of water consumers safety, occur. Therefore, the development of plans for drinking water supply in emergency, for various critical situations, as well as the detailed analysis of risk of the possibility that undesirable events in the WDS will occur, in order to develop a complex program of the system safety management, is so important [8],[11],[17]. The water distribution subsystem consists mainly of: water-pipe network (main, distributive and household connections) and the specific fittings (gate valves, check valves, hydrants, drainage, aeration, flow meters).

The main objective of this paper is to present the issue of failure risk analysis in the water distribution system. The paper presents a new method for water pipe network failure risk analysis.

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## 2. Risk in the Functioning of a Water Distribution System

Haimes [3], suggests that risk assessment looks at what can go wrong as well as its likelihood and consequences. Risk is a measure of the probability and severity of adverse effect. Safety, on the other hand, is the level of risk that is deemed acceptable.

Kaplan and Garrick [6]-[7] introduced the theory of scenario and the triplet questions in the risk assessment process:

what can go wrong?,

what is the likelihood?,

what are the consequences?.

They introduced the following mathematical definition of risk  $r$ :

$$R = \{S_i, P_i, C_i\}, \quad (1)$$

where:  $S_i$  denotes the  $i$ -th risk scenario (initiating events scenarios),

$P_i$  denotes the likelihood of that scenario,

$C$  denotes resulting consequences.

Aven [1] defines risk by two –dimensional combination of:

- events  $A$  and the consequences of these events  $C$ , and
- the associated uncertainties  $U$  (will  $A$  occur and what value will  $C$  take?).

To perform effective risk assessment and management, the analyst must understand the system and its interactions with its environment, and this understanding is requisite to modelling the behaviour of the state of the system under varied probabilistic conditions [1]. Failure is defined as an event in which the system fails to function with respect to its desired objectives. Failure can be grouped into either structural failure or performance failure. A structural failure, such as pipe breakage or a pump failure, can cause demands not to be met [12],[16].

The complexity of the distribution system (many kilometres of pipes of different materials and ages), occurrences of physical/chemical/biological processes and the lack or absence of timely data make forensic analyses of water quality failure events very challenging [13]-[14]. With regard to a specific character of water-pipe network operation the system of failure repair is inseparably connected with the maintenance of network operational reliability and a priority is to provide consumers with suitable quality water [15],[19].

As far as water-pipe network is concerned, we have a database of failure but the database contains only the final data which do not identify the primary causes of failures. We can answer the question what kind of failure took place, *e.g.*, corrosion, transverse crack, longitudinal crack. It is much more difficult to identify the cause of failure. It can be shown on an example of failure connected with pipeline corrosion. The possible causes can be the following: ground corrosivity, lack of anticorrosion protection (passive and active), water corrosivity [4]. Failures of water-pipe network and its fittings are the random events and they can be caused by the events connected with [4]:

- groundwork (eg. water-pipe is mechanically damaged by an excavator),
- water-pipe technical state,
- errors at mounting or sudden temperature changes.

The causes of high failure frequency in water-pipe network are often:

- the incorrectly assumed concept of network structure (network in open, annular or mixed system),
- incorrect gates layout,
- wrongly chosen operating hydraulic conditions (too high working pressure, lack of fittings protecting against hydraulic strikes).

One should remember that water-pipe network operates with the changeable pressure and flow parameters, which is connected, mainly, with a change in an amount of water used by consumers over time. The important problem which occurs in many urban water-pipe networks is also a considerable water-pipe network redimensioning, which causes drop in water flow speed, water-pipes silting up and, as a consequence, the unfavourable flow conditions that can cause the deterioration of water-pipe network water quality. The important problem concerning subsystem operation is a system of capturing, processing and archiving data on all failures in the WDS operation. Database must be developed and computer systems, *e.g.*, SCADA must be used.

The factors which form the probability that the negative consequences occur are, among others, the following:

- the probability that the undesirable event occurs,
- frequency and a degree of exposure,
- the possibility of avoidance or minimization of the negative consequences.

Risk assessment is a process consisting of a number of the systematic steps, in which the study of different kinds of threats connected with the WDS operation is carried out [9]-[10]. The basic purpose of this kind of activities is to collect the information necessary to estimate the safety of the system.

Risk assessment should contain [2],[4], [18],[21]:

- establishment of a ranking of the undesirable events (failures),
- determination of the level (value) of risk,
- proposal of the activities aimed at risk minimization,
- establishment of time after which the risk can obtain its critical value, as a result of different processes, *eg.* materials ageing.

To evaluate the risk analysis of a water distribution system a relationship should be established between pipe failures and other parameters of the system, such as:

- type of water – pipe network (diameter):
  - main ( $\phi > 300\text{mm}$ ),
  - distributional ( $\phi 100\text{mm} \div 300\text{mm}$ ),
  - household connections ( $\phi < 100\text{mm}$ ),
- depth and pressure,
- age of network,
- material (quality and type),
- ground hydrological conditions,
- place of network (dynamic load, density of underground development).

### 3. Risk Analysis

In order to analyse the risk of failure in the water supply network the following measure of risk was assumed [18]:

$$R=f(P,C)=\sum_S P \cdot C \quad (2)$$

where:

$S$  - a series of the successive undesirable events (failures),

$P$ - the probability (likelihood) of  $S$  or a single failure (a point value, depending on the failure rate, Table 2)

$C$ - a point value of losses caused by  $S$  or a single failure (depending on the failure index (FI), (.3), Table 4).

According to equation (2) the qualitative risk matrix was developed, assuming a descriptive point scale for the particular risk parameters:

For probability (P):

- Little (LP) – 1,
- Medium (MP) – 2,
- High (HP) – 3.

For consequences (C):

- Little (LC) – 1,
- Medium (MC) – 2,
- High (HC) – 3.

Risk matrix:

$$R = \begin{vmatrix} \text{LPLC} & \text{LPMC} & \text{LPHC} \\ \text{MPLC} & \text{MPMC} & \text{MPHC} \\ \text{HPLC} & \text{HPMC} & \text{HPHC} \end{vmatrix} = \begin{vmatrix} 1 & 2 & 3 \\ 2 & 4 & 6 \\ 3 & 6 & 9 \end{vmatrix}$$

According to the basic matrix for risk assessment given above we can analyse various undesirable events, assuming the following scale of risk: the tolerable risk ( $R_T$ ), the controlled risk ( $R_C$ ), the unacceptable risk ( $R_U$ ), Table 1.

**Table 1:** The Risk Categories

a number of points	risk categories
1÷2	the tolerable risk ( $R_T$ )
3÷4	the controlled risk ( $R_C$ )
6÷9	the unacceptable risk ( $R_U$ )

For the parameter P we assume that the parameter value depends on the failure rate of a given failure. The point weights for the parameter P are presented in Table 2.

**Table 2:** The proposed weight values P depending on the failure rate ( $\lambda$ ).

$\lambda$ number of failure km · year	P		
	Little 1	Medium 2	Large 3
	connections		
	$\leq 1$	(1÷3]	>3
	distributional		
	$\leq 0.5$	(0.5÷1]	>1
	main		
	$\leq 0.3$	(0.3÷0.5]	>0.5

For the parameter C we assume that the parameter value depends on the so called failure index value (FI), calculated from the equation 3 [18].

$$FI = \sum_{i=1, j=1}^{n, m} (RA_i \cdot W_j) \quad (3)$$

where,

$RA_i$  – rank of factor number  $i$  (a degree of importance),

$i=1, \dots, n$

$n$  – a number of factors (classes),

$W_j$  – the point weights ,

$j= 1, \dots, m$

$m$  – a value of weight,  $m=1,2,3$ ,

All factors which influence the cost of failure repair are grouped into classes (according to the amount of costs) and these classes have assigned the ranking point value  $RA_i$ , depending on a degree of the influence of the given factor on the susceptibility index and risk value.

For the purposes of this paper the following notions have been defined:

- For the factor  $RA_i$ :  
 $R_i = [0-1]$  – ignored,  
 $R_i = [2-4]$  – low importance,  
 $R_i = [4-6]$  – medium importance,  
 $R_i = [7-8]$  – important,  
 $R_i = [9-10]$  – very important.

Inside each class the so-called weights are assigned, which differentiate the impact of a given factor depending on its type (eg. as you can see in table 3, in class 1 the factor is a type of the network which has a significant impact on costs associated with failure repair, therefore  $RA_1=10$ , but inside this class there are three types of water network, which we differentiate by the weight value  $W_j$ : main network  $W=3$ , distributional network  $W=2$ , household connections  $W=1$ ).

- For the factor weight value  $W_j$ :  
  - $W_j = 1$ -low,
  - $W_j = 2$ -medium,
  - $W_j = 3$ -high.

In Table 3, the proposed classes and the weight values  $R_i$ ,  $W_j$  are shown.

**Table 3:** The proposed classes and the weight values  $R_i$  and  $W_j$

i	Class	$R_i$	$W_j$		
			j=1	j=2	j=3
1	Type of water-pipe network	10	connections	distributional	main
2	Material of network	5	plastics	Grey cast iron	steel
3	Place of network (area fittings, ground conditions, surface, infrastructure)	8	small	medium	big

In Table 4, the assumed losses categories depending on the value FI (calculated according to eq.( 3) and Table 3 are presented.

**Table 4:** The proposed losses categories according to FI.

Losses category (C)	FI
Little $C=1$	$<50$
Medium $C=2$	$[50÷100]$
Large $C=2$	$>100$

In this way we can create the so-called maps of risk, draw the areas of tolerable, controlled and unacceptable risk on the plan of network

#### 4. An Example of Application

For example, the analysis of the WDS failures in a town with a population of 50 000 was carried out, based on the data obtained from the waterworks (from the years 2005-2009). The designed maximum daily productivity of water intakes equals the maximum production of treated water, which is 60 500 m<sup>3</sup>/d. The participation of particular intakes is the following:

- 36 000 m<sup>3</sup>/d, which constitutes 59.5 %,
- 17 000 m<sup>3</sup>/d, which constitutes 28.0 %,
- 7 500 m<sup>3</sup>/d, which constitutes 12.5 %.

Daily production of water in periods of maximum demand is 17 500 m<sup>3</sup>/d. The water supply system has the total length of 600 km and is made from the following materials:

- steel – 34 %,
- grey cast iron – 26 %,
- PVC – 22 %,
- PE – 18 %.

The functional structure of the water network pipes is as follows:

- main pipes  $L_{mw} = 87$  km; (DN 150÷500),
- distribution pipes  $L_{dw} = 246$  km; (DN 80÷110),
- household connections  $L_{wc} = 267$  km; (DN 32÷63).

Exploitation time of the network:

- up to 5 years – 6 %,
- from 6 years to 10 years – 12 %,
- from 11 years to 20 years – 25 %,
- above 20 years – 57%:
- from 21 years to 30 years – 22 %,
- from 31 to 50 years – 33 %,
- above 50 years – 3 %.

Cast-iron pipes are the oldest, their age is over 30 years, and in the city centre and the industrial district even 70 years. The cast iron was used in the construction of 60 % main and distribution pipes.

The number of failures in the particular kinds of water-pipe network has been analysed, referring to the water-pipe network length. The values of failure rate were calculated according to equation 4.

$$\lambda = \frac{k(t, t + \Delta t)}{L \cdot \Delta t} \quad (4)$$

where :

$k(t, t + \Delta t)$  – a total number of failures in a time interval  $\Delta t$ , in the given kind of network,  
 $L$  – length of the given kind of network (main, distributive, house connections) where failures occurred, in the given time interval [km],

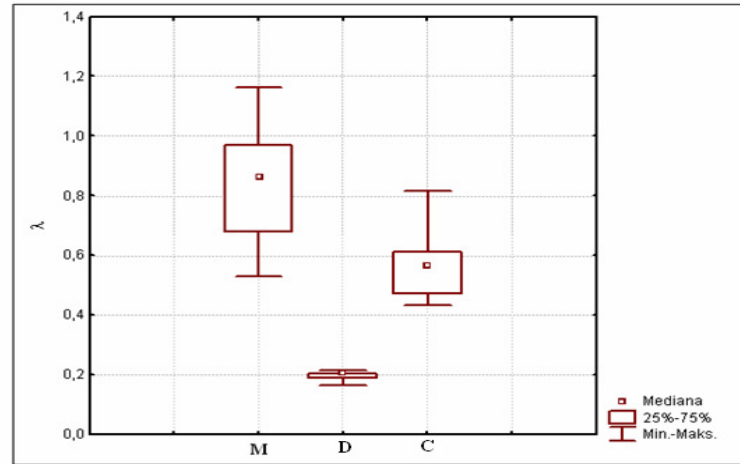
For the exemplary town, the WDS failure analysis in the years 2005-2009, brought the following results :

- failure intensity of main pipes  $\lambda_M = 0.84$  [number of failure/km·year], in view of the required [11]:  $\lambda_{Mreq} = 0.3$  [number of failure/km·year],
- failure intensity of distribution pipes  $\lambda_D = 0.19$  [number of failure/km·year], in view of the required [11]:  $\lambda_{Dreq} = 0.5$  [number of failure/km·year],
- failure intensity of waterworks connections  $\lambda_C = 0.58$  [number of failure/km·year], in view of the required [11]:  $\lambda_{Creq} = 1.0$  [number of failure/km·year].

In figure 1 the average values of the failure intensity (in the examined period of time) for three types of water network:

- the main network,
- distribution network,
- household connections,

are presented.



**Figure 1:** The failure intensity for the main network -  $\lambda_M$ , distribution network -  $\lambda_D$  and household connections -  $\lambda_C$

Based on the data concerning the water-pipe network failures that could be attributed to the specific streets, 4 streets, where the traffic difficulties caused by the water-pipe network repair occurred the most often, were selected, the mean failure intensity  $\lambda$  for the particular segments of the network for every street was calculated, and the results are presented in Table 5.

**Table 5:** Failure rate for the selected streets in the analysed WDS

Street name (type of network)	Length of segment [km]	$\lambda$ <u>number of failure</u> km · year
S 1 (water main)	4.5	0.8
S 2 (water main)	2.0	0.6
S 3 (distributive network)	1.0	0.08
S 4 (distributive network)	0.5	0.15

The characteristic of the network needed to determine FI and the values  $R_i$  i  $W_j$  are given in Table 6.

According to Table 2 and equations (1) and (2), the risk values are calculated and shown in Table 7. The steps of risk analysis method are the following:

- step 1: water pipe network analysis (type, materials, place and failure analysis)
- step 2: calculation of the failure rate  $\lambda$  and the failure index FI,
- step 3: assuming the losses parameter, according to the failure index (according to Table 4):  $FI \Rightarrow C$ ,
- step 4: assuming the likelihood parameter, according to the failure rate (according to Table 1):  $\lambda \Rightarrow P$ ,
- step 5: calculation of risk value,  $R = P \cdot C$ ,
- step 6: assuming of risk categories according to Table 1,

- step 7: decision making.

**Table 6:** The Characteristic of the Network

Street	Class characteristic	$R_i$	$W_j$	$R_i \cdot W_j$
S1	Water main network	10	3	30
	Material of network: grey cast iron	5	2	14
	Place of network: big	8	3	9
	<b>FI</b>			<b><math>\Sigma=64</math></b>
S2	Water main network	10	3	30
	Material of network: grey steel	5	3	15
	Place of network: small	8	1	8
	<b>FI</b>			<b><math>\Sigma=53</math></b>
S3	Water distributional network	10	2	20
	Material of network: plastics	5	2	14
	Place of network: big	8	3	9
	<b>FI</b>			<b><math>\Sigma=33</math></b>
S4	Water distributional network	10	2	20
	Material of network: plastics	5	2	10
	Place of network: medium	8	2	16
	<b>FI</b>			<b><math>\Sigma=46</math></b>

**Table 7:** The Risk Values

FI	C	$\lambda$	P	Risk value	Risk categories
for street S1					
64	2	0.9	3	6	unacceptable
for street S2					
53	2	0.4	2	4	controlled
for street S3					
33	1	0.08	1	1	tolerable
for street S4					
46	1	0.15	1	1	tolerable

This type of analysis is very helpful to classify these segments of water-pipe network which need repairing.

If the calculated values indicate that risk is:

- tolerable – one can assume that the water pipe network fulfils its functions in the satisfying way,
- controlled – an improvement in the work of some elements or repair of some sections of water pipe network should be considered.
- unacceptable – the water pipe network does not fulfil its functions and should undergo a complete modernization or even redesigning.

## 5. Conclusions

The goal of the paper is to demonstrate the value of an objective risk assessment tool for estimating the WDS decision-maker's sensitivity to failure risk. The usefulness of the objective risk assessment tool was demonstrated by defining three risk-sensitive (tolerable, controlled and unacceptable) decision response alternatives that are encountered by the



typical WDS decision-maker. Analysis of risk connected with the WDS functioning should be the main element of complex WDS risk management. The exploitation of urban WDS should take into account the minimization of water losses, operational and safety reliability. The procedures of the WDS correct designing, construction and operating should be completed with the detailed subsystem failure analyses, which are a base to estimate the subsystem reliability in a right way.

A very important role in the procedures of the failure analysis plays the right failure record, as well as opinions and estimations of experts and users. Risk is a measure which defines the safety level of water supply systems. Numerous failures which happen in water-pipe network force waterworks to carry out some modernizations and renovations, in order to minimize risk of failure. The presented method for the determination of the degree of exposure to failure can be used to classify the sections of the network for renovation or modernization. Using the operating data, field investigations and analyses made by experts, one can draw up the map of risk on the plan of water-pipe network in a very simple way and be able to identify particular areas of the tolerable, controlled and unacceptable risk. The GIS (geographic information system) program could significantly support the application of the described method in practise. The pipe failure data have been collected from a real water distribution network. During the study several parameters which affect the failure rate were collected (pipe diameter and type of network, length, age, depth, average hydraulic pressure).

## References

- [1]. Aven, T. *A Conceptual Framework for Risk Assessment and Risk Management*. Journal of Polish Safety and Reliability Association, 2010;1: 15-27.
- [2]. Ezell B.C. and J.V. Farr and I. Wiese. *Infrastructure Risk Analysis Model*. Journal of Infrastructure Systems. 2000; 6(3):114–7.
- [3]. Haimes. Y.Y. *On the Complex Definition of Risk: A Systems-based Approach*. Risk Analysis. 2009; 29(12): 1647-1654.
- [4]. Hastak H. and E. Baim. *Risk Factors Affecting Management and Maintenance Cost of Urban Infrastructure*. Journal of Infrastructure Systems, ASCE.2001; 7 (2): 67–75.
- [5]. Hradey, S.E. *Drinking Water Quality: A Risk Management Approach*. Water. 2001; 26(1): 29–32.
- [6]. Kaplan S. and B. J. Garrick. *On the Quantitative Definition of Risk*. Risk Analysis. 1981; 1(1):11-27.
- [7]. Kaplan S. *The Words of Risk analysis*. Risk Analysis. 1997; 7(4): 407-417.
- [8]. Mays L.W. *The Role of Risk Analysis in Water Resources Engineering*. www.public.asu.edu/lwmays . 2005: 8-12.
- [9]. Michaud D. and G. E. Apostolakis. *Methodology for Ranking Elements of Water- supply Networks*. Journal of Infrastructure Systems.2006; 12(4): 230–42.
- [10]. Pollard, S. J.T. and J. E. Strutt, B. H. Macgillivray, P. D. Hamilton, and S. E. Hradey. *Risk Analysis and Management in the Water Utility Sector: A Review of Drivers, Tools and Techniques*. Process Safety and Environmental Protection. 2004; 82(6): 1-10.
- [11]. Rak J. *Selected Problems of Water Supply Safety*. Environmental Protection Engineering. 2009; 35(2): 29-35.
- [12]. Shinstine D.S. and I. Ahmed and K. Lansey. *Reliability/Availability Analysis of*

- Municipal Water Distribution Networks: Case Studies*. Journal of Water Resources Planning and Management. ASCE. 2002; 128(2): 140-151.
- [13]. Sadig R., H. Najjaran and Y. Kleiner. *Investigating Evidential Reasoning for the Interpretation of Microbial Water Quality in a Distribution Network*. Stochastic Environmental Research and Risk Assessment. 2006; 21(1): 63-73.
  - [14]. Sadiq, R., E. Saint-Martin, and Y. Kleiner. *Predicting Risk of Water Quality Failures in Distribution Networks under Uncertainties using Fault Tree Analysis*. Urban Water. 2008; 5(4): 287-304.
  - [15]. Tanyimboh, T.T., R. Burd, R. Burrows, and M. Tabesh. *Modelling and Reliability Analysis of Water Distribution Systems*. Water Science Technology. 1999; 39(4): 249-255.
  - [16]. Tchórzewska-Cieślak, B. *Method of Assessing Risk of Failure in Water Supply System*. European Safety and Reliability Conference ESREL., Risk, reliability and societal safety. Norway, Stavanger, November , 2007; 2: 1535–1539.
  - [17]. Tchórzewska-Cieślak B. *Water Supply System Reliability Management*. Environmental Protection Engineering. 2009; 35(2): 29-35.
  - [18]. Tchórzewska-Cieślak B. *Failure Risk Analysis in the Water Distribution System*. Journal of Polish Safety and Reliability Association. 2010; 1: 247-255.
  - [19]. *Water Safety Plans (Revised Draft)*. Report publication WHO/SDE/WSH/02.09 (World Health Organization, Geneva, 2002.
  - [20]. *Guidelines for Drinking Water Quality*, 3rd edn. (draft).World Health Organization, Geneva, 2004.
  - [21]. Zio E. *An Introduction to the Basics of Reliability and Risk Analysis*. World Scientific, Singapore, 2007.

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