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Risk Indicators of Water Network Operation

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Indicators used for water pipe risk assessment are shown. The paper contains an example of risk assessment for a part of water distributing network using an expected equivalent resident water demand as a measurement o risk. This indicator clearly evaluates the consequences of pipe failures and at the same time retains the simplicity of estimation, which allows for its widespread usage in risk management.

1. Introduction

Risk in the technical literature is understood as the expected value of losses, therefore it is the sum of the product of the likelihood of undesirable events and associated with them losses, in the considered time interval (EN, 1050):

$$r = \sum_{i} P_i \cdot C_i \tag{1}$$

where P_i is probability of the i-th undesirable event and C_i are losses associated with the i-th event.

In many publications, both domestic and foreign, the results of numerous studies on water supply pipe failures were presented, therefore it can be concluded that the probability of failure of pipes is a problem well recognized in the scientific and technical literature (Mays, 1998). We analysed a number of water supply systems and obtained results for virtually full range of wire diameters, distinguishing between age and pipe material, operating conditions, and seasonality.

The issue of losses resulting from failure of pipes still remains to be developed. Obtaining real values of losses, expressed in monetary units, appears to be the optimal solution for the purpose of further applications in risk management, but this is an extremely complicated problem (Haimes, 1998). Risk issues associated with the operation of water supply should be considered in two aspects: the risk of Water Supply Company and the risk of water consumers. It results in a wide range of losses, both financial losses (cost of failure repair, loss of revenue resulting from the reduction in water sale, water supply company liability, losses of production, etc.) and, more difficult to estimate values, for example, related to the reduction of quality of life or loss of health (Ezell et al., 2000), resulting from lack of water (Tchórzewska-Cieślak, 2009) or its poor quality (Rak and Pietrucha, 2008a), which can be estimated only on a discretionary basis (e.g. in relation to water consumers the Willingness to Pay method). As a result, it seems necessary to develop new indicators of losses resulting from failure of water pipes, whose estimation would be as simple as possible and at the same time the obtained results would be satisfactorily reliable. Such approach will enable the widespread use of risk in water supply systems management.

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The subject of this paper is to analyse risk indicators used so far and attempt to present new values. The focus is on consumer's risk arising from the failure of water pipes. The presented values were illustrated by risk operational values obtained for one of the districts of the town of Krosno in last 6 years.

2. Water supply risk indicators

Among a large number of values used to describe losses C the descriptive indicators predominate. The magnitude of both, the probability of failure as well as losses resulting from them, was presented in the form of risk weights and obtaining the risk matrices (Rak and Pietrucha, 2008b). These methods have evolved through the introduction of higher number of factors affecting the amount of losses, for example, exposure to threat, the number of people potentially affected by the consequences of failure, the influence of protective barriers preventing the occurrence and consequences of threats and others (Tchórzewska-Cieślak et al., 2011).

One of the first value was an expected value of water shortage K_u - the indicator which binds the probability of failure and resulting water shortage. It is determined according to the relation:

$$K_u = 1 - \frac{E(N)}{V_n} \tag{2}$$

where E(N) is an expected value of water shortage during the relevant period (m^3) and V_n is total volume of water needed in the given balancing period, usually calculations are carried out for 1 day, hence V_n is assumed as a nominal daily demand Q_n (m^3).

In practical applications the calculations related mainly to the entire water supply systems rather than individual water pipes, the numerical limit values of this indicator for water supply systems of various sizes, have been developed (Martorell et al., 2010).

The value that can be defined as a measure of risk is time in which the water supply does not meet the requirements of the consumer. This value expresses the time in which the consumer is exposed to the water supply below the acceptable standards, both quantitative and qualitative. The value of indicator is expressed by time (minutes) of exposure of the statistical water consumer per year - Substandard Supply Minutes - SSM (Blokker, 2006). SSM is determined from the relation:

$$SSM = \frac{\sum_{i=1}^{n} t_i M_i}{M} \tag{3}$$

where t_i is duration of the i-th failure (min), M_i is a number of residents affected by the i-th failure and M is a number of residents supplied by the water supply system.

Risk can be also described by indicators used in other industries, for example in energy industry, such as: Average Short Interruption Frequency Index, Average Long Interruption Frequency Index, Average Water Volume Not Supplied, and others.

In the case of water pipes the range of the consequences of failure can be seen as the expected number of customers without water due to failure of the pipe. In this case the risk indicator is the expected number of residents affected by water deficit E(M):

$$E(M) = \sum_i P_i M_i \tag{4}$$

This indicator has some limitations arising from the fact that other groups of water consumers - mainly industry and services - are not taken into account. This disadvantage can be eliminated by expressing losses as the expected number of water connections without water supply E(J), according to the relation:

$$E(J) = \sum_i P_i J_i \tag{5}$$

where J_i is a number of water connections affected by the consequences of water pipes failure.
This value does not include the value of water consumed by individual customers and can falsify the obtained results. Therefore, as a negative consequence of failure, the universal value, equal to the demand for water for all groups of receivers, per capita, called further "the equivalent resident", has been introduced.

$$E(M_E) = \sum_i P_i \frac{Q_{Ni}}{q_{si}} \tag{6}$$

where Q_{Ni} is the expected volume of water not delivered to recipients (m^3), q_{si} is the demand for water for a statistical resident ($m^3 \cdot d^{-1}$), equal to the average daily demand Q_{da} divided by the number of residents serviced by water network M.

This indicator allows to differentiate water customers for residential consumers and institutional consumers. Although it does not specify the issue from a financial point of view, however, it clearly evaluates the consequences of pipe failures and at the same time retains the simplicity of estimation, which allows for its widespread usage in risk management.

3. The application method

The estimation of risk of water pipes for a district in one of the cities in the south - eastern Poland, was presented. The network diagram with the basic information on pipes is shown in Figure 1. In this segment of the network there are distribution pipes made of PVC and cast iron, with nominal diameters of 100 and 150 mm, connected in rings. Based on the revised pipe network hydraulic model the simulations of the exclusion of the individual pipes from the operation were performed. The analysis shows that in the case of distribution pipes the consequences of failure affect only the customers connected directly to these sections. The exception to this rule is the sections of the network terminal, where, because of the area configuration and the spatial distribution of buildings, the water supply network becomes radial. In the case of the main pipelines, because the city is supplied from 3 sources and water is stored in the network tanks, it can be stated that the closure of the main pipes does not adversely affect the pressure distribution in the water supply network (in the analysed area) until the network tanks are emptied. It means a minimum time of 4 h, depending on the volume of water demand and filling the tanks (Studziński, 2011). Therefore, because the probability of simultaneous failure of one of the analysed distribution pipes and the main pipe is close to 0, only simultaneous exclusion of the individual distribution pipes from the operation, was considered.
The probability of exclusion of pipes was calculated on the basis of operational data from the years 2005-2010. It can be determined using the relationship describing the empirical probability:

$$P_i = \frac{T_{pi}}{T_{pi} + T_{ci}} \tag{7}$$

where T_{pi} is the average working time without failures (d), $T_{pi} = 1/\lambda_i$ and T_{ci} is the average segment closing time during its repair, d.

$$T_{pi} = \frac{1}{\lambda_i l_i} \tag{8}$$

where λ_i is failure rate ($d^{-1} \cdot km^{-1}$) and l_i is pipe length (km).

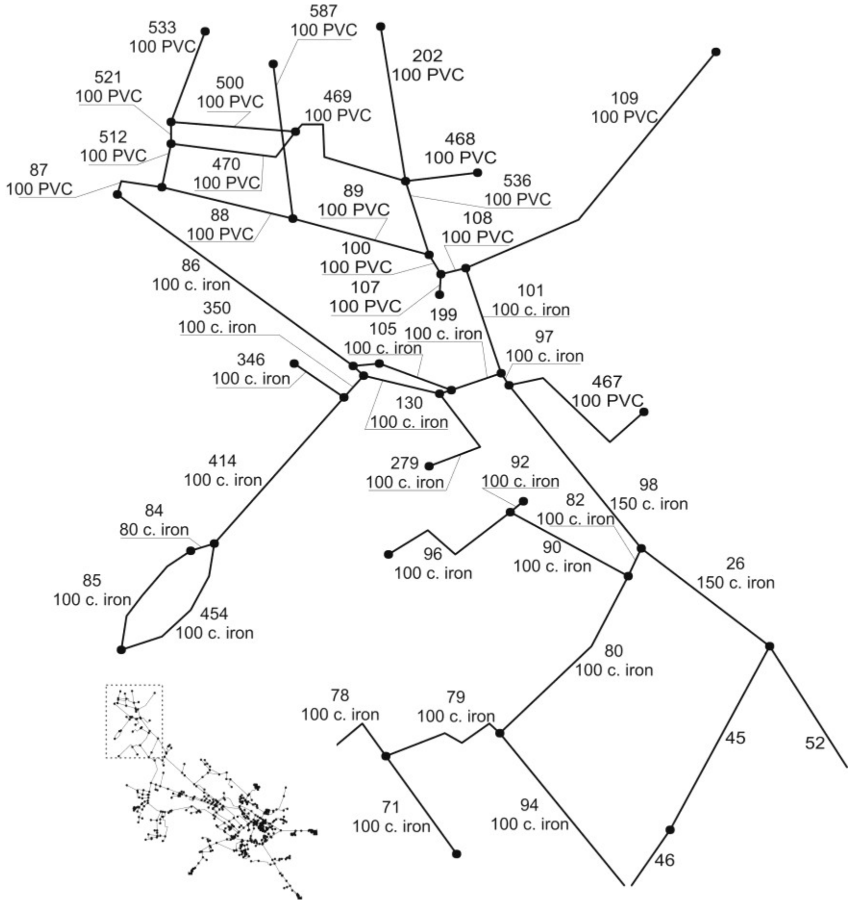

Figure 1: Diagram of the water network, number of pipeline/nominal diameter, material

The following values were obtained: T_{ci} = 3.96 h for DN 100 mm and 3.76 h for DN 150 mm, for cast iron pipes λ_i = 0.36 $km^{-1}\cdot a^{-1}$, for PVC 0.35 $km^{-1}\cdot a^{-1}$ (Pietrucha and Studziński, 2011). Risk calculations were based on Eq.6. The results are summarized in Table 1 and shown graphically in Figure 2. The unit water demand for a statistical resident is q_{si} = 276.5 $dm^3\cdot d^{-1}$.

The value r_i = 0 results from the lack of water partition in the segment (no water pipe connections). The obtained values result from the probability of failure and segmental partition. The compiled values indicate risk, expressed as the expected value of the equivalent residents, in the range 0.00014-0.041. The average risk value for the distribution pipes is 0.0079, and the standard deviation σ = 0.011. Figure 2 shows a graphical picture of the risk of the analysed water network segment. You can notice that for the analysed water network segment there is no dependence between risk and such parameters as age, material or pipe diameter. So we get another tool to manage water supply network.

Table 1: Summary of risk calculations for the water network

Pipe no	l_i	DN_i	P_i	$r_i\cdot10^4$	Pipe no	l_i	DN_i	P_i	$r_i\cdot10^4$
	m	mm	-	-		m	mm	-	-
26	276	160	$4.1\cdot10^{-5}$	65	108	25	110	$4.0\cdot10^{-6}$	0
71	303	100	$4.9\cdot10^{-5}$	32	109	759	110	$1.2\cdot10^{-4}$	106
78	1354	100	$2.2\cdot10^{-4}$	405	115	2,5	100	$4.1\cdot10^{-7}$	0
79	324	100	$5.3\cdot10^{-5}$	205	121	33	110	$5.2\cdot10^{-6}$	0
80	267	100	$4.3\cdot10^{-5}$	0	130	148	110	$2.3\cdot10^{-5}$	0

Table 1: Summary of risk calculations for the water network (continued)

Pipe no	l_i m	DN_i mm	P_i -	$r_i \cdot 10^4$ -	Pipe no	l_i m	DN_i mm	P_i -	$r_i \cdot 10^4$ -
82	53	100	$8.6 \cdot 10^{-6}$	0	136	24	110	$3.8 \cdot 10^{-6}$	1
85	760	100	$1.2 \cdot 10^{-4}$	93	199	112	110	$1.8 \cdot 10^{-5}$	0
86	873	100	$1.4 \cdot 10^{-5}$	330	202	1270	110	$2.0 \cdot 10^{-4}$	468
87	107	110	$1.7 \cdot 10^{-5}$	5	346	137	100	$2.2 \cdot 10^{-5}$	9
88	340	110	$5.4 \cdot 10^{-5}$	86	350	40	100	$6.5 \cdot 10^{-6}$	25
89	558	110	$8.8 \cdot 10^{-5}$	7	414	578	100	$9.4 \cdot 10^{-5}$	281
90	230	100	$3.7 \cdot 10^{-5}$	61	454	836	100	$1.4 \cdot 10^{-4}$	102
92	33	100	$5.4 \cdot 10^{-6}$	3	467	413	110	$6.5 \cdot 10^{-5}$	94
94	484	100	$7.9 \cdot 10^{-5}$	72	468	187	100	$3.0 \cdot 10^{-5}$	24
96	562	100	$9.1 \cdot 10^{-5}$	46	469	589	100	$9.6 \cdot 10^{-5}$	15
97	32	160	$4.8 \cdot 10^{-6}$	0	470	413	100	$6.7 \cdot 10^{-5}$	22
98	381	160	$5.7 \cdot 10^{-5}$	46	500	365	100	$5.9 \cdot 10^{-5}$	23
100	67	100	$1.1 \cdot 10^{-5}$	7	512	101	110	$1.6 \cdot 10^{-5}$	0
101	176	100	$2.9 \cdot 10^{-5}$	5	521	60	100	$9.8 \cdot 10^{-6}$	0
105	148	110	$2.3 \cdot 10^{-5}$	0	533	175	110	$2.8 \cdot 10^{-5}$	11
107	23	110	$3.6 \cdot 10^{-6}$	0	587	317	110	$5.0 \cdot 10^{-5}$	54

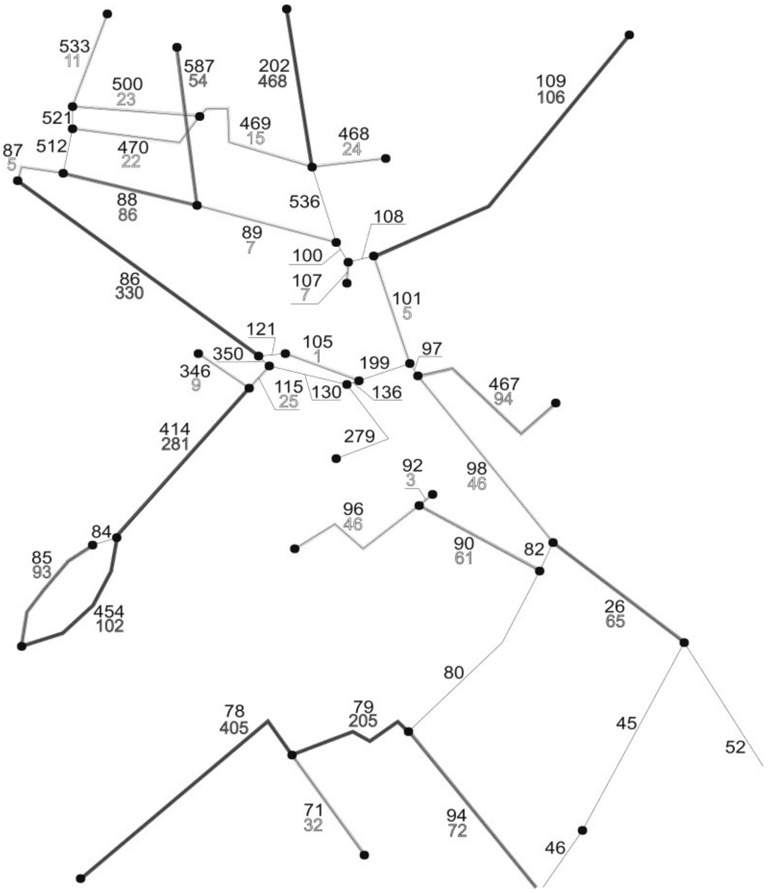

Figure 2: Map of risk, number of pipeline/risk $r_i \times 10^4$

4. Conclusion

Although the beginnings of the science of risk date back to the 60's of the twentieth century there is still a wide spectrum of issues that require research. The difficulties arising from the global way of describing the risk are particularly pointed out. It is commonly believed that we should aim to develop methods of risk assessment and reliable numerical values of risk, expressed in monetary values. Given the scope of potential losses, such approach is still in research. This also applies to the risk arising from failure of water pipes. Used so far methods and indicators for estimating the risk of failure of water pipes are not very reliable, as a result of taking into account an individual aspect of the losses, or extremely complicated and then they do not find wider application in the waterworks companies management practice. We proposed to express losses resulting from failure of water pipes as the expected value of the number of the equivalent residents without water. It is the value that allows numerical estimation of losses and, especially, the comparison of the consequences of undesirable events - thus it can facilitate decision-making processes in the waterworks company. The presented methodology is also relatively simple and the range of data necessary for risk assessment usually coincides with the values currently used in operational practice. Although this indicator brings us closer to a quantitative description of the risk, however, it is still only a step towards the determination of monetary losses.

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