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# FAILURE RISK ANALYSIS OF WATER DISTRIBUTIONS SYSTEMS USING HYDRAULIC MODELS ON REAL FIELD DATA

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ABSTRACT: At this paper the analysis of failure risk in the two water supply systems in the south-eastern Poland is presented. For this purpose the hydraulic models of the water networks created in the EPANET 2 on the basis of data obtained from the water networks operation were used. The consequences of failure of individual pipelines were determined. The areas that are most vulnerable to pressure fluctuations in the water supply system resulting from the failure of these pipelines, were located.

KEY WORDS: water supply, failure, hydraulic models, risk indicators, reliability analysis

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## Introduction

The hydraulic and quality water supply network models are a huge source of information about the system being operated. The dynamic models of water distribution systems are particularly useful in diagnosing the state of the operating system, developing the concept of expansion or modernization of water supply systems (Haimes, 1998; Hallmann, Suhl, 2016; Mielcarzewicz, 2000; Zimoch, 2012; Zimoch, Lobos, 2012).

The failure in water supply network can disturb the operation of water supply network (Blokker, 2006; Boryczko et al., 2014; Tchórzewska-Cieślak et al. 2018; Tchorzewska-Cieslak, Pietrucha-Urbanik, 2014; Tchorzewska-Cieslak, Rak, 2010). The failure occurrence of water pipes can influence waterworks company and the water consumers. The emerging consequences can cover the following spectrum of losses, from financial losses to losses which are difficult to estimate, such as losses related to the decrease of life quality or health loss due to lack of water or poor quality water (Iwanejko, Wieczysty, 2001; Rak, 2004; 2008; Zimoch et al., 2007). In this case calculating the real value of losses in the monetary units can be the best solution for the further implementation in risk management. However, obtaining such values can constitute the extremely difficult issue, also related to criterial reliability values of communal water supply systems (Roman, 1986).

A number of water supply systems and obtained results for almost whole range of pipe diameters, distinguishing pipe age and material, operating conditions and seasonality, were analysed (BS EN 15975-2:2013; Hotloś, 2007; Karamouz et al. 2010; Kowalski et al. 2015; Kozłowski, 2018; Królikowska, 2011; Kutylowska, 2015), but the issue of losses resulting from failure of water pipes still remains to be developed.

By conducting computer simulations it is possible to test various possible solutions and to compare the effects between them (Bene, Selek, 2012; Knapik, 2001; Wierzbicki, 2015). The effect of the study is that universal indicators of losses resulting from the failure of waterworks pipes seem necessary to be obtained.

## Research methodology

### Research object

In the work two water supply systems were distinguished.

Water supply system (A) is supplied from three independent water intakes. The distribution of water to consumers takes place through water supply network, which has a ring-radial system, which positively affects the assessment of the reliability of the water supply system. The total length of the water supply network is approximately 400 km. The material structure of the water supply network is as follows: grey cast iron 30%, steel 1%, PVC 34% and PE 35%. In terms of the age structure of the water supply network pipes is as follows 5 years – 5%, from 6 to 10 years – 11%, from 11 to 20 years – 28%, over 20 years – 56%, where: from 21 to 30 years – 22%, from 31 to 50 years – 32%, over 50 years – 2%. Almost 50 thousand of inhabitants are being supplied from distinguished water supply network with the average daily water demand through the year equal to 13,3 thousand $m^3/d$. The failure rate for distributional pipes in last year of observation equals to 0,38 $km^{-1} \cdot year^{-1}$. The failure rates in the concerned system are below the 0,5 $km^{-1} \cdot year^{-1}$, which can be considered as an average failure rate according to the criteria presented in (Kwietniewski, Rak, 2010; Kwietniewski, et al., 1993).

Network of water supply system (B) is made almost entirely of PVC, pipelines that have been damaged are converted into PE. The total length of the network is 250 km. The intake of water is a set of four wells with a total operating capacity of 110 $m^3/h$. Distribution of water to users is conducted through the water supply network system, which is ring-radial, which positively affects the water supply reliability. The average daily water consumption is 500 $m^3/d$. Comparing the determined failure rate of the tested network (0,11 $km^{-1} \cdot year^{-1}$) to the rigorous criteria related to the main network and amounting to 0,3 $km^{-1} \cdot year^{-1}$ (Rak, 2005). This is probably due to the young age of the water supply network, the oldest sections of which are only 25 years old.

## The Hydraulic Model of Water Supply Network

The hydraulic model of the water supply network was created in the Epanet 2 program on the basis of real operational data received from the water supply company.

The research methodology consists in determining the consequences of failure of selected sections, including the water supply risk indicators presented in point 3.2. For each pipe in which the failure was simulated, the duration and consequences of the failure were determined. In the work, the hydraulic model of the water supply network was created using the EPANET 2.0 program. It is a program that performs extended hydraulic simulations and simulations of water quality behaviour in pressure networks. The network is made of pipes, nodes, pumps, valves and storage tanks or reservoirs. During the simulation, the EPANET program enabled tracking water flow in pipes, pressure changes in individual nodes, changes in water level in all tanks.

The purpose of the water supply failure analysis is to present the hydraulic effects of failure of individual water supply network pipes of the considered water supply systems. The following factors such as range, duration of failure and the number of inhabitants without water, were examined. The hydraulic models created on the basis of the program Epanet 2 were used for the analysis of failures of each distributional pipe by determining the difference in pressure in the network nodes in failure-free conditions and during failures. State of emergency was simulated by closing the individual sections of the network.

## Implementation of Water Pipe Failure Risk Indicators

The following water pipe failure risk indicators were implemented according to the methodology presented in (Pietrucha-Urbanik, Studziński, 2018) and adapted from (Kwietniewski et al., 1993; Wieczysty, Iwanejko, 1996).

The probability of pipes exclusion was calculated on the basis of operational data. It can be determined using the formula describing the empirical probability (Kwietniewski et al. 1993; Wieczysty, Iwanejko, 1996):

$$P_i = \frac{T_{wi}}{T_{wi} + T_{ci}}, \tag{1}$$

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

$$T_{wi} = \frac{1}{\lambda_i l_i}, \tag{2}$$

where:
$\lambda_i$ is the failure rate ($d^{-1} \cdot km^{-1}$),
$l$ is pipe length (km).

The risk indicator is based on the expected value of water shortage $R_t$ – the indicator which binds the probability of failure and resulting water shortage.

It is determined according to the dependence (Wieczysty, Iwanejko, 1996):

$$R_t = 1 - \frac{E(S)}{V_n}, \quad (3)$$

where:

$E_{(S)}$ is an expected value of water shortage during the relevant period [$m^3$],

$V_n$ is total volume of water needed in the given balancing period, usually calculations are carried out for 1 day, hence Vn is assumed as a nominal daily demand $Q_n$ [$m^3$].

Index of Average Time of Water Not Supplied (ATWNS) distinguish the time in which the water supply does not meet the requirements of the consumer, below the acceptable standards, both in quantitative and qualitative way and is expressed by time (hours) of exposure of the statistical water consumer per year, determined as (Pietrucha-Urbanik, Studziński, 2019) the multiplication the duration of the *i*-th failure (h) – $T_{ti}$ and the number of inhabitants affected by the *i*-th failure – $INH_i$ per a number of residents supplied by the water supply system – $INH_i$.

The range of the failure consequences can be calculated 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 $E(INH)$ (Pietrucha-Urbanik, Studziński, 2019).

Failure consequences can also be expressed by the losses of the expected number of water connections without water supply, as a result of the consequences of water pipes failure.

The other risk indicators can distinguish interruption frequency and length, as well as not supplied average water volume (Hotloś, 2007; Królikowski, Królikowska, 2010; Marques, Monteiro, 2001, Mays, 1998).

## Results

### Hydraulic simulation of consequences of water pipes failures – a case study concerning the most serious failures

Due to the large number of obtained results of the failure analysis, it was decided to present only those that have the largest operating range and cause the highest pressure drops in the distribution network.

## Water network (A)

Simulation of pipe failure No. 347 with a diameter of 160 mm and a length of 716 meters. The failure caused the close of section 347 for 7 hours: 7:00 – 14:00. The pipe is located in the Polanka district on Skłodowska-Curie Street (figures 1 and 2). During the renewal of the section without water will be 152 inhabitants.

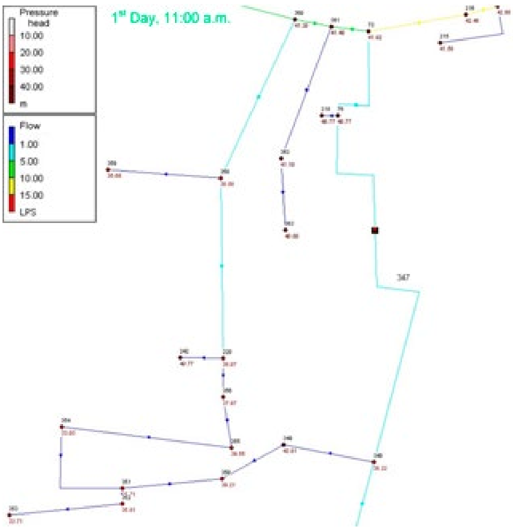


Figure 1. Model of water supply system during failure-free operation – no 347

Source: author's own work.

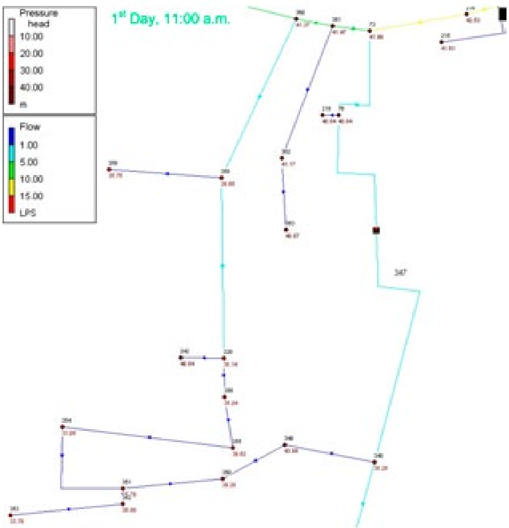


Figure 2. Model of water supply network during failure operation – no 347

Source: author's own work.

The results of calculations of failure of section 347 regarding only selected network nodes are shown to cause the following pressure changes in the nodes:

- node 348 – pressure drop by 2,17 m $H_2O$ to the level of 36,05 m $H_2O$ at 11:00 a.m. (4th hours of failure) in relation to the work of a failure-free model,
- node 353 – pressure drop by 1,96 m $H_2O$ to the level of 31,75 m $H_2O$ at 11 a.m. (4th hours of failure) in relation to failure-free operation,
- node 349 – pressure drop by 2,09 m $H_2O$ to the level of 41,72 m $H_2O$ at 11 a.m. (4th hours of failure) in relation to failure-free operation.

## Water network (B)

The failure was simulated on section 226, it is the main power supply for the commune, from water treatment plant towards city. The diameter of the pipe is 225 mm and length of 100 m. Failure caused the section to be closed for 7 hours from 7 a.m. to 2 p.m. During the renewal of the section, the majority of the commune residents will struggle with large water problems. This is the most serious failure, which covers a very large area of the commune, the worse situation from the above is the damage of the main from the water treatment plant, when the whole commune will remain without water for the period of repair (figures 3 and 4).

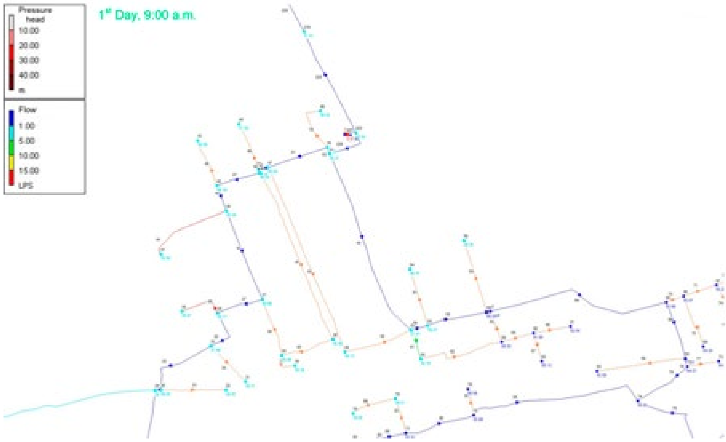


**Figure 3.** Model of water supply system during failure-free operation – no 226

Source: author's own work.

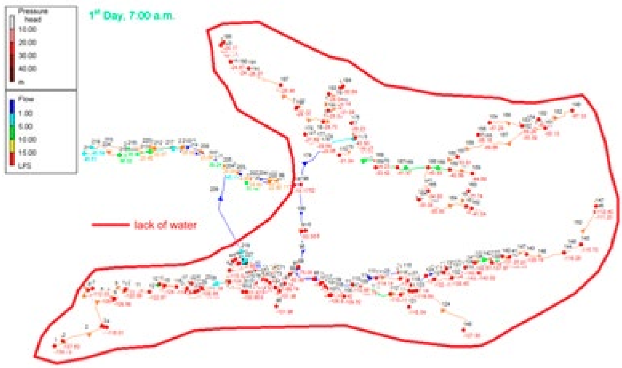


**Figure 4.** Simulated failure of water pipe section no 226 – the first to the third hour of failure-free operation – no 226

During the first three hours, only one commune had access to the water, the remaining part of the commune was without water. A significant drop in pressure was noted compared to work without failure in places where water was available, without water was in total 5274 inhabitants.

## Comparison of Risk Indicators of Water Networks Operation

On the basis of formulas presented in point 2.3 the risk indicators of the consequences of failure in water pipeline in two concerned water supply systems were calculated.

The results are summarized in figures 5-10.

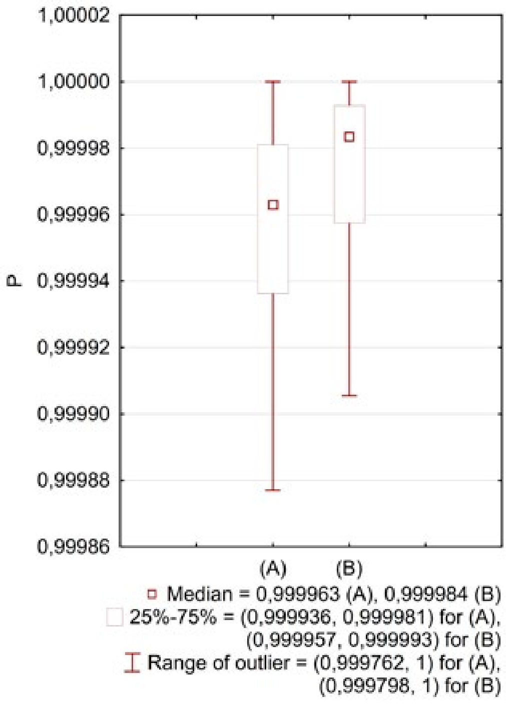


**Figure 5.** Summary of risk calculations for the water networks (A) and (B): the probability of pipes exclusion – P

Source: author's own work.

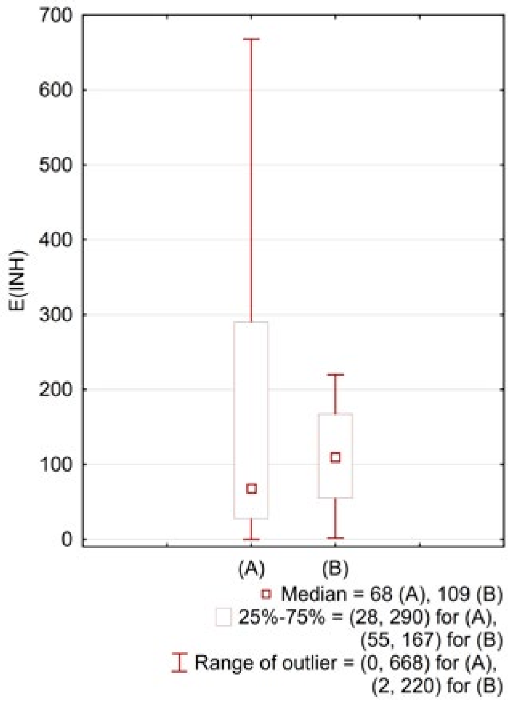


**Figure 6.** Summary of risk calculations for the water networks (A) and (B): the expected number of residents affected by water deficit – E(INH)

Source: author's own work.

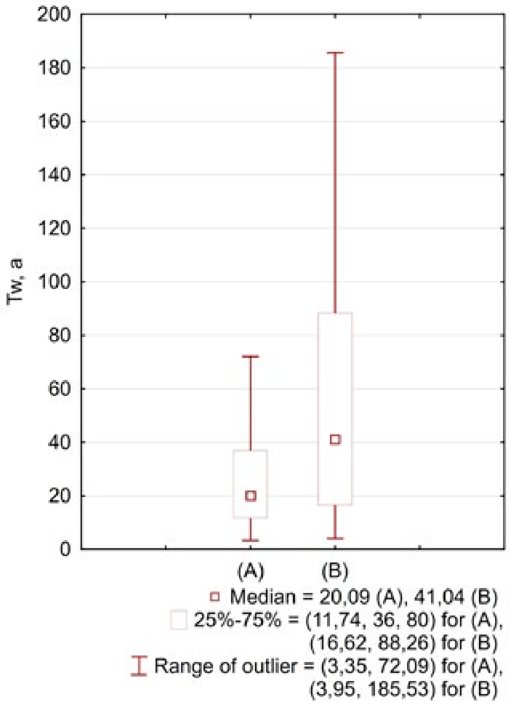


**Figure 7.** Summary of risk calculations for the water networks (A) and (B): the average working time without failures – Tw

Source: author's own work.

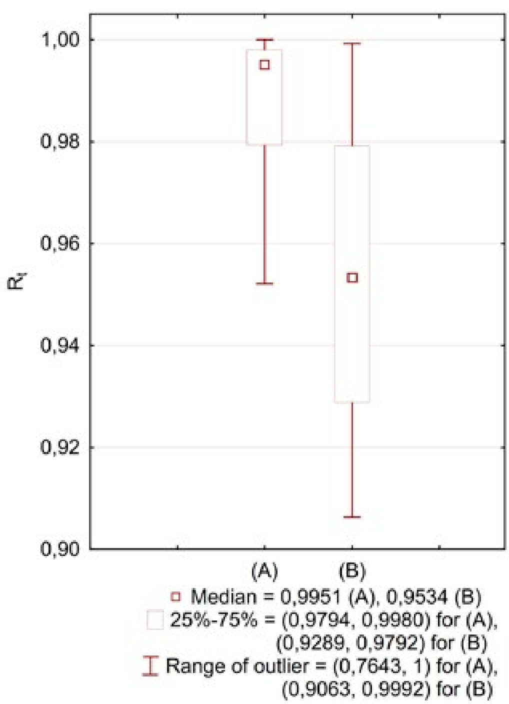


**Figure 8.** Summary of risk calculations for the water networks (A) and (B): the risk indicator – Rt

Source: author's own work.

The results confirm the specificity of the considered systems. Water network (A) is characterized by lower values of average time of water not supplied (ATWNS), with median value in this system 0,0099. In comparison to water network (B) with median value of ATWNS 0,99, such difference is a result of water-ring network in (A) case, and cause smaller consequences of failures. The branch structure of water network (B) influence dependent indicators, such as risk indicator and the expected number of residents affected by water deficit.

The obtained values indicate the necessity of providing the calculations as to propose the criteria values of risk indicators.

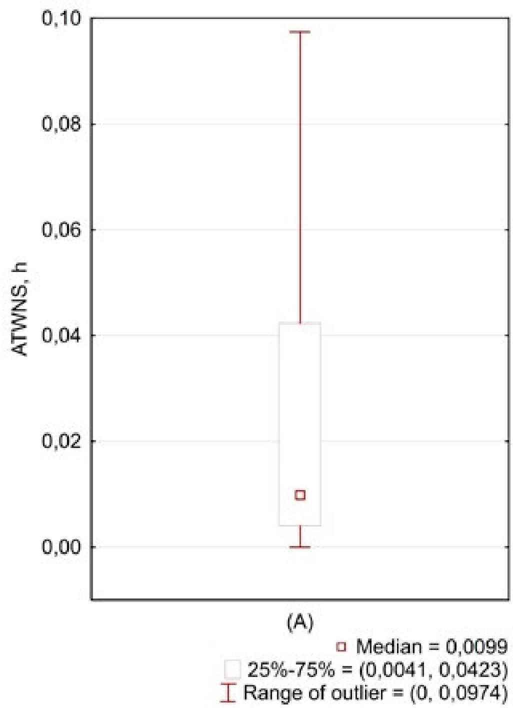


**Figure 9.** Summary of risk calculations for the water network (A): average time of water not supplied – ATWNS, hour

Source: author's own work.

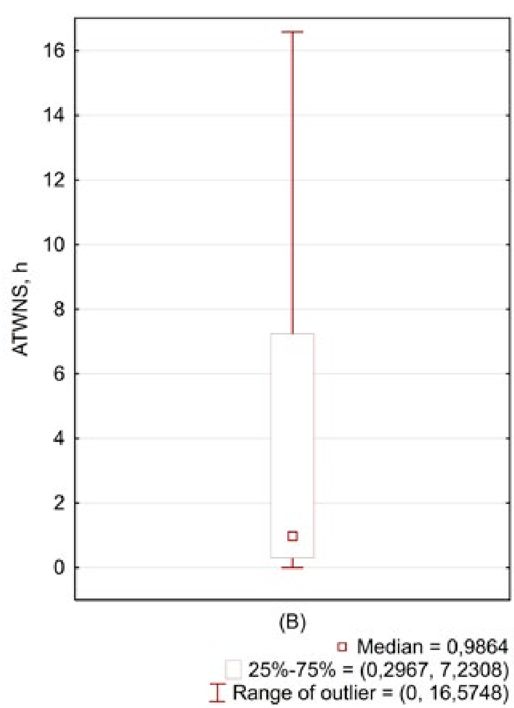


**Figure 10.** Summary of risk calculations for the water network (B): average time of water not supplied – ATWNS, hour

Source: author's own work.

## Discussion of results

### Water network (A)

The largest decreases in pressure were recorded on the other seven sections: 281, 265, 617, 149, 368, 475 and 45. The range of effects of failure of individual pipes is local. It results from the fact that the analyzed water supply network has in the majority of cases ring structure, which significantly affects the minimization of the failure consequences of a single section. The following results were obtained: pressure drop to 0 meters $H_2O$: 95 sections, pressure drop above 5 m $H_2O$: 3 sections, pressure drop 2-5 m $H_2O$: 8 sections, pressure drop 1-2 m $H_2O$: 14 sections, pressure drop below 1 m $H_2O$:

100 sections. After analyzing the pressure drops in the distribution network and the minimum value of the economic pressure (depending on the number of buildings floor), it was stated that the limit values were not exceeded. All the more so considering the required pressure will be maintained during fire on the outside hydrant of 0,1 MPa (Journal of Laws No. 121 item 1139). It can therefore be concluded that failures on individual sections will not have a significant impact on the supply of water to residents of other streets.

### Water network (B)

During the failure-free operation, it was noticed that the water supply network is considerably oversized, the flow velocities are almost lower than 0,2 m/s in almost entire water supply network. This is due to the need to adapt the water supply network to the fire regulations, the water network is extensive and during fire distribution oversized diameters allow to reduce pressure losses and keep the required pressure on the head of the hydrant in accordance with applicable regulations. The negative effect is the significant time of water remaining in water network and the possibility of its secondary contamination. Counteract this phenomenon requires frequent flushing of pipes, which at the extent of the water supply network generates significant water loss. Oversizing the water pipes forming the ring: 58, 64, 69, 76, 84, 86, 89, 90 helps to maintain high pressure in the event of failure of one of them. The consequences of the failure only affect the recipients supplied from this section. The sections whose failure influences the largest number of water consumers are aforementioned section 226, the remaining sections deprive the water to a smaller number of residents 2937 and 2391, respectively, during the most unfavorable conditions on the network (the largest hourly distribution during a failure). In most cases, the radial geometric structure of the water supply network causes that failure of the sections results in lack of water of all subsequently supplied sections. Therefore, it seems necessary to connect another ring between nodes 162 and 137 or at the end of the western network between nodes 147 and 149.

## Conclusions

The obtained values of the indicator $E(INH)$ specified by the formula (5) result from two components: the probability of failure and its consequences understood as the number of recipients experiencing water deficit. The probability of failure is mainly related to the age and material of the pipe, it also results from the assembly technology or the diameter of the pipe and has been thoroughly characterized in (Kwietniewski, Rak, 2010). The number of recipients experiencing water deficit is mainly the result of the structure of the water supply network. Comparing the results obtained for the city A and for the city B, it can be noted that in the municipal water supply A the median is much smaller than in B, which results from the fact that during the repair of pipes being part of a closed ring it is possible to detach customers directly connected to the excluded section, the other water consumers use it without any quantitative restrictions. At the same time the average value of the median of water network (A) and the obtained maximum value significantly exceed those values for water network (B). This is due to the areas of high population density (the residential areas with a high population density) supplied by the individual pipes. Such a situation is not observed in the municipal water supply system.

An interesting reference is made to compare the obtained values to water network (C) in the city concerned in (Pietrucha-Urbanik, Studziński, 2019), where the water supply system is entirely constructed contemporarily (the beginning of the water network reaches the seventies of the last century, refers to both the structure of the material and geometric of water supply system, in particular of similar distribution of diameters). The city (C) has the size and population density close to A (1073 inhabitants/km$^2$ in A and 982 inhabitants/km$^2$ in C, respectively), but the median of indicator $E(INH)$ is only 19, and the average value is 35. The observed difference in relation to A should be explained primarily by the geometric diversity of the water supply network. The waterworks (C) has the smallest network terminals in the open structure, which determine the largest number of residents affected by water deficit. In turn, the highest values of $E(INH)$ concern the water supply (B) with dominant open structure, which proves that the geometric structure of the water supply network is one of the key risk factors for the lack of water supply for residents. The results obtained for waterworks confirm the conclusion presented in (Pietrucha-Urbanik, Studziński, 2019), that values of water network (C) can be treated as desirable reference values for other waterworks.

## The contribution of the authors

All authors contributed equally to the manuscript.

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