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RESEARCH ARTICLE

Approaches to Assess Water Distribution Failure

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Abstract
In the thesis failure analysis and assessment of water supply system in considered city was presented. The analysis was prepared on the basis of the exploitation data obtained from water company. The characteristic of water distribution system was presented. Indicators of failure rates were calculated. Data were presented in division to diameter, material, type, season and month of failure.

Keywords
water supply system, failures, failure analysis, failure rate, failure seasonal changeability

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1 Introduction

Water suppliers more and more often deal with the problem of maintaining water supply with appropriate parameters. It is caused by a number of factors which are inevitably associated with the development of civilization and its unavoidable consequences [1]. Losses, which appear as a cause of water pipe failure can be related to the producer as well as to the water consumers [2]. With regard to water companies losses resulting from the failure of water pipes include the cost of failure removal, including the cost of preparing to repair, its execution, inclusion repaired section to the operation and return the site to its original state, the losses associated with the volume of water unsold as a result of the failure, additional losses resulting from the failure, e.g. the costs of flooding removal, changes in traffic organization, the costs arising from responsibility of the water company to the water customers, e.g. penalties for lowering the standards of water supply to consumers and the costs associated with the maintenance the repair service in full availability [3]–[4]. The water consumer bears the costs associated with the lack of water supply, which in case of industry and services is understood as a reduced production or producing lower quality goods [5], [6], [7], in case of housing the costs are more difficult to estimate, related to, for example, the purchase of bottled water and the potential costs of losing health resulting from the difficulties in maintaining hygiene or related to the inability to use tap water to extinguish fires [8].

To assess water supply network operation the failure rate is used [9], its criteria values were proposed in various studies, among others in [10], [11], [12]. In the work [12] the failure criteria with regard to reliability were presented and three classes were distinguished. The first class is characterized by the low failure rate and high reliability for the failure rate of less than 0.1 failure/km/year, the next is the average failure rate and reliability with the failure rate in the range from 0.1 to 0.5 failure/km/year and the last with high failure rate and low reliability for the failure rate over 0.5 failures/km/year).

In the study [11] for water pipes the following boundary criteria depending on the function performed by the water supply pipeline were proposed:

- failure rate for mains $\lambda_{Mdem} = 0.3$ failure/km/year,
- failure rate for distributional pipes $\lambda_{Ddem} = 0.5$ failure/km/year,
- failure rate for water connections $\lambda_{WCdem} = 1.0$ failure/km/year.

The failure rate of pipes can be a determinant to perform the water supply network renewal and to plan repairs and replacement of individual pipes.

In the world literature there are many studies concerning problem of water pipes failures, taking into account such causes of those failures as, for example, land subsidence e.g. [13], corrosiveness of water flowing inside the water pipe e.g. [14], freezing of ground around the water pipe e.g. [15], climatic or ground conditions eg. [16], [17], failures caused by earthworks e.g. [19], an external load by traffic e.g. [20], material defects e.g. [21], errors made during construction or in water pipes designing e.g. [22] or by the course of failure e.g. [23], [24], [25], [26], [27].

The occurrence of mentioned above factors influence the water pipe failure by the occurrence of corrosion pits, longitudinal and transverse cracks, leaks of pipes connection.

Due to the importance of the subject in this work the analysis and assessment of water supply network failure in the chosen city were performed. For the analysis and assessment of water network failure data of network operating, failure reports submitted by the water company to the Central Statistical Office (CSO) and other available information on the functioning of the water supply company were used.

2 Characteristics of studied object

Water supply system in the considered city is located in the south-eastern part of Polish river Wisloka, in Podkarpackie province, in Poland. In the city there are a lot of industrial plants, mainly in the economic zone. According to CSO data at the end of 2014 the city had a population of 60 827 inhabitants and covers area of 46.86 km^2, including 664 ha of forests and forestry land.

The first water supply system was built in 1938 and was supplied from the underground water intake. In 1954 the first intake of water from the Wisloka river was made and Water Treatment Plant was built. The new intake was put into operation in 1987 and is used till now. It was made as a typical boundary intake on the right bank of the Wisloka river between the old intake and the damming threshold. Capability of water intake and existing water permit is 445 dm^3/s.

The total time of failure removal in the water supply system is from 3 to 6 hours. This time depends on the type of failure and the diameter of the damaged pipe. The most common causes of network failure made from cast iron are breaking, from asbestos-cement - longitudinal cracks, from PVC - mechanical damage.

Currently, the water supply system works as general supply system, pump, single-zone system without expansion tanks. The greater part of the city is covered by a network ring, only a small part of the network is working as branch network.

Material composition of water supply network

Due to over 60 years of operation of the water distribution system, the network is characterized by a great diversity of age and material. The material structure of the supply network is an important issue because this parameter indirectly characterizes the technical condition of the water supply network. The percentage of materials in the entire pipe network is shown in Figure 1. The water supply network is built mostly of PVC (55%) and cast iron (31%). The remaining 14% is a network made of HDPE (high-density polyethylene), PE (polyethylene), galvanized steel and AC (asbestos cement).

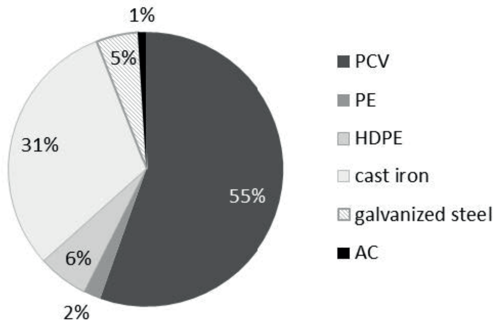

Fig. 1 The percentage of materials in the entire water supply network

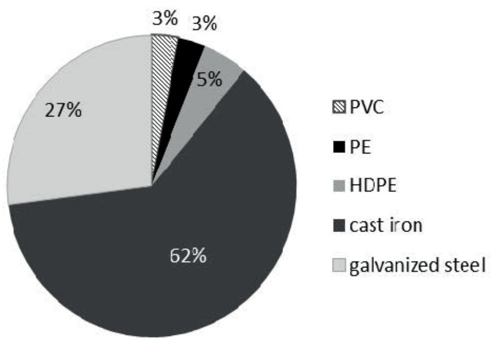

Fig. 2 The percentage of materials in the mains

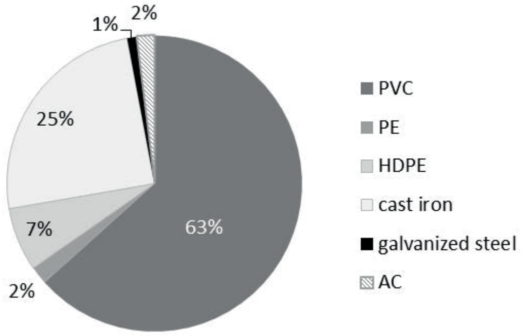

Fig. 3 The percentage of materials in the distributional network

Considering material structure depending on the network type it can be noticed that the most part of the main network is made of cast iron (62%) and galvanized steel (27%). The rest (11%) is made of HDPE, PE and PVC (Fig. 2). Galvanized steel and asbestos cement are not included in the material structure of the main network. The distribution network is made of PVC (63%) and of cast iron (25%) (Fig. 3). In the examined water supply system material structure of water network has changed significantly since 1990, which was caused by the fact that in recent years for the construction of water supply system were used pipes and fittings made of polyvinyl chloride (PVC), polyethylene (PE) and HDPE. It can be observed for the entire network a significant increase in the use of PVC pipes by 17.6%, PE pipes by 1.3%, HDPE by 6.3%, compared to 1990. In the case of steel pipes the use of this type of material has decreased by 3.1% whereas cast iron decreased by 21.1%. Analysing the material structure of the examined water supply system it can be stated that the factor influencing the type of material which was used to build the water supply system was the period when the network was built and global trends of using in recent years plastic materials in the construction of water supply network.

The age structure of the water supply network

The age structure of the water supply network is shown in Figures 4–6, which indicates that approx. 17.4% of the entire length of the studied network is more than 50 years old, while only 10.7% is less than 5 years old.

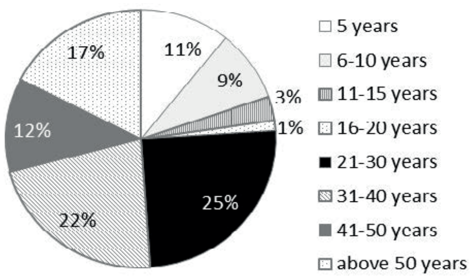

Fig. 4 Percentage age structure of the entire water supply network

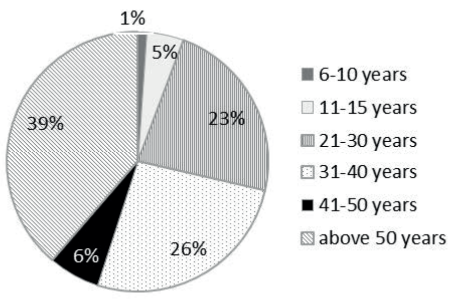

Fig. 5 Percentage age structure of the mains

As for the mains it can be seen that pipes over 50 years old constitute almost 40% of the entire network. This is due to the fact that since 2010 no water mains were modernized. The distributional pipes which age does not exceed 5 years represent 12,5% of the total length of pipes that type.

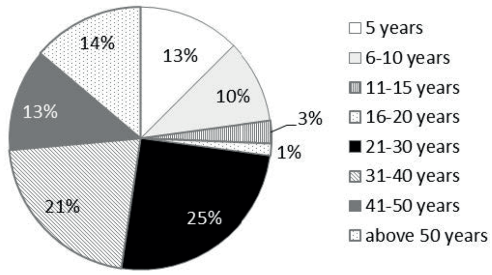

Fig. 6 Percentage age structure of the distributional network

The operating time and the material from which water pipes are made have significant impact on the water supply network failure rate. Analysing Figure 4 it can be seen that the pipes with time operation less than 6 years represent 11% of the total length of the network. However, the pipes older than 20 years constitute about 76%. Therefore it can be stated that the water supply system is characterized by a decades-long operation. In the time intervals to 5 years and 16–20 years, there is lack of the operating mains.

3 Results of studies

3.1 Failure frequency of water supply network expressed by the failure rate

To assess technical condition of the water supply system the index of failure rate (λ) [9], describing the frequency of the number of failures in the time interval per length of examined pipes (km), was used (Eq. 1).

$$\lambda_i = \frac{n_i(t, t+\Delta t)}{l_i \cdot \Delta t} \tag{1}$$

where n_i is number of failures in a time period Δt and l_i is the length of particular type of water pipes, on which failures appeared per one year, in km.

3.1.1 Failure rate of the network depending on the pipe function

In Figure 7 the values of the failure rates in years 2012-2015 for different types of water pipes: the mains (λ_M), the distributional pipes (λ_D), the water supply connections (λ_{WC}) and for the entire water supply network (λ_{M+WC+P}) were shown.

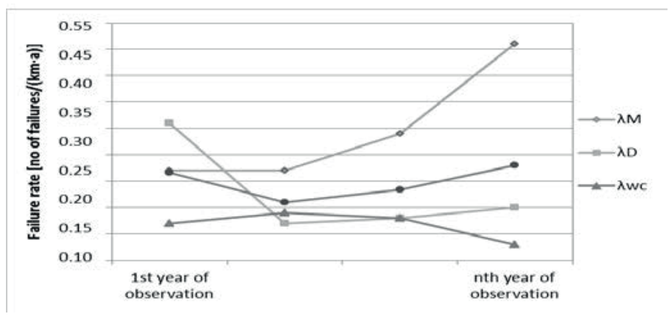

Fig. 7 The average value of failure rate for different types of water pipes

Preliminary analysis shows that the value of the failure rate of the main network in past two years does not fulfil the recommended European criteria, that is less than 0.3 failure/km/year. The failure rates for distributional pipes and water supply connections are much less than the recommended value, in the case of distributional pipes the critical value should not exceed 0.5 failure/km/year and in the case of water connections 1.0 failure/km/year. The value of the failure rate in particular years does not exceed 0.5 failure/km/year, except in case of the mains in the last year of observation, thanks to it the water supply network is classified as pipes with average reliability.

3.1.2 Failure rate of the network depending on the pipe material

Failure frequency of the water supply network also depends on the material from which it is made. In Figures 8–12 the failure rates depending on the material were shown, also the equation of the trend line was presented.

It should be mentioned that the examined water supply system is mostly made of PVC (56%) and cast iron (30%), then from PE (8%) and galvanized steel (4%), while the pipes made from asbestos-cement constitute about 1% of the total length of the network, which determines the failure rate. The percentage structure of the material is very important for the failure rate for proper results assessment and analysis.

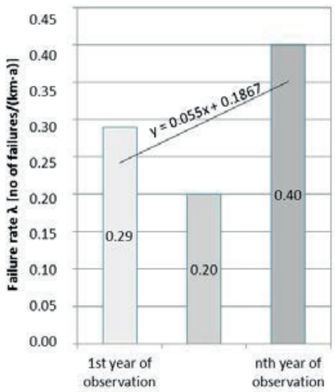

Fig. 8 Failure rates of pipes made from cast iron

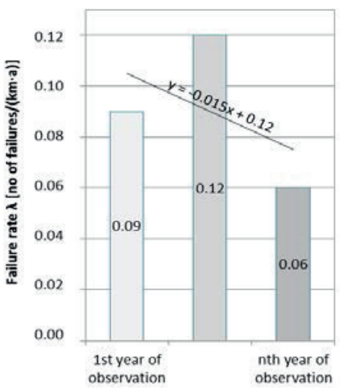

Fig. 9 Failure rates of pipes made from PVC

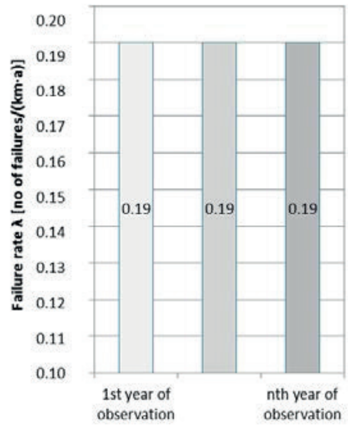

Fig. 10 Failure rates of pipes made from PE

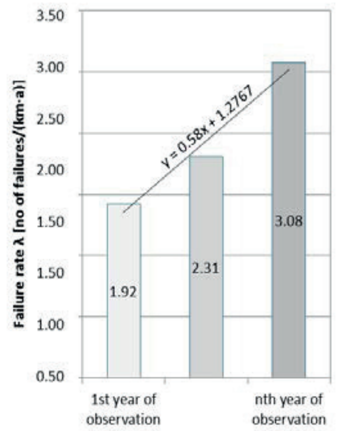

Fig. 11 Failure rates of pipes made from AC

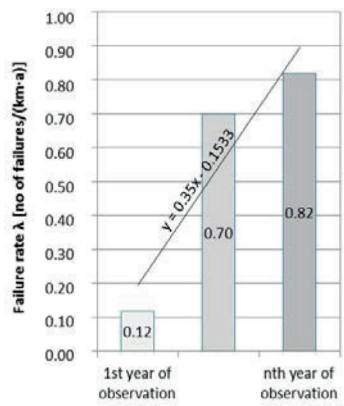

Fig. 12 Failure rates of pipes made from galvanized steel

The analysis of the studies presented in Figures 8-12 indicate that the least operational problems occur on pipes made of PE and PVC (plastic). Pipes made of PVC can be classified as pipes with high reliability (except 2014 with λ = 0.12 failure/km/year), while the pipes made from PE as pipes with average reliability because the failure rate was higher than 0.1 failure/km/year according to [12]. The low value of the failure indicator results from the fact that more than half of the network is made from PVC. Pipes made from cast iron are included in the average reliability category, as well as those made from PE. The highest failure rate have pipes made from asbestos cement, what is due to the network length, which is only 1% of the total length of the network. Also clear decline in reliability of the network made of galvanized steel after 2014 can be observed. Pipes made of this material are classified as pipes with high failure rate ($\lambda \geq 0.5$ failure/km/year). Main network is made mostly of cast iron (62%) and galvanized steel (27%). Detailed analysis of the problem shows that the failure rate of materials such as cast iron (on average $\lambda = 0.33$ failure/km/year) and galvanized steel (on average $\lambda = 0.62$ failure/km/year) of which the mains are made exceed the recommended European criteria values for this type of pipes. For the distributional pipes the recommended level of failure rate is exceeded for the network made of asbestos-cement (on average $\lambda = 2.18$ failure/km/year) and of galvanized steel (on average $\lambda = 0.51$ failure/km/year). The part made of asbestos cement constitutes only 2% of the total length of the distribution network and galvanized steel about 1%, it means that the number of failures on these pipes is much larger than on the pipes made of other materials.

3.1.3 Failure rate of the network during the year

Failure rate is also influenced by seasonal and climatic conditions occurring in each month. Increased failure frequency in winter months is caused by low temperature, thus freezing the ground around the pipes or repeatedly water freezing in the pipe what causes cracking of the material of which pipe is made (on average $\lambda = 0.23$ failure/km/year). The average reliability of pipes can be observed in spring, while in summer a decrease of reliability can be caused by intensive ground works performed during this period (on average $\lambda = 0.17$ failure/km/year. In division to months high reliability is observed in the months of April and May. On the other hand, in February, August and December are characterised by increased failure rate in comparison to other months, which confirms the analysis of seasonality in the next section.

3.2 Analysis of seasonal fluctuations of failures in the water supply network

Failures are characterized by irregularity in distinguished period of time, then the question of the so-called periodic fluctuations occurs. [28] One of such case are seasonal fluctuations characterised by the annual cycle of fluctuations, which can be divided into sub-periods such as for example months or other type of period. Another characteristic is the systematic repetition of fluctuations at specific intervals during the year [29].

To determine the seasonal fluctuations the seasonal index is used, which is based on the average homonymous periods. The sum of monthly seasonal indices should be equal to 1200. The seasonal index of failure is calculated according to the formula [29]:

$$C_S = \frac{\bar{A}_l \cdot p}{\sum_{i=1}^{p} \bar{A}_l} \cdot 100 \tag{2}$$

where C_s is the seasonal index for the i^{th} sub-period; $\bar{A}_l$ is the arithmetic average of the size of studied phenomenon in homonymous sub-periods and p is the number of sub-periods.

The absolute level of seasonal fluctuations, which determines the average level of the examined phenomenon is calculated according to the formula [29]:

$$fluc_i = C_i \cdot \bar{A} - \bar{p} = \bar{A}(C_i - 1) \tag{3}$$

where $fluc_i$ is the absolute levels of seasonal fluctuations; $\bar{A}$ is the average level of the examined phenomenon for $p = 12$, $\bar{A} = 6{,}158$.

The standard deviation of the absolute levels of monthly seasonal fluctuations is a measure of the seasonality degree, which is calculated as follows [29]:

$$S_D(fluc_i) = \sqrt{\frac{\sum_{i=1}^{p} fluc_t^2}{p}} \tag{4}$$

The calculation results are shown in Figure 13.

The sum of the monthly seasonal indices of failure in the examined period reached the required value 1200, so there is no need to introduce the correction factor.

During the months of February, August, September, October and December the number of water pipes failures was higher than the average monthly value due to the seasonal nature. The highest index value equal 146.14 was recorded for August, September and December and was higher by 46.14% from the average monthly value, while in February this value was higher by 25.03%. In other months the seasonal index value was below the monthly average.

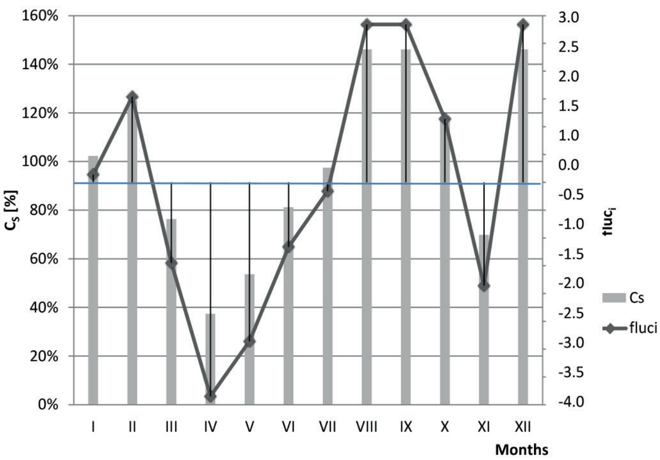

Fig. 13 The relative fluctuations of monthly seasonality and absolute fluctuations of monthly seasonality for a number of failures in the water supply network

The standard deviation of absolute levels of seasonal fluctuations for the considered period amounted to 2.195.

The sum of the absolute seasonal fluctuations of failures in the water supply network has reached value zero, which is correct. An average monthly number of failures was = 6.158 failures/month. As a result of seasonal fluctuations the number of failures was higher than the monthly average in the months of August, September and December by 1.84 and in February by 0.54. In other months, the number of failures was lower than the monthly average value.

For the analysis of seasonal fluctuations the starting point is to determine the trend of the time series, which is represented by the calculated moving averages centred for quarters, for example, for the fourth quarter the average calculated according to the formula [30] is:

$$\overline{A}_4 = \frac{\frac{1}{2} f_2 + f_3 + f_4 + f_5 + \frac{1}{2} f_6}{4} \quad (5)$$

where f is the number of failure in the each quarter.

While calculating the seasonal indices the original time series should be compared to the time series representing the trend, i.e. to the series of moving averages. Method of comparing the series depends on how seasonal variations overlap the trend of network failure rate. The following cases can be distinguished: a) the additive case - fluctuations have a constant amplitude and are summed with the trend b) multiplicative - magnitude of the fluctuations is proportional to the level of the phenomenon characterized by the trend [30].

a) The additive seasonal fluctuations for fluctuations cycle for the homonymous sub-periods were determined by the formula [30]:

$$A_i' = \frac{1}{n_i - 1} \Sigma_{t \in Ni} (f_{total} - \overline{A}_t) \quad for \ i = 1, ..., p \quad (6)$$

The index A_i' is corrected in order to balance the positive and negative seasonal deviations in the cycle of fluctuations in the following way [30]:

$$A_i = S_i' - \frac{1}{p} \Sigma_{i=1}^{p} A_i' \quad for \ i = 1, ..., p \quad (7)$$

The sum of the corrected indices A_i is equal 0, because it is the purpose of correction.

b) In the multiplicative case the index of seasonal fluctuations is defined by the formula [30]:

$$M_i' = \frac{1}{n_i - 1} \Sigma_{t \in Ni} \frac{f_t}{A_t}. \quad for \ i = 1, ..., p \quad (8)$$

Deviations above and below the trend are balanced if the sum of indices is equal p, for this purpose the index is introduced according to formula [30]:

$$M_i = M_i' \frac{p}{\Sigma_{i=1}^{p} M_i'} \quad for \ i = 1, ..., p \quad (9)$$

Time series is determined for the additive case and for the multiplicative case because of the lack of noticeable trend of failure occurrence.

In Figure 14 are presented data and calculations for uncorrected and corrected indices for the additive case and the multiplicative case.

The size and nature of the changes throughout the considered period are defined by the series of chain indices necessary for appointing the average rate of change in network failure frequency.

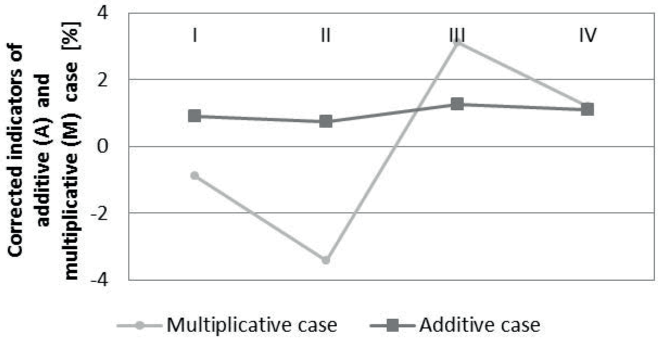

Fig. 14 Calculation of indices for the additive and the multiplicative case

On the basis of data relating to the number of failures, the individual single basechain indices were calculated, taking for comparison the number of failures in the first year of analysis, according to the formula [30]:

$$I_{t/t-1} = \frac{f_t}{f_{t-1}} \quad (10)$$

and the geometric mean of the chain indices was calculated by the formula [30]:

$$\overline{I}_{t/t-1} = \sqrt[n-1]{I_{2/1} \bullet I_{3/2} \bullet ... \bullet I_{n/n+1}} \quad (11)$$

The average rate was obtained which is equal to determined values of single base indices and means that the number of failures of water supply network increased yearly by an average of 4.2%.

3.3 Analysis of random fluctuations of water supply network failure

Random fluctuations are characterised by random factors and occur irregularly. Residual components are used to calculate random fluctuations that are calculated according to the formula [29]:

$$c_t = f_t - \hat{f}_t - fluc_{it} \quad (12)$$

where c_t is residual components for $t = 1, 2, ...$ n, f_t is empirical value of the examined phenomenon in individual subperiods,are theoretical values and $fluc_{it}$ are absolute levels of seasonal fluctuations.

Measure of random seasonal fluctuations is the standard deviation of the residual component calculated from the formula [29]:

$$S_D(c_t) = \sqrt{\frac{\Sigma_t c_t^2}{n - k}} \quad (13)$$

where $S_D(c_t)$ is standard deviation of the residual component for $t = 1, 2, 3…$n, and $i = 1, 2, 3…$k, is the sum of the squared residuals.

In Table 1 some part of calculations of random seasonal fluctuations of water supply network failure was presented.

Table 1 Part of the results of calculations of random seasonal fluctuations associated with the failure in the water supply network

Year of observation	Months	y_t	$\hat{y}_t$	g_i	z_t	z_t^2	y_t -	$(y_t -)^2$
1st year of observation	I	8.0	5.90	0.14	1.96	3.84	1.84	3.39
	II	8.0	6.00	1.54	0.46	0.21	1.84	3.39
	III	6.0	6.05	-1.45	1.40	1.96	-0.16	0.02
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	.	.	.	.	.	.	.	.
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nth year of observation	XI	4.0	6.40	-1.86	-0.54	0.29	-2.16	4.66
	XII	9.0	6.41	2.84	-0.25	0.06	2.84	8.08

Using the appropriate data from Table 1 the standard deviation of the residual component was determined. The result indicates an average strength of random fluctuation, which was $S_D(c_t) = 2.17$ in the considered period. The low values of the standard deviation of the residual component means that the fluctuation model better describes analysed reality variable over time.

In order to determine the coefficient of residual variation, the ratio of the standard deviation of the residual component $S_D(c_t)$ was compared to the average level of the examined phenomenon, which is 6.158.

Random deviation expressed by the coefficient of residual variation is 35.24% of the average level of noticeable variable number of failures. Residual components reached varied values from negative to positive which shows different impact of random seasonal fluctuations on the occurrence of failures in particular months.

Through statistical analysis which was conducted it can be seen that the number of failures is affected by seasonal fluctuations repeated regularly every year according to a certain pattern. Seasonal fluctuations are formed by natural factors such as seasons and weather. Accidental seasonal fluctuations are caused by action of random factors.

4 Conclusions and perspectives

In recent years in the considered water network steady increase in the reliability of the water supply network operation is seen. Failure of water supply network is the fundamental problem of operating of water supply systems around the world. To protect the water recipient every effort should be made to minimize interruptions in water supply through reducing the failure frequency of water supply network.

Water supply network made of cast iron and galvanized steel is characterized by high failure rate ranging from 0.2 to 1.0 failure/km/year, indicating that pipes made of these materials have reached the end of their technical life due to technological constraints, susceptibility to cracking, corrosion, inadequate quality of pipes made in the 80s, defects in materials, as well as decades of pipes operation, in case of the considered water supply network, even over 60 years. The age structure is dominated by pipes above 20 years old, which constitute 76% of the entire network length, while only 11% of the network length does not exceed 5 years. In order to improve the technical condition of water pipes and reduce the number of failures the oldest pipes made of cast iron or galvanized steel are being replaced by plastic, which ensures the low failure rate. The analysed water network is characterized by diversity in materials from which it is made and pipe age, which cause that the failure occurrence is difficult to be predicted and the failure rate exceeds the limit values. In order to improve the water supply network operation it is necessary to conduct technical renewal.

The planned reconstructions are also conditioned by the losses occurring on the water pipes. In order to reduce the failure rate and the costs associated with it, the examined water supply system are being gradually modernized in order to improve the reliability of water distribution, which results in gradual decline in the failure rate of water pipes.

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