A study of the water supply system failure in terms of the seasonality: analysis by statistical approaches

Dariusz Młyński, Tomasz Bergel, Anna Młyńska and Kazimierz Kudlik

ABSTRACT

Among the many factors affecting water supply system failures are the weather conditions that change over the year. Since this is an important research issue, as part of this study, investigation of water supply system failure seasonality by the selected statistical approaches was presented. The basis of the research was monthly number of the pipelines' failures from the multi-year period of 2007–2017 of the municipal water network located in southern Poland. Mann–Kendall test results proved decreasing seasonal trend of the failure rate indexes λ. In turn, the results of the Colwell indexes' calculations allowed it to be stated that seasonal course of the water pipelines' failure events can be relatively easy to predict. As it turned out, it is difficult to determine unambiguously the impact of a given period of the year on the water pipeline failure events' occurrence. However, greater failure-free operation of the water pipelines may be expected in spring and summer months than in autumn and winter months. Because using Colwell indexes for seasonality analysis has no limitations compared to other methods, Colwell indexes may be considered as reliable tools for the assessment of the seasonal course of the water pipelines' failure events.

Key words | failure rate index λ, seasonality, statistical analysis, trend, water pipelines, water supply system

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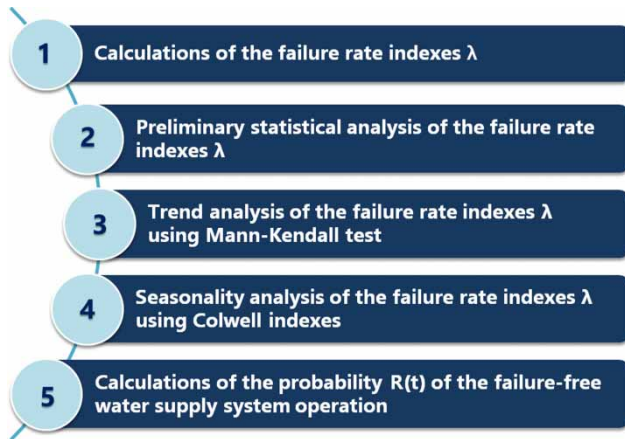Mickiewicza 24/28, 30-059, Cracow,
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HIGHLIGHTS

- Statistical analysis of the water supply system failure seasonality.
- Using the selected statistical approaches for the analysis of water pipelines failure rate indexes λ.
- Seasonal course of the water pipelines failure events can be relatively easy to predict by using the Colwell indexes.
- Not clear impact of a given period of the year on water supply system failures was found.

GRAPHICAL ABSTRACT

1. Calculations of the failure rate indexes λ

2. Preliminary statistical analysis of the failure rate indexes λ

3. Trend analysis of the failure rate indexes λ using Mann-Kendall test

4. Seasonality analysis of the failure rate indexes λ using Colwell indexes

5. Calculations of the probability $R(t)$ of the failure-free water supply system operation

NOTATION

α	significance level
Δt	time interval
λ	pipeline failure rate index
$\rho_S(i)$	autocorrelation function of the ranks of the observations
C	constancy
H_0	null hypothesis
H_1	alternative hypothesis
$H(X)$	uncertainty regarding the time of a given phenomenon occurrence
$H(Y)$	uncertainty regarding the state of a given phenomenon
$H(XY)$	uncertainty regarding the interaction of time and state of a given phenomenon
i	number of the previous element in time series
j	number of the next element in time series
k	number of the pipeline failures
L	length of the pipeline
M	contingency
n	length of the data set in time series (number of the observations)
n_s^*	'effective' number of the observations (due to the autocorrelation)
$\dfrac{n}{n_s^*}$	correction due to the autocorrelation;
P	predictability
p	test probability
p^*	correction of the test probability
$R(t)$	probability of the failure-free operation of the water supply system
S	Mann–Kendall test statistic
s	number of the analysed class intervals describing a given phenomenon
t	considered period of time
$Var(S)$	variance
$Var^*(S)$	correction of the variance
x_i, x_j	time series elements in chronological order
Z	standardized test statistic
Z^*	correction of the standardized test statistic

INTRODUCTION

Failure-free operation of technical infrastructure facilities, among them, water supply systems, is what both facility operators and their users expect. Water supply systems' failures may affect the comfort of using tap water to a varying degree. Water network failures may result in some problems regarding delivery to the consumers of the right amount of water under the required pressure, and thus, comfortable water intake from plumbing fixtures; sometimes, it can even result in complete lack of water in some network areas. For example, pressure management in water networks

along with reducing leakages through pressure regulators' installation or active leakage control is considered as a priority for water loss reduction (Tsanov *et al.* 2020). It is also important to pay attention to the drinking water quality safety; this is a key element of safe water systems' use and this issue is also related to the technical conditions of water pipelines. Also, it should be mentioned – as the paper by Zhang (2019) shows – many environmental studies from the last two decades have paid more and more attention to the problem of drinking water pollution, as one of the main water pollution problems. Returning to the point, it must be noted that, especially corrosion of internal pipelines' surfaces creates the risk of secondary potable water pollution. As is known, this is not the only problem concerning corrosion; corrosion contributes to the deterioration of a pipe's material properties and causes its gradual degradation. Although corroded water pipelines do not create such seriously hazardous environmental consequences, e.g., like deteriorated oil or gas pipelines (Nikitin *et al.* 2019), it remains a costly problem too. It must be emphasized that unexpected failure events very often require really high financial costs for failure removal and for future failure prevention; thus, it is important to prevent it in advance. Thanks to the use of some tools, such as the indices for evaluation of water pipes' deterioration and pipelines' maintenance management systems elaborated by Sakai *et al.* (2020), it is possible to manage and control water supply infrastructure effectively.

Previous water supply systems' operational experiences and numerous research studies conducted on such basis indicate the different factors that may affect water supply systems' failures. During water network planning, designing and building, different mistakes may be made, which may result in increased probability of network failures in the future. As the authors of many research papers prove, the factors related to failure events include mainly the type of pipe material (Mansoorian *et al.* 2016; Tye *et al.* 2017; Barton *et al.* 2019), network exploitation period, i.e., pipelines' age (Boxall *et al.* 2007; Berardi *et al.* 2008; Tye *et al.* 2017) and pipelines' function (main pipes, distribution pipes and water connections) (Bergel *et al.* 2013; Piegdoń *et al.* 2015; Tchórzewska-Cieślak *et al.* 2018). Apart from that, some water system operational factors, including water pressure changes (Clark *et al.* 1982; Pluvinage *et al.* 2009; Rezaei *et al.* 2015) and metal pipes' susceptibility to

internal corrosion through contact with water with aggressive properties (Yaminighaeshi 2009; Yamini & Lence 2010), should be considered as real threats to the technical conditions of pipelines. Also some 'environmental' factors may have an impact on water pipes' failure. For example, the type of soil and its properties (aggressiveness) affect external pipes' corrosion (Sadiq *et al.* 2004; Rajani & Tesfamariam 2005; Liu *et al.* 2010). The dynamic phenomena, i.e., soil mass movements (Skipworth *et al.* 2002; Gould *et al.* 2011; Uckan *et al.* 2016), should be mentioned in this case too. In addition, the changes of soil and water temperature may expose the pipelines to the failure events. Therefore, water networks' failure problem in relation to the so-called seasonality, i.e., weather conditions or climate conditions, has been considered by some authors (Milone 2012; Fuchs-Hanusch *et al.* 2013; Piegdoń & Tchórzewska-Cieślak 2018).

In order to avoid all the above problems, first, it is necessary to design and build water networks carefully. Apart from that, proper operation and technical support of the water system facilities, especially their systematic maintenance and current rehabilitation, is very important as well as planning water networks' renovation. In addition, an effective water supply system operation should be supported by using highly reliable and complex automation technology (Olsson 2020). Certainly, the ability to predict undesirable failure events and identify the factors affecting water supply systems' failures are valuable sources of knowledge; first of all, for designers and constructors as well as for companies managing water supply infrastructure facilities. For water supply companies, this knowledge allows an increase in the efficiency of water supply systems' operation and tends to improve the quality of the transported water. In addition, this is helpful for proper assessment of the need for water network renovation and for correct costs' estimation. However, it should be emphasized, that the complexity and different relations between some factors affecting water network failures, make it difficult to identify clearly the failure problem. Taking into consideration the importance of this issue, but also some difficulties related to this, modelling of water supply systems' failures is still being explored and subjected to multidirectional analysis by scientists involved in this research area. The evidence of this are models presented by some authors, e.g., by

Pietrucha-Urbanik & Tchórzewska-Cieślak (2018), Winkler *et al.* (2018) and Kutyłowska (2019); these are used for the forecast and evaluation of the risk of failure events and the reliability of water supply systems' operation. Among them is the model proposed by Snider & McBean (2018), which enables to forecast quite precisely the time of failure occurrence. As the literature studies show, water network failures' modelling methods may be classified into several groups; these include deterministic, probabilistic, stochastic, artificial intelligence and machine learning methods (Karimian 2015; Gao 2017; Kakoudakis 2019). A wide presentation of different models used for statistical description of water supply networks' failures with its critical review may be also found in the paper by Kleiner & Rajani (2001). The authors of this study analysed the use of deterministic models (time-exponential and time-linear models) and probabilistic models, including probabilistic multi-variate and probabilistic single-variate models. The characteristic of these models in terms of their use in water supply systems' failures forecasting was provided by Large *et al.* (2014). Based on over 200 research papers, a study of development and progress of transient water supply systems' modelling methods along with transient defects' detection methods was made by Duan *et al.* (2020). The achievements and advances of their practical implications and future recommendations for transient research were discussed by the authors too. In the current literature, we can also find a method for failure risk assessment in large-diameter water pipelines (Huang *et al.* 2019). This was elaborated based on the combination of multi-criteria analysis (MCA) and geographic information system (GIS); thanks to this, it is possible to create a map of different pipelines' failure risk levels (from high, through middle to low risk), used for short-, medium- and long-term detection planning depending on the risk level.

Climate conditions force sustainable water resources management because of their impact on water resources' availability (Imad *et al.* 2019). However, this is not the only difficulty in this aspect. As was stated earlier, weather or climate conditions is one of the many factors affecting water pipes' failures. These conditions determine both the temperature of the flowing water and ground conditions, e.g., ground temperature or humidity. The temperature and its fluctuations should be considered as the most significant in assessment of the impact of weather conditions on technical conditions of pipelines. For example, Kutyłowska & Hotloś (2014) showed that a failure frequency of the tested water pipes in one Polish city was greater in autumn and winter (from November to February), i.e., during seasonal temperature drops, than in spring and summer (from March to October). A similar tendency, i.e., growth of the pipelines' failure rate indexes in winter as well as clear correlation between the air temperature, ground temperature or water temperature and number of pipe breaks, may be found in the research papers of Fuchs-Hanusch *et al.* (2013), Pietrucha-Urbanik & Żelazko (2017) and Bruaset & Sćgrov (2018). Increased pipelines' failure rate is mainly the result of thermal stresses and pipe–soil interactions. Bruaset & Sćgrov (2018) also predict that climate changes and observed temperature growth will positively affect the failure rates over the next 50 years. Of course, the impact of climate conditions on pipelines' failure rate should be considered by taking into account, e.g., pipes' age and material. As it was shown by Wols & van Thienen (2014), while the failure rate of asbestos-cement pipes and steel pipes increases by high temperature, in the case of cast iron pipes, growth of the failure rate is observed by temperature decrease. What is more, it was noticed that any weather conditions affect the failure rate of plastic pipes. In addition, an interesting study was done by Wols *et al.* (2019), who showed that during stormy weather with gusty winds, trees uprooting caused damage to the water pipes located near the trees.

Remaining with the issue of the impact of seasonal weather conditions on water pipelines' failures, this study attempts to analyse the impact of a season of the year on water supply systems' failures by selected statistical approaches. As presented above, investigations of water networks' failure in terms of the weather conditions and seasonality are commonly undertaken; these are mainly based on the direct observation of the failure events. In the literature, there are not many studies whose statistical analysis provides information about the seasonal course of water pipelines' failure events. However, for example, declining trend of the number of failures was discussed by Piegdoń & Tchórzewska-Cieślak (2018); typical failure

seasonality, i.e., high failures' frequency in autumn and winter months and lower failure rate in spring and summer months was stated. In general, for seasonality investigations, autocorrelation analysis or Fourier analysis is usually used, but because these methods have some limitations, sometimes, using them is difficult. Therefore, used in this paper, among others, the Colwell indexes were proposed as alternative tools for seasonality analysis. This method has not been used in water supply failures' assessment before, which makes this paper novel.

This paper is divided into five main sections. The aim of the study and the issue of water supply systems' failure along with water pipelines' failure problem in terms of the weather conditions as well as knowledge related to the failure events modelling are discussed in the section 'Introduction'. The next section 'Case study' is followed by the section 'Methodology', where the authors present the methods and equations used in the conducted statistical analysis along with the next steps of the performed calculations. Finally, in the section 'Research results', the obtained calculations results are shown and discussed and the main findings noted. The paper ends with 'Summary and conclusions'.

CASE STUDY

Statistical analysis of the water supply system failure seasonality was made based on the operational data of the water network located in the city of Nowy Sącz (Poland) (Figure 1(a)). The water network in Nowy Sącz was built in 1912. In the first year of its existence, the source of the transported water was underground water supplied via a 28 km long water pipelines to 180 farms. Nowadays, water from the infiltration intake and the surface intake is transported to about 71,000 consumers by main and distribution pipelines with a total length of about 313 km. Grey cast iron and ductile cast iron are the prevailing materials in the material structure of the considered network; these materials represent 50% of all pipelines. The rest of the water system is made of PE and PVC (35%) and steel (15%).

In 2008, the analysed water supply network was divided into eight smaller measurement zones, where temporary water consumption and water pressure may be controlled. This action was aimed at significant acceleration of the detection of the water pipes' failures and immediate failures' removal; thus, it tended to result in a significant reduction of
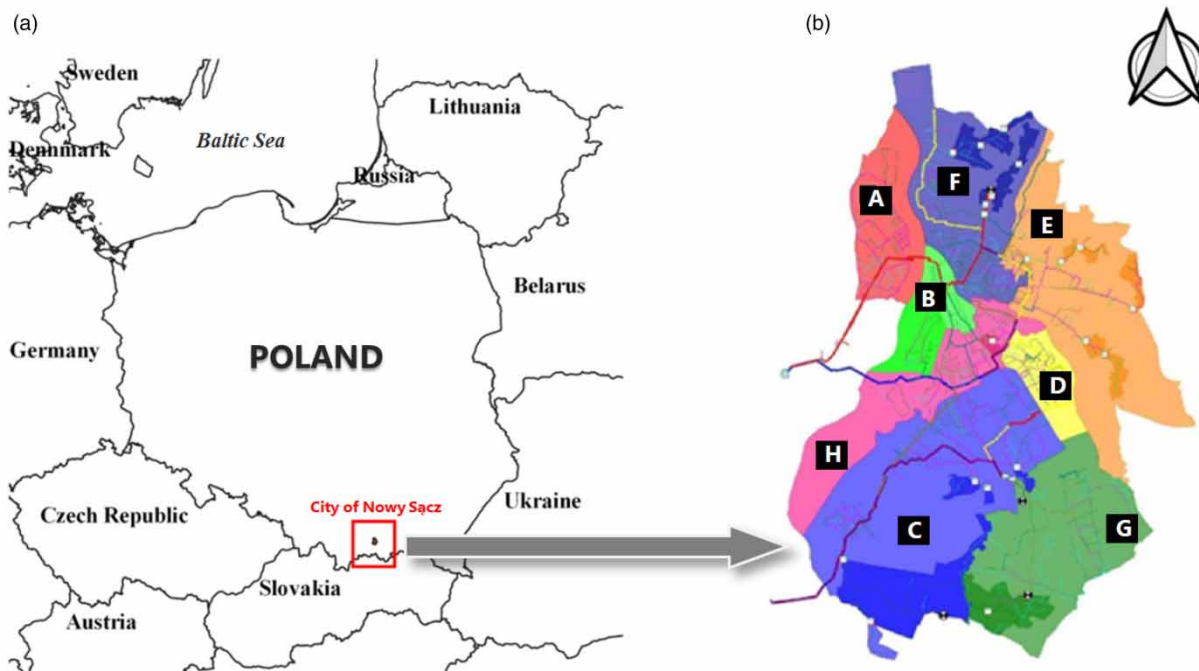
Figure 1 | Location of the study object (a) along with the division of the water supply system in Nowy Sącz into the measurement zones (b).

water losses. Currently, the water supply system in Nowy Sącz is divided into the eight measurement zones (from zone A to zone H) (Figure 1(b)). Since in zone G, water pipe failures were noted only in July and in September 2015, zone G was not considered in this paper.

METHODOLOGY

The input data for this study included monthly number of failures noted in each measurement zone of the water supply system in Nowy Sącz in the multi-year period of 2007–2017, as well as lengths of the water pipelines in these zones. In total, 1,360 failures were noted. For each year, the analysis was carried out both in relation to the months (from January to December) and in relation to the seasons (winter: from December to February, spring: from March to May, summer: from June to August, and autumn: from September to November). Generalized research methodology of this study is presented in Figure 2.

At first, based on the monthly number of the failures and the pipelines' lengths, failure rate indexes λ were calculated using Equation (1) (Kwietniewski & Rak 2010; Pietrucha-Urbanik & Tchórzewska-Cieślak 2014):

$$\lambda = \frac{k}{L \cdot \Delta t} \tag{1}$$

where λ is the pipeline failure rate index (failure·km^{-1}·time interval^{-1}), k is the number of the pipeline failures in time

Figure 2 │ A flowchart of the research methodology.

interval Δt, L is the length of the tested pipelines in time interval Δt (km), Δt is the considered time interval.

Based on the monthly values of the failure rate indexes λ, descriptive statistics for the multi-year period of 2007–2017 were determined. These included measures of location (minimum, maximum, mean and median), measures of dispersion (standard deviation and coefficient of variation) as well as measures of shape (kurtosis and skewness).

Then, both for months and for seasons, statistical analysis of trend significance of the failure rate indexes λ was performed using Mann–Kendall test. Null hypothesis H_0 of the test assumed no monotonic data trend, while the alternative hypothesis H_1 assumed the existence of monotonic data trend. The calculations were carried out for the significance level of $\alpha = 0.05$. Mann–Kendall test statistics were determined based on Equations (2)–(5) (Kendall 1938; Mann 1945; Rutkowska & Ptak 2012):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{2}$$

$$sgn(x_j - x_i) = \begin{cases} 1 & \text{for } (x_j - x_i) > 0 \\ 0 & \text{for } (x_j - x_i) = 0 \\ -1 & \text{for } (x_j - x_i) < 0 \end{cases} \tag{3}$$

where S is Mann–Kendall test statistic, n is the length of the data set in time series (number of observations), i is the number of the previous element in time series, j is the number of the next element in time series, x_i, x_j are the time series elements in chronological order.

After Mann–Kendall test statistic S determination, standardized test statistic Z was calculated according to Equation (4):

$$Z = \frac{S - sgn(S)}{Var(S)^{1/2}} \tag{4}$$

where Z is standardized test statistic, $Var(S)$ is variance, determined using Equation (5):

$$Var(S) = \frac{1}{18} \cdot (n \cdot (n - 1) \cdot (2n + 5)) \tag{5}$$

The main assumption of the Mann–Kendall test is lack of the autocorrelation in data series. In the case of the months' analysis, such dependence may be observed more often than in the case of the seasons' analysis. While the autocorrelation is stated, this may lead to the
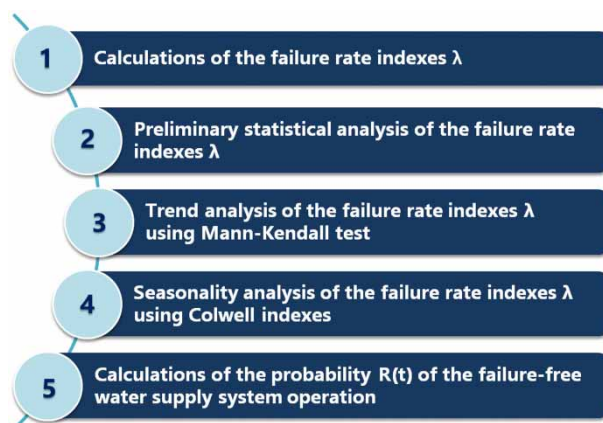
underestimation of the variance $Var(S)$. Therefore, based on Equations (6) and (7), correction of the variance $Var^*(S)$ (Hamed & Rao 1998; Pingale *et al.* 2016) was calculated only for data with a significant partial autocorrelation. Then, correction of the standardized test statistic Z^* was determined similarly like Z parameter by using Equation (4).

$$Var^*(S) = \frac{n}{n_s^*} \cdot Var(S) \tag{6}$$

where $Var^*(S)$ is correction of the variance, $\frac{n}{n_s^*}$ represents a correction due to the autocorrelation and was calculated as follows:

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)}$$
$$\cdot \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2)\rho_S(i) \tag{7}$$

where n_s^* is an 'effective' number of the observations (due to the autocorrelation), $\rho_S(i)$ is the autocorrelation function of the ranks of the observations.

In the next stage of the study, the assessment of the failure rate indexes λ seasonality was made using Colwell indexes. These include predictability P and its two components: constancy C and contingency M; they can take values from 0 to 1. Predictability P is a measure of the regularity of a given phenomenon. Constancy C describes a susceptibility of the variable to remain unchanged throughout the whole analysed period of time. Constancy C assumes maximum value, when the tested variable has the same value in each analysed period of time. Contingency M is a measure of the seasonal variability of a given phenomenon. High values of the seasonality index M indicate the reproducible values of the tested variable in the same periods of time. Colwell indexes P, C and M were determined based on the following equations (Colwell 1974; Wałęga & Młyński 2017):

$$P = C + M \tag{8}$$

$$C = 1 - \frac{H(Y)}{\log(s)} \tag{9}$$

$$M = \frac{H(X) + H(Y) - H(XY)}{\log(s)} \tag{10}$$

where P is predictability, C is constancy, M is contingency, s is the number of the analysed class intervals describing a given phenomenon, $H(X)$ is an uncertainty regarding the time of a given phenomenon occurrence, $H(Y)$ is an uncertainty regarding the state of a given phenomenon, $H(XY)$ is an uncertainty regarding the interaction of time and state of a given phenomenon.

Additionally, for each month, the average values of the probability $R(t)$ of failure-free operation of the water supply system were determined using Equation (11) (Kapur & Pecht 2014):

$$R(t) = exp\left[-\int_0^t \lambda\right] \tag{11}$$

where $R(t)$ is the probability of failure-free operation of the water supply system, t is the considered period of time.

RESEARCH RESULTS

As part of the preliminary statistical data analysis, basis on the calculated failure rate indexes λ in each tested measurement zone, basic descriptive statistics for the multi-year period of 2007–2017 were determined. The results of the preliminary assessment of the failure events' frequency of the tested water network are shown in Table 1.

Based on the results summarized in Table 1, it was found that for the considered ten-year period, the changes of the failure rate indexes λ of the analysed water supply system were at high and very high level. This is evidenced by the values of the coefficients of variation; for most of the tested measurement zones, these values were greater than 1.0. The obtained results may be explained, among other things, by improving over time the efficiency of the water pipe failures' detection by using some modern methods. For this purpose, in general, water companies use, e.g., stationary systems for leak detection, hydrophones, online inspection devices, self-flowing systems for leak location and airbags, or gas injection systems (Puust *et al.* 2010; Lange 2014). Returning to the point, because in every case the values of skewness were greater than zero, right-sided asymmetry of the tested variables was stated; this is

Table 1 | Descriptive statistics of the failure rate indexes λ of the tested water pipelines in the multi-year period of 2007–2017

	Descriptive statistics							
Zone	**Minimum (failure·km^{-1}·month^{-1})**	**Maximum (failure·km^{-1}·month^{-1})**	**Mean (failure·km^{-1}·month^{-1})**	**Median (failure·km^{-1}·month^{-1})**	**Standard deviation (failure·km^{-1}·month^{-1})**	**Coefficient of variation (–)**	**Kurtosis (–)**	**Skewness (–)**
A	0.00	0.12	0.02	0.00	0.02	1.67	5.09	2.06
B	0.00	0.40	0.08	0.05	0.08	1.05	2.13	1.33
C	0.00	0.12	0.03	0.02	0.03	1.06	0.94	1.17
D	0.00	0.37	0.08	0.06	0.09	1.21	0.59	1.16
E	0.00	0.28	0.04	0.03	0.05	1.28	5.16	1.98
F	0.00	0.19	0.06	0.04	0.05	0.82	0.18	0.83
H	0.00	0.24	0.04	0.02	0.05	1.18	4.86	1.88

because most of the failure rate indexes λ were smaller than their mean values. In turn, positive values of kurtosis for each measurement zone result from the accumulation of the failure rate indexes λ close to the calculated mean values.

For all tested measurement zones, both in terms of the months and seasons, statistical analysis of trend significance of the failure rate indexes λ in the multi-year period of 2007–2017 was conducted using Mann–Kendall test (Table 2). Calculations were performed for the significance level of $\alpha = 0.05$. When the absolute value of the standardized test statistic Z^* was greater than the critical value (for the assumed significance level of $\alpha = 0.05$, the critical value was 1.96), the trend was then considered as statistically significant.

Mann–Kendall test results proved that in almost all of the tested measurement zones (except zone D), there was a decreasing trend of the monthly pipelines' failure indexes λ; this is evidenced by the negative values of the modified Mann–Kendall test statistic Z^*. In turn, in the case of the seasons' analysis, it was found that all tested zones were characterized by decreasing trend of the failures' events. Referring to the critical value of the test statistic, it should be emphasized, however, statistically significant results in months' analysis were obtained only for three zones (C, F and H), while for seasons, statistically significant results related to five out of the seven tested zones. Additionally, it was noticed that in months' analysis, $\frac{n}{n_s^*}$ parameter was different from 1.0 in the case of zone B, D, E, F and H, while in seasons' analysis, it was observed in the case of zone D and E. These results prove that for

Table 2 | The results of trend analysis of the failure rate indexes λ of the tested water pipelines in the multi-year period of 2007–2017

| Zone	p	Var(S)	z	$\frac{n}{n_s^*}$	p*	Var*(S)	Z*
For months							
A	0.126	180,086	−1.53	1.00	0.126	180,086	−1.53
B	0.387	241,998	−0.87	1.39	0.462	335,928	−0.74
C	0.000	241,338	−5.09	1.00	0.000	241,338	−5.09
D	0.965	230,483	0.04	0.54	0.952	124,118	0.06
E	0.018	233,086	−2.37	2.80	0.157	652,573	−1.42
F	0.008	251,174	−2.67	1.25	0.017	314,979	−2.38
H	0.000	240,929	−3.57	1.82	0.008	438,742	−2.65
For seasons							
A	0.385	9,111	−0.87	1.00	0.385	9,111	−0.87
B	0.596	9,614	−0.53	1.00	0.596	9,614	−0.53
C	0.000	9,660	−4.02	1.00	0.000	9,660	−4.02
D	0.774	9,514	−2.87	1.16	0.789	11,053	−2.66
E	0.066	9,552	−1.84	0.41	0.004	3,903	−2.88
F	0.019	9,681	−2.34	1.00	0.019	9,681	−2.34
H	0.016	9,607	−2.42	1.00	0.016	9,607	−2.42

p is test probability, $Var(S)$ is variance, Z is standardized test statistic, $\frac{n}{n_s^*}$ represents a correction due to the autocorrelation, p^* is correction of the test probability, $Var^*(S)$ is correction of the variance, Z^* is correction of the standardized test statistic.

the considered time series, a significant autocorrelation of random variables occurred. This may indicate the irregular seasonality of the pipelines' failure rate indexes λ. To summarize, the main finding of the conducted Mann–Kendall test indicated decreasing seasonal trend of the pipelines' failure indexes λ.

The assessment of seasonal variability of the water network failure rate indexes λ was performed using Colwell indexes: predictability P and its components – constancy C and seasonality (contingency) M. In addition, C/P and M/P ratios were determined (Figures 3–6).

Comparing with each other the tested measurement zones by months' analysis (Figure 3), the most stable course of the water pipelines' failure rate indexes λ related to zone A. However, in other zones, the parameter of constancy C reached a high level too. When it comes to the seasonality M, the highest value of about 0.20 was reached in zone D, while the other measurement zones were characterized by slightly smaller values. Finally, predictability P, as the sum of the constancy C and seasonality M, was the highest in zone A (over 0.70) and in zone D and zone E (over 0.50). In other measurement zones, predictability P was a little bit lower than 0.50. Based on Figure 4, it was found
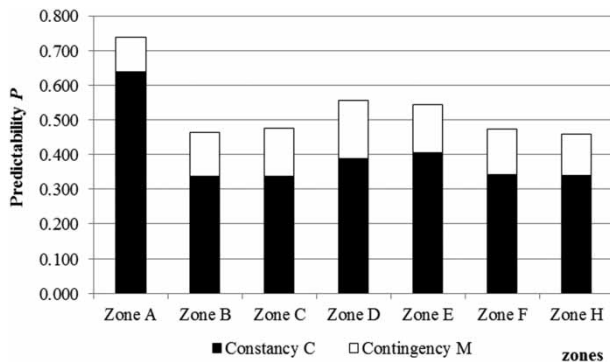
Figure 3 │ The values of the Colwell indexes P, C and M for the monthly failure rate indexes λ of the tested water pipelines.
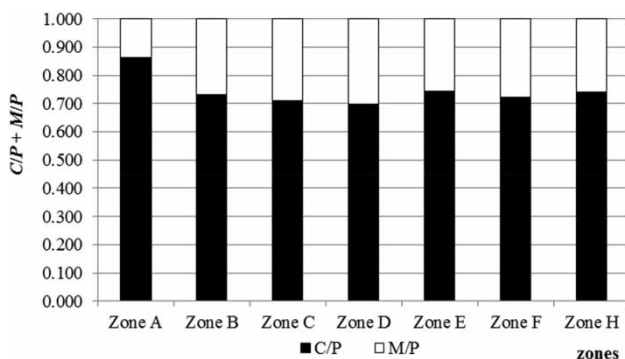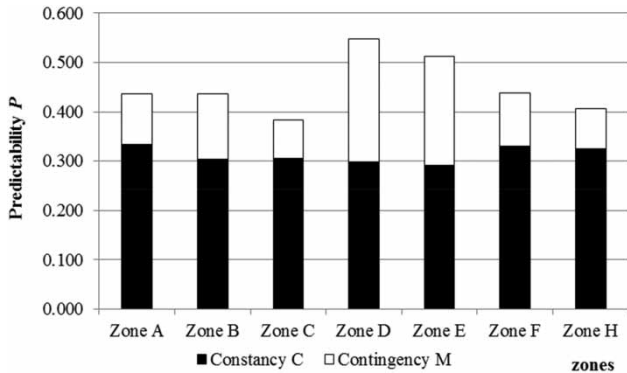

Figure 4 │ The values of the Colwell indexes ratios C/P and M/P for the monthly failure rate indexes λ of the tested water pipelines.

that except for zone A, predictability P was achieved similar values of constancy C; what is important, predictability P was achieved by greater constancy C than contingency M. The main finding of the above analysis is that the monthly course of water networks' failure events can be relatively easy to predict. This is stated based on high values of predictability P. In addition, because greater values of constancy C than seasonality M were observed, the tendency of the water pipelines' failure rate indexes λ to remain unchanged throughout the year is stated.
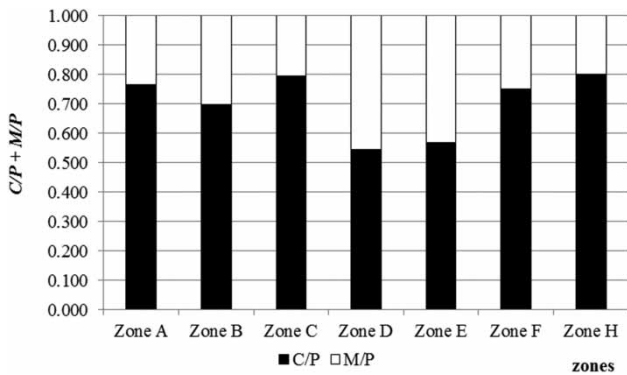
The analysis of the Colwell indexes in terms of the seasons (Figure 5) provided some similar findings as the months' analysis (Figure 3). Namely, relatively high values of probability P made it possible to state that the seasonal course of the water networks' failure events can be relatively easy to predict. Although the predictability P was achieved by greater values of constancy C than contingency M too (Figure 6), it should be emphasized that in seasons' analysis, seasonality M had greater impact on predictability P than in the case the months' analysis. Similarly, as in the case of the monthly failure rate indexes' λ analysis, the greatest values of the constancy index C related to zone A (and additionally zone F and zone H), while the greatest seasonality M also was noted in zone D (Figure 5). However, the analysis of seasons proved the greatest predictability P in zone D, not in zone A like the months' analysis.

Referring to the above calculations, it should be emphasized that the analysis was carried out only in relation to the impact of a specific period of time on water pipelines' failure occurrence. At this point, it must be noted that water supply systems' failures also depend on many other factors, among which are water pipelines' functions, age, materials, water pipes' laying depth, water pressure along with its fluctuations and the regularity of current pipelines' maintenance and renovation.

Increase in the water network failures cases is noted usually in autumn and winter periods and partially in winter and spring periods. However, water pipeline failures may also be observed in summer months (Kwietniewski *et al.* 2011). The results of the Colwell indexes' calculations in terms of the months (Figure 3) and seasons (Figure 5) confirm and prove the above, that it is difficult to determine unambiguously the period of the year when failures are recorded.

Figure 5 │ The values of the Colwell indexes P, C and M for the seasonal failure rate indexes λ of the tested water pipelines.

Figure 6 │ The values of the Colwell indexes ratios C/P and M/P for the seasonal failure rate indexes λ of the tested water pipelines.

Finally, as part of the statistical data analysis, the average monthly values of the probability $R(t)$ of failure-free operation of the tested water pipelines in each measurement zone were determined (Figure 7).

As can be seen in Figure 7, for each of the seven measurement zones, average monthly values of the probability $R(t)$ have reached high level by exceeding 0.8; what is more, in most cases, the value of 0.9 was exceeded significantly. Especially in zone A and zone E, in most months, calculated values of the probability $R(t)$ of failure-free operation of the water pipelines were close to 1.0. It was observed that zone D also was characterized by high values of the probability $R(t)$, but at the same time, by the largest disproportion between the highest and the lowest $R(t)$ value. When it comes to the period of the year when the highest and the lowest probability $R(t)$ may be noted, in general, it was found that the highest probability $R(t)$ of

failure-free operation of the water pipelines usually related to the spring and summer seasons, while the lowest probability – autumn and winter seasons. However, it should be emphasized, that in the case of the seasonality analysis for each zone separately, it is impossible to separate homogeneous periods for the specific probability values; these values can be noted in spring, summer, autumn and winter months alternately.

SUMMARY AND CONCLUSIONS

Many water networks' operational experiences show a significant impact of the weather conditions, especially temperature, on technical conditions of the water pipelines, and hence, an impact on pipelines' failures. As the weather conditions change over the year, this impact also may vary to some degree in particular seasons. Thus, this issue requires special attention. Although the water networks' failure seasonality is a commonly undertaken research issue because of its practical importance, not many studies related to the seasonal course of the water pipelines' failure events may be found. Due to this, as part of this paper, investigation of the water supply system failures' seasonality by the selected statistical approaches was conducted. Compared to the other methods that are used in studies of seasonality, Colwell indexes have no limitations and they are easy to use. Thus, Colwell indexes were applied in this paper as the alternative statistical tools for seasonality analysis.

Summarizing all the obtained results, calculated values of the pipelines' failure rate indexes λ in a ten-year research period indicate high and very high monthly variability of the failure events of the tested water supply system. In turn, statistical analysis of trend significance by Mann–Kendall test proved decreasing seasonal trend of the failure rate indexes λ. The results of the Colwell indexes' calculations made it possible to state that seasonal course of the water networks' failure events can be relatively easy to predict. However, as the performed analysis for months and for seasons showed, it is difficult to determine clearly the impact of a given period of the year on the water pipelines' failure events' occurrence. Nevertheless, calculations of the probability $R(t)$ proved that greater failure-free operation of the water
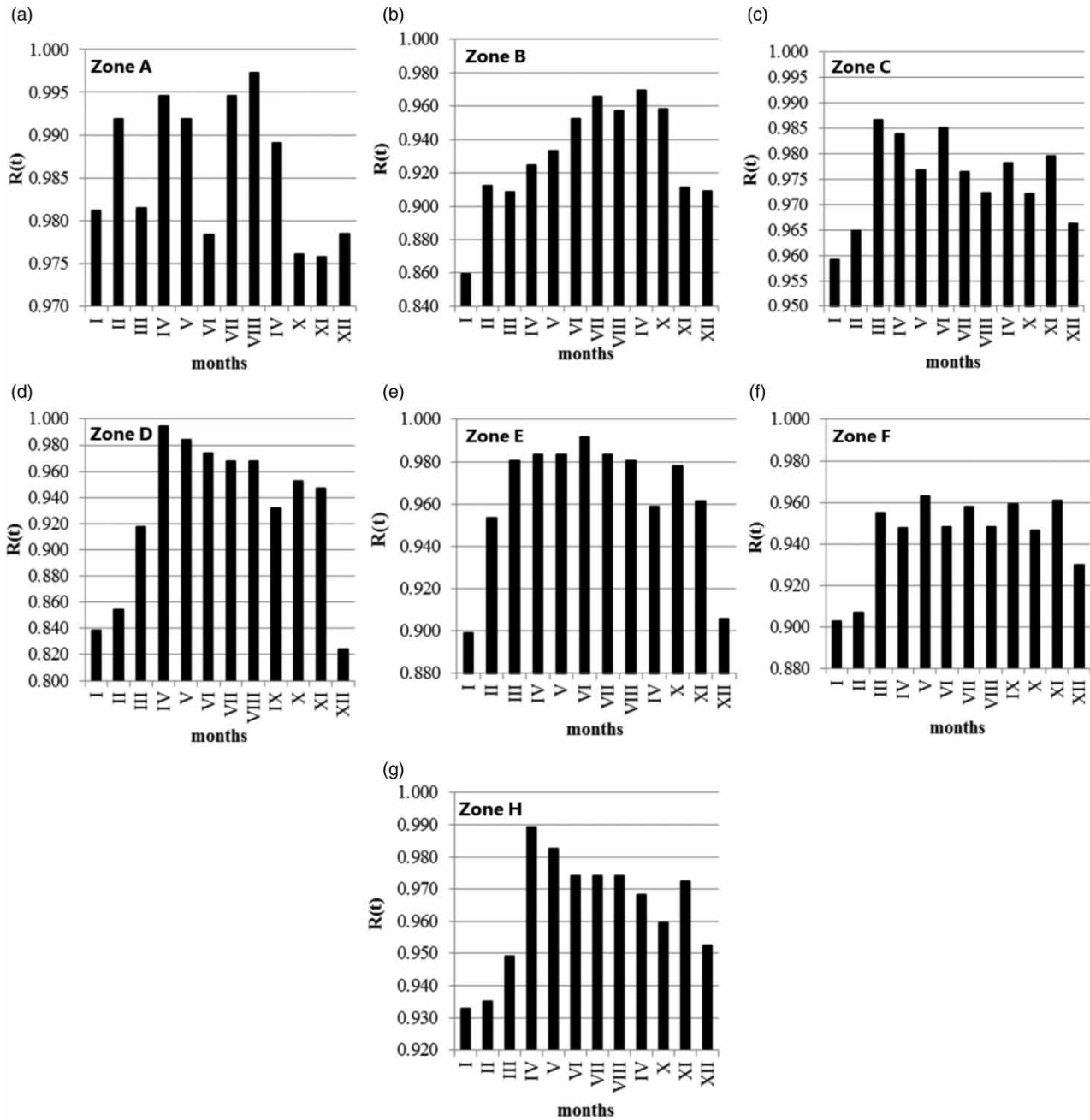
Figure 7 | The average monthly values of the probability *R(t)* of failure-free operation of the tested water pipelines in each measurement zone.

pipelines may be expected in spring and summer months than in autumn and winter months.

Performed analysis enabled us to state that Colwell indexes may be considered as reliable tools for the assessment of the seasonal course of water pipelines' failure events. But what is important, because the selection of time intervals for such analysis affects the values of Colwell indexes, time intervals should be assumed carefully. When it comes to future plans, it is planned to focus further research on the comparative analysis of the results obtained by calculating the Colwell indexes and by using the other methods. In addition, an attempt may be made to use the Colwell

indexes for statistical description of other water supply systems' operational characteristics, for which, seasonality is an important factor.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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