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ANALYSIS OF WATER LOSSES AND FAILURE FREQUENCY IN AN URBAN-RURAL WATER SUPPLY SYSTEM

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ABSTRACT: This article presents the results of analysis of an urban-rural water supply system. The level of water losses and failure frequency of the water supply system were evaluated. Tests and analyses of the level of water losses were conducted for the years 2010-2016. Tests and analyses of failure frequency were conducted for the years 2013-2016. The guidelines of the International Water Association were applied in calculations. Analyses showed an influence of season on the failure frequency of the urban-rural water supply system. An influence of the number of failures on the volume of water lost in a single failure was also observed. Obtained results were compared with data from domestic literature and the guidelines of standard PN-EN 60300-3-4:2008.

KEY WORDS: water supply system, water losses

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Introduction

In 1999, Lambert et al. published the IWA Task Force One guidelines for water balancing and evaluation of water losses in water supply systems. These guidelines set forth a water balance table for water supply systems (table 1) as well as water loss indicators. Among other things, the ILI (Infrastructure Leakage Index) index was established for objective evaluation of water losses and comparison of different water supply systems. ILI slowly began to replace evaluation of water losses in water supply networks employing the water loss percentage index. The guidelines and methodology for evaluating water losses in water supply systems according to the IWA began to function in Polish literature concerning water losses. Every so often, articles are published in which authors evaluate the water losses or failure frequency of various water supply systems (Bergel, 2012; Bergel, Pawelek, 2008; Bergel et al, 2013; Kwietniewski, 2013; Ociepa, Kędzia, 2015). In 1998, Dohnalik reported a mean level of water losses in Poland amounting to 18.6% (Dohnalik, 1998). This became a point of reference for other water supply systems in Poland (Hotloś, 2003). According to numerous authors (Farley et al., 2008; Lambert et al., 2018; Thornton et al., 2008), the percentage index should be departed from in the evaluation of water losses, and the CARL, UARL and ILI indices should be used instead. These indices are defined as (Farley et al., 2008; Lambert et al., 1999; Thornton et al., 2008).

NRW (Non-Revenue Water), unmetered water for which the water company did not receive payment. This quantity arises from the difference between the amount of water pumped into a water supply network and the amount of invoiced water, which is then divided by the amount of water pumped into the water supply network (the former amount).

CARL (Current Annual Volume of Real Losses) is the volume of water lost from the water supply network as a result of leakage in the transmission and distribution systems, tanks and as well as pipe leaks from the point at which water is pumped in to the point of water purchase by a consumer. The value of this index is given in dm^3/day or dm^3/year.

UARL (Unavoidable Annual Real Losses) are the volume of water lose from a water supply system considered to be the amount of water whose loss is unavoidable due to the difficulty of detecting small leaks in water pipelines, economically unfeasible repair, difficult access to the site of the leak, reaction time between the occurrence of a leak and its detection and repair. The volume of water described by the UARL index is a function of the length of the distribution system, the number and length of service lines, and the mean pressure value in the water supply network. The value of this index is given in dm^3/day or dm^3/year.

ILI (Infrastructure Leak Index) is the index recommended by the IWA for evaluation of water losses in a water supply network and planning of undertakings intended to limit the volume of water lost. ILI is defined as the ratio of Current Annual Volume of Real Losses (CARL) to Unavoidable Annual Real Losses (UARL). Values of the ILI index are classified into 4 or 8 categories (Farley et al., 2008; Lambert et al., 1999).

Calculation of failure frequency indices may provide valuable information about the condition of a water supply network. Failure frequency indices can be calculated for an entire water supply network but also for individual groups, i.e. water mains, distributing pipes, service lines, fittings, etc. Index values are expressed as the number of failures per km of pipe and per unit of time within which the number of failures was counted. Acceptable failure frequencies are described in standard PN-EN 60300-3-4. In his article, Bergel gave mean failure frequency values based on tests in 374 water supply systems for water mains, distribution pipes, service lines and systems as a whole (Bergel, 2012).

The literature also defines a unit water loss index that describes the amount of water lost from one service line over the course of the year. The unit loss index is the quotient of real losses divided by the number of service lines. It is also applied for evaluation of water losses in a water supply network (Farley et al., 2008).

Table 1. Water balance in water supply system according to IWA

System Input Volume	Authorised Consumption	Billed Authorised Consumption	Billed Metered Consumption	Revenue Water
			Billed Unmetered Consumption	
	Water Losses	Unbilled Authorised Consumption	Unbilled Metered Consumption	
			Unbilled Unmetered Consumption	Non-Revenue Water
		Commercial Losses	Unauthorised Consumption	
			Customer Meter Inaccuracies and Data Handling Errors	
		Physical Losses	Leakage on Transmission and Distribution Mains	
			Leakage and Overflows from the Utilities Storage Tanks	
			Leakage on Service Connections up to the Customer Meter	

Source: (Farley et al., 2008).

Material and methods

Tests concerning analysis of water losses and failure frequency were conducted at a water company servicing an urban-rural water supply system. The primary method of acquiring data involved specially prepared input data sheets, which were used as the basis for obtaining information for further analyses. Water loss analysis according to IWA guidelines was conducted for the years 2010-2016. Analysis of the water supply network's failure frequency covered the years 2013-2016. The following formulas were applied in calculations (Farley et al., 2008):

$$\text{Revenue Water} = \text{Billed Authorised Consumption} = \text{Billed Metered Consumption} + \text{Billed Unmetered Consumption} \quad (1)$$

$$\text{NRW} = \text{System Input Volume} - \text{Billed Authorised Consumption} \quad (2)$$

$$\text{CARL} = \text{Non-Revenue} - \text{Unbilled Authorised Consumption Water} - \text{Commercial Losses} \quad (3)$$

$$\text{UARL (litres/day)} = (18 \times Lm + 0.8 \times Nc + 25 \times Lp) \text{ x } P \quad (4)$$

where:
Lm – mains length (km),
Nc – number of service connections,
Lp – total length of private pipe, property boundary to customer meter (km),
P – average pressure (m).

$$\text{ILI} = \text{CARL}/\text{UARL} \quad (5)$$

Failure frequency index (Kwietniewski, Rak, 2010):

$$\lambda(\Delta t) = n(\Delta t) / L^{*}\Delta t \quad (6)$$

where:
$\lambda(\Delta t)$ – unit failure intensity [fail·km-1·a-1],
$n(\Delta t)$ – number of failures within time interval Δt,
L – length of pipes tested within time interval Δt (mean length within this interval), km,
Δt – considered time interval, year.

Results

As a result of analyses conducted, values of RW, NRW, CARL, UARL and ILI indices in successive years from 2010 to 2016 were obtained (table 2). The Non-Revenue Water (NRW) index reached its highest level in 2013, amounting to 20.30%, and its lowest value, 14.57%, in 2016. In the same year, ILI reached a value of 1.34, which corresponds to the interval of group A, being ILI<2.00 for developed countries. This means that further limitation of real losses may be economically unfeasible, and precise analysis of the profitability of decisions made must be conducted (Lambert, 2012). During the considered period, the water supply network achieved a result of ILI<2.00 twice. The ILI's highest values were 2.46 in 2011 and 2.43 in 2013. In other years, the water supply network received a B result, meaning 2.00<ILI<4.00. This means that it is possible to improve the profitability of the water supply network by implementing pressure management, active leak control, etc. (Lambert, 2012).

Table 2. Changes in the values of ILI, UARL, CARL, NRW indices in individual years during the period of 2010-2016

Index	Unit	2010	2011	2012	2013	2014	2015	2016
RW	%	82.80	80.09	80.59	79.70	82.20	80.11	85.43
NRW	%	17.20	19.91	19.41	20.30	17.80	19.89	14.57
CARL	thous. m^3/year	433.79	532.65	525.59	564.00	473.68	545.14	363.08
UARL	thous. m^3/year	208.81	216.65	226.88	232.83	238.76	244.73	270.76
ILI	[-]	2.08	2.46	2.32	2.42	1.98	2.23	1.34

Source: author's own work.

During analyses, the total number of failures over the course of a year during the years 2013-2016 were gathered and presented in a chart (figure 1). These values changed within the range of 0 to 8 failures per month. The most failures were recorded in 2013 – 62 failures. The least failures were recorded in 2014 – 22 failures. The most failures in one month were recorded in January and February 2013 as well as in January 2016 and September 2015. During the analyzed period, only 4 months without failures were registered.

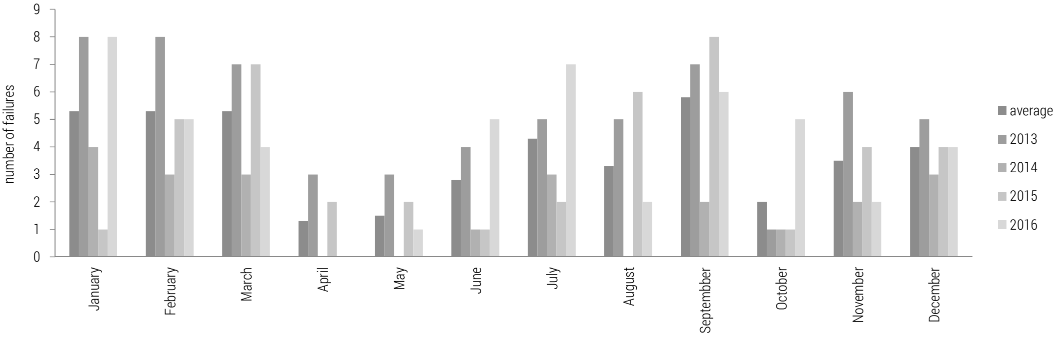

Figure 1. Number of failures in individual months during the years 2013-2016
Source: author's own work.

The months with the highest number of failures are January, February, March and September (table 3). There were 5.3 to 5.8 failures per month on average. The least failures occur in April, May and October. There were 1.3 to 2.0 failures per month on average. The mean number of failure per month amounted to 3.7 during the studied period.

Table 3. Share in annual number of failures

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Mean share of annual failures	11.9%	11.9%	11.9%	2.8%	3.4%	6.3%	9.7%	7.4%	13.1%	4.5%	8.0%	9.1%
Mean number of failures	5.3	5.3	5.3	1.3	1.5	2.8	4.3	3.3	5.8	2.0	3.5	4.0
Share of annual failures in 2013	12.9%	12.9%	11.3%	4.8%	4.8%	6.5%	8.1%	8.1%	11.3%	1.6%	9.7%	8.1%
Share of annual failures in 2014	18.2%	13.6%	13.6%	0.0%	0.0%	4.5%	13.6%	0.0%	9.1%	4.5%	9.1%	13.6%
Share of annual failures in 2015	2.3%	11.6%	16.3%	4.7%	4.7%	2.3%	4.7%	14.0%	18.6%	2.3%	9.3%	9.3%
Share of annual failures in 2016	16.3%	10.2%	8.2%	0.0%	2.0%	10.2%	14.3%	4.1%	12.2%	10.2%	4.1%	8.2%

Source: author's own work.

During the studied period, 0 to 6 service line failures occurred every month, 2.1 failures occurred per month on average during this period. There were 0 to 6 failures on distribution pipes per month. In this group, 1.3 distribution pipe failures occurred per month on average. No water main failures were registered during the period of study. However, 0 to 4 network fitting failures were recorded every month. The mean value of the number of fitting failures amounted to 0.3 failures per month. Values of failure numbers are given in tables 4, 5 and 6.

Table 4. Failures of service lines of the urban-rural water supply network during the years 2013-2016

Year	Sum of service line failures	Minimum monthly value	Maximum monthly value	Mean monthly value	Median
2013	31.0	0.0	5.0	2.6	2.5
2014	14.0	0.0	3.0	1.2	1.0
2015	26.0	0.0	5.0	2.2	2.0
2016	30.0	0.0	6.0	2.5	2.0

Source: author's own work.

Table 5. Failures of distribution pipes of the urban-rural water supply network during the years 2013-2016

Year	Sum of distribution pipe failures	Minimum monthly value	Maximum monthly value	Mean monthly value	Median
2013	23.0	0.0	5.0	1.9	1.5
2014	6.0	0.0	2.0	0.5	0.0
2015	16.0	0.0	6.0	1.3	0.5
2016	16.0	0.0	3.0	1.3	1.5

Source: author's own work.

Table 6. Failures of fittings of the urban-rural water supply network during the years 2013-2016

Year	Sum of fitting failures	Minimum monthly value	Maximum monthly value	Mean monthly value	Median
2013	8.0	0.0	4.0	0.7	0.0
2014	2.0	0.0	1.0	0.2	0.0
2015	1.0	0.0	1.0	0.1	0.0
2016	3.0	0.0	1.0	0.3	0.0

Source: author's own work.

In every year, failure frequency indices of water supply networks for service lines and the distribution network (table 6) were below the recommended value of the failure intensity index according to the European criteria described in PN-EN 60300-3-4:2008. It is worth comparing the obtained failure index values to mean values of these indices in Poland, as described in Bergel's studies (Bergel, 2012). In 2013, the value of the index for service lines and the general index for all pipes was higher than the average national value of the index in individual groups. The value of the failure frequency index for distribution pipes in 2013 was lower than the mean value of this index described by Bergel. In the years that followed in the period of study, obtained index values were lower than mean values in Poland according to Bergel.

Table 7. Failure frequency indices of the urban-rural water supply network during the years 2013-2016

	2013	2014	2015	2016
Service line failure frequency index	0.51	0.22	0.39	0.44
Distribution pipe failure frequency index	0.15	0.04	0.11	0.09
Network failure frequency index	0.29	0.10	0.19	0.19

Source: author's own work.

Assuming that the entire volume of water making up CARL will be lost as a result of the reported failures, the mean loss of water volume due to a single failure can be calculated. The chart (figure 2) presents the results under this assumption. It can be seen that, the greater the number of failures, the lesser the water volume lost as a result of a single failure.

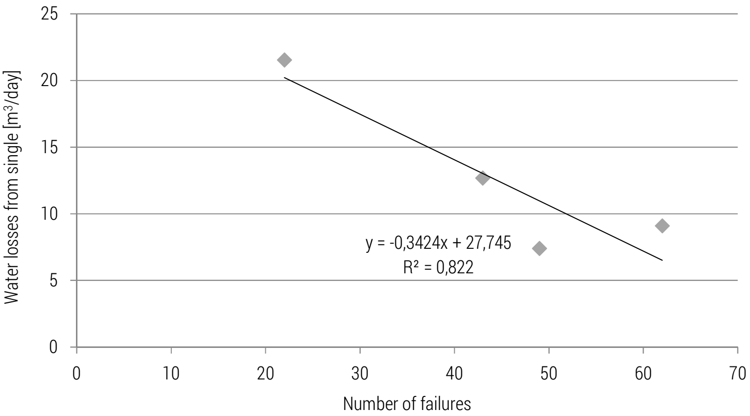

Figure 2. Dependency of water losses per single failure on number of failures

Source: author's own work.

It can be assumed that the total volume of water lost as a result of a failure corresponds to the CARL water volume reduced by the UARL water volume. Under this assumption, the mean water volume lost due to a single failure can be obtained. The chart (figure 3) presents the results under this assumption. It shows that, at the beginning, the mean water volume per single failure decreases as the number of failures grows. Next, the mean water volume per single failure begins to grow.

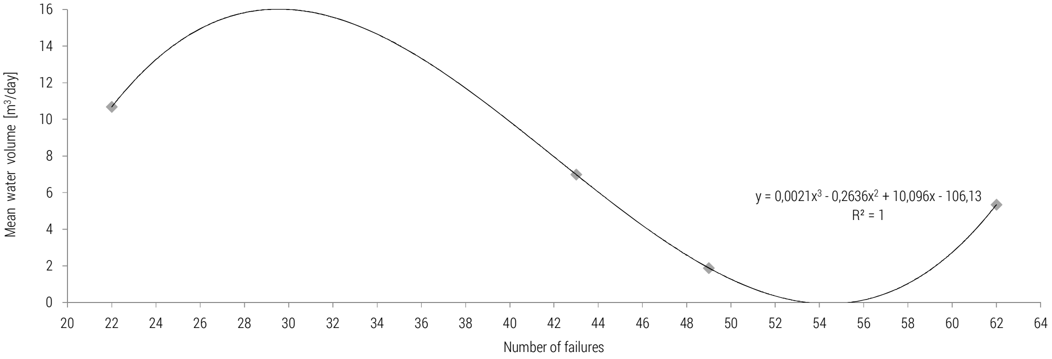

Figure 3. Dependency of water losses per single failure on number of failures accounting for UARL

Source: author's own work.

Real losses, expressed in litres per service line per day, grew as ILI values increased, which can be seen on the chart (figure 4). These values changed within the range of 112.7 to 192.6 liters/connection/day. This result is typical of a B evaluation according to IWA guidelines for pressure group <40 m H_2O. Mean pressure in the analyzed network was evaluated to be 35 m H_2O.

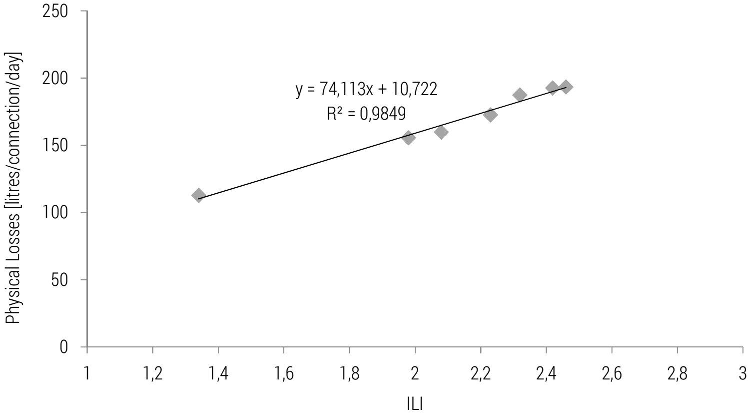

Figure 4. Dependency between Physical Losses per connection per day and ILI

Source: author's own work.

The chart (figure 5) shows how the value of losses from a single service line changed during the analyzed period. This value changed within the range of 100 to 200 liters/connection/day. This value is characterized by a B evaluation for mean pressure in water supply network <40 m.

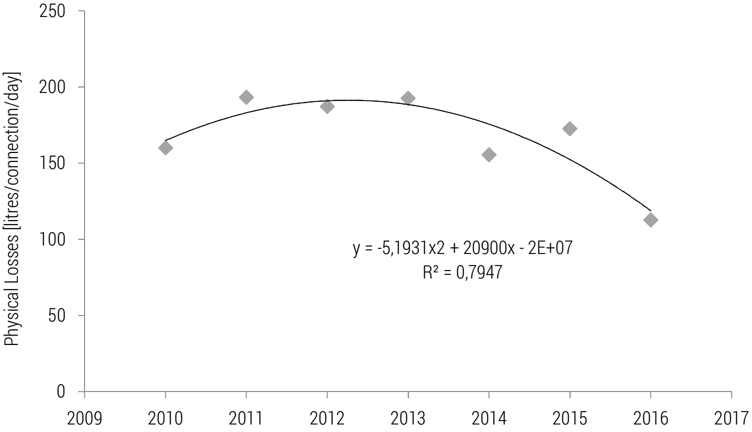

Figure 5. Physical Losses per connection per day in successive years of study

Source: author's own work.

Summary

The analyses conducted provided information on how the level of water losses in the urban-rural water supply system changed over the course of successive years. The urban-rural water supply network received an A or B evaluation in successive years according to the scoring scale recommended by IWA for ILI. NRW fluctuated between 14.57% and 20.30%. The volume of water losses from a single service line over the course of one day is characterized by a B score according to the scoring scale recommended by IWA for the pressure group up to 40 m H_2O throughout the entire period of analysis.

The months characterized by the most failures during the year within the period of study are January, February, March and September. Thanks to this information, it can be determined that intensified inspection of the water supply network should be conducted in precisely these months, e.g. through active leak control. The least failures occur in April, May and October. On this basis, it can be stated that it is not profitable to conduct preventive acoustic inspections of the water supply network in order to find hidden failures during this period.

The most failures were registered on water service lines during the period of study. No water main failures were observed during this period. The failure frequency index of the entire water supply network changed within the range from 0.10 to 0.29 failures/km/year. This is a very good result. The greater the failure frequency index of the network, the greater the ILI. The year 2016 was the exception, in which the failure frequency index was at a level similar to that of 2015, however ILI was nearly half of its 2015 value. This may be owed to the fact that the network increased its length by over 25 km in 2016, which is 10% more than in the previous year.

There was an absence of data about the number of failures in the entire period of study. It would also be interesting to compare the number and type of failures depending on the diameter, material and age of pipes. However the authors were unable to obtain such data from the water company.

In order to conduct precise analyses of the water losses and failure frequency of water supply networks, precise event logs must be kept. IT solutions aiding in the creation and storage of water supply network databases, e.g. GIS-class systems, would also be helpful.

The authors perceive a need to keep datasets and conduct analyses of water losses and failure frequency in networks, which may serve for making economically and technically justified decisions related to the implementation of solutions limiting water losses in the water supply network. It is also worth using several indices during evaluation, e.g. evaluation using ILI followed by verification of unit water loss values. Thanks to such an approach, a water supply system can be reliably evaluated in terms of water losses.

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The contribution of the authors

Joanna Gwoździej-Mazur – concept and objectives, literature review, research – 40%
Kamil Świętochowski – concept and objectives, literature review, research – 40%
Bartosz Kaźmierczak – objectives, literature review, research – 20%

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