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Analysis and assessment of water losses reduction effectiveness using examples of selected water distribution systems

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ABSTRACT

The paper presents an analysis and assessment of water losses in the distribution systems of two water supply companies. The figures necessary to calculate water losses were obtained from the analyzed companies. They were used to determine: amounts of water losses in individual years, percentage water loss indices (WS), percentage index of network efficiency (*D*) as well as indices recommended by the International Water Association: real leakage balance, non-revenue water basic, unavoidable annual real losses, infrastructure leakage index, and also unit indices of losses per inhabitant (Q_{los}), and network kilometer. Because of the relationship between the network failure intensity and water losses the failure intensity index was determined. The results of the carried out analysis allow to state that because of systematic actions in a complicated and extensive system of water distribution operated by company *A* in the years 2013–2018, the water losses maintained on a low level against a background of national figures as well as with respect to international standards. An average index of network failure intensity for distribution system *A* in the analyzed period was approximately 0.30 failure/(km y), in 2018, it was 0.25 failure/(km y) for the network, and 0.43 failure/(km y) for connections. For the distribution system of company *B*, situated in the area of underground mining impact, in the years 2013–2018 numerous loss indices were very dynamically reduced. An average failure intensity index for the entire water supply system went down from 2.4 failure/(km y) in 2013 to 0.44 failure/(km y) in 2018, which shows a low failure intensity for the system operating in the area of underground mining impact. The analysis and assessment of numerous water loss indices throughout the years proves the effectiveness of loss limitation strategies adopted by the analyzed companies. Within active loss management the analyzed waterworks for more than 10 y are implementing actions in the field of active leakage control, proper pressure management in water supply networks, speed, and quality of repairs, and also systematically carry out the pipe materials management. Because of the specific nature of water supply systems operation each company developed an own action program for losses reduction.

Keywords: Water loss; Failure frequency index; Water loss indices; Monitoring of the water supply network

1. Introduction

The increasing costs of water supply force the suppliers to improve effectiveness of water supply companies inter alia via reduction of water losses. The water resources must be effectively used to satisfy the demand of permanently growing population, taking into account limited, and decreasing availability of water [1].

The detection and removal of leakages on the one hand mean financial benefits for the company, and on the other hand – protection of water resources useful for consumption, reduction of energy consumption necessary for pumping, and also reduced production of water treatment chemicals.

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Energy is used at the stage of water production, pumping, in the process of water treatment, and during distribution. It is estimated that the energy used for water distribution is approximately 7% of the global energy consumption [2]. There is a strict relationship between the pressure in the water supply network and water losses and energy consumption. Numerous studies present research on this issue and suggestions of methods to improve energy efficiency of water supply systems [3–5]. In their study, Perrone et al. [6] showed that the reduction of water demand by 20% results in the reduction of required energy consumption by the same percentage. The study of Hotloś [7] shows that the removal of water leakage of 1 m^3 translates into savings of approximately 1.0–1.5 kWh of energy needed for the water production and transport in the distribution system. The annual amount of water losses originated in distribution systems worldwide is huge and is estimated at 126 billion m^3 a year, which costs approximately USD 39 billion annually [8]. The World Bank estimates that nearly 30 million m^3 of water is supplied to customers every day, but not invoiced primarily due to measurement inaccuracy or theft.

Total elimination of losses is impossible and not justified. Companies should aim at maintaining water losses in a given distribution system on a level justified from technological and economic point of view [9–11]. The comparison of savings originating from reduction of water losses with incurred costs leads to economic justification of carried out actions under specific conditions of water supply network operation. The goal is achieved, when the lowest losses are maintained at the lowest operating costs [12–14].

However, it should be emphasized that numerous reasons resulting in water losses include such that are dependent on and independent of water supply companies. Results of studies on numerous systems situated in 68 countries show that many factors are beyond the influence of water supply companies. The period of network operation, the material of pipes and equipment, the density of connections, the layout, situation and reach of the distribution system, the pumping or gravity transport are significant factors, independent of companies, affecting the amount of losses. They are primarily related to the urbanization layout and the ground shape [15,16]. Instead, numerous factors affecting the amount of losses, which the companies can influence, include the detection time and the speed of leakage removal. The issue of quick leakage detection and removal as a crucial one is indicated by numerous researchers [2,3,6,12,17].

Therefore, to reduce water losses it is necessary to analyze numerous factors affecting the water losses and to apply a comprehensive approach to the issue. Actions resulting in quick leakage detection and removal include active leakage control (AKW), pressure management in water supply networks, speed and quality of repairs, and also systematically carried out pipe materials management [18]. Prior to starting such actions, it is necessary to check the water balance and determine loss indices. Their determination is indispensable to develop loss limitation programs, showing detection, repair, or investment actions [4,19–21].

Domestic and foreign research shows that despite developed and disseminated methods for losses calculation their proper determination is still difficult. Frequently the analysis of losses in waterworks is based only on loss percentage indices, which does not provide a full and reliable picture. To obtain full knowledge about the amount of water lost from the system many European countries, like United Kingdom, Germany, Switzerland, Austria, Denmark, and Spain, developed and implemented special programs for very precise analysis of technical, economic, and reliability factors for water distribution systems [21–23]. The International Water Association (IWA) fulfills an important role in the implementation of best practice in the field of sustainable water management and should be given the credit for development and implementation of methods and programs for water losses limitation [23–26]. The guidelines developed by the IWA, related to the determination, analysis, and assessment of water losses in distribution systems, enable comparing losses in various water supply systems and assessment of their amounts. The studies show that the methods recommended by the IWA should be applied broader and broader [19,26–28]. However, for many water supply companies the lack of or uncertainty of data on water production and consumption for individual purposes, including own needs of the water supply system, as well as shortages and inaccuracies in the network inventory taking are an important impediment to determine indices recommended by the IWA. To have reliable water losses analyses and assessments, and to indicate actions for their limitation it is necessary to present examples of companies that use the IWA standards.

The paper is aimed at analysis and assessment of water losses amounts and at presentation and indication of additional actions resulting in water losses limitation for two polish distribution systems. The distribution system operated by one of the biggest companies from this sector on the polish market, water and sewage works in Częstochowa (company *A*), is the first of analyzed ones. This company operates a big and complicated distribution system with a total network length of 2,400 km, supplying approximately 315,000 customers with water. Elevation differences in the area where the network is located exceed 170 m, which makes it difficult to regulate the pressure in the network and can negatively affect the failure rate. The company produces and distributes water, supplies water from own deep well sources. The second company is the Chorzów–Świętochłowice water and sewage works (company *B*). Company *B* operates a water supply system (which is about 350 km) smaller than company *A*, but in the area of underground mining impact, where maintaining the failure frequency low is especially difficult. This company does not have own intakes and the cost of wholesale water purchase is relatively high, which undoubtedly affects the company finances and motivates to undertake actions toward losses reduction.

Standard research methods, such as the water balance account to the IWA and an index method, were used to determine water losses. The calculated values of loss indices were assessed based on the IWA, American Water Works Association (AWWA), and Water Band Index (WBI) guidelines. The data necessary to calculate water losses, such as the amount of water supplied to the network, water sold, water used for own needs of the company, the network length, the number, and length of water connections, the number of customers, an average pressure in the network, and the number of failures were obtained from the analyzed companies. They were used to determine: total water losses in individual years, percentage water loss index (PWS), percentage index of network efficiency (D) as well as indices recommended by the IWA: real leakage balance (RLB), non-revenue water basic (NRWB), unavoidable annual real losses (UARL), infrastructure leakage index (ILI), and also unit indices of losses per inhabitant and network kilometer. Because of a close relationship between water losses and the network failure frequency the failure intensity indices were determined in the study. Actions leading to losses reduction from the point of view of discussed companies were presented and assessed. The results obtained for the discussed system were compared with other distribution systems.

2. Material and methods

The network failure intensity index and the water balance as well as water loss indices recommended by the IWA, and those widely used in Poland, were calculated based on Eqs. (1)–(12).

The failure intensity indices λ in total for distribution pipes and water mains in the companies studied were calculated from the Eq. (1):

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

where λ is the failure intensity index (failure/(km y)), N is several failures per year, L is a total length of distribution pipes and water mains (km), and t is a time in which a given number of failures occurring was equal to 1 y.

Water loss indices, widely described in the literature [24,26] and characterized in detail in the further part of the study, were calculated from Eqs. (2)–(12).

CARL (current annual real losses) – water loss in the distribution system (m^3/y):

$$\text{CARL} = \text{SIV} - \text{UAC} - \text{BAC} \tag{2}$$

where system input volume (SIV) is the water supplied to the network (m^3/y), unbilled authorized consumption (UAC) is the water used for own needs of the company (m^3/y), and billed authorized consumption (BAC) is the water sold (m^3/y).

WS is the percentage water loss index (%):

$$\text{WS} = \frac{\text{CARL}}{\text{SIV}} \times 100\% \tag{3}$$

where CARL is the water loss in the distribution system (m^3/y), and SIV is the water supplied to the network (m^3/y).

S is the percentage water used for own needs of the company (%):

$$S = \frac{\text{UAC}}{\text{SIV}} \times 100\% \tag{4}$$

RLB_1 is the unit coefficient of water loss per km of the network (m^3/(h·km)):

$$\text{RLB}_1 = \frac{\text{CARL}}{L_m} \tag{5}$$

where CARL is the water loss in the distribution system (m^3/h).

RLB_2 is the Unique RLB index (dm^3/(connection d)) – where the connection density is greater than 20 per km of the grid:

$$\text{RLB}_2 = \frac{\text{CARL} \times 1{,}000}{N_c \times 365} \tag{6}$$

where N_c is the number of service connections (pcs).

NRWB is the non-revenue water basic (%):

$$\text{NRWB} = \left(\frac{\text{SIV} - \text{BAC}}{\text{SIV}}\right) \times 100\% \tag{7}$$

where BAC is the water sold (m^3/y).

UARL is the unavoidable annual real losses (m^3/y):

$$\text{UARL} = \left(18 \times L_m + 0.8 \times N_c + 25 \times L_p\right) \times 0.365 \times p \tag{8}$$

where L_m is the length of mains (km), L_p is length of private service pipes from property boundary to the meter (km), p is average pressure in the tested network (m H_2O), 0.365 is conversion factor per year, and m^3.

ILI is the infrastructure leakage index (–):

$$\text{ILI} = \frac{\text{CARL}}{\text{UARL}} \tag{9}$$

Q_{los} is the unit loss per capita (dm^3/(inhabitant d))

$$Q_{\text{los}} = \frac{\text{CARL} \times 1{,}000}{\text{IN} \times 365} \tag{10}$$

where IN is the number of inhabitants using the water supply system.

D is the percentage of network efficiency (%):

$$D = \frac{\text{BAC}}{\text{SIV}} \times 100\% \tag{11}$$

q_0 is the hydraulic load index for the network (m^3/(km d)):

$$q_0 = \frac{\text{SIV}}{\left(L_m\right) \times 365} \tag{12}$$

3. Results and discussion

3.1. General characterization of water supply networks in the analyzed companies

3.1.1. Distribution system of water and sewage works in Częstochowa (company A)

The company operates water supply networks in the city of Częstochowa and in the area of nine neighboring municipalities. The distribution system covers the area of approximately 1,000 km^2, supplying water to more than 50,000 water supply connections and approximately 315,000 inhabitants. The total length of operated water supply pipes (water mains, distribution pipes, and connections) is approximately 2,400 km. Water to the network is supplied from 20 water intakes, fed by 62 deep wells and 1 source.

Analyzing the water supply network in terms of materials – cast iron pipes constitute approximately 40% of total network length, steel pipes – approximately 6%, PVC – 36%, and PE approximately 15% of the total network length. The remaining 3% of the network pipes are constructed from asbestos cement and spheroidal graphite cast iron. Detailed data on the water production and sales as well as the network characteristics are presented in Table 1.

3.1.2. Distribution system of Chorzów–Świętochłowice water and sewage works (company B)

The Chorzów–Świętochłowice water and sewage works supplies water to customers from the municipalities of Chorzów and Świętochłowice. Within the carried out water supply activity the company supplies water to nearly 7,300 connections and serves approximately 145,500 inhabitants. In the studied period, all connections were metered. The company does not have own intakes, it purchases water of potable quality from the water mains network owned by the Upper-Silesian Waterworks in Katowice, which is a producer and wholesale supplier of water for regional waterworks.

In terms of materials, pipes made of PE, PVC, and spheroidal graphite cast iron prevail, constituting approximately 71%, and the period of operation does not exceed 40 y. Steel pipes constitute approximately 20% of water supply network, they were made primarily in the years 1960–1980. Pipes more than 60 y old constitute approximately 6% of the network length.

Detailed data on the water production and sales as well as the network characteristics are presented in Table 1.

3.2. Failure intensity of the distribution system

The failure intensity index λ of the network is especially important for the assessment of the network technical condition and also for the assessment of the distribution system management method. Average failure intensity indices (according to Eq. (1)) for all failures in a given year were calculated for the analyzed systems and as well as total lengths of water mains, distribution pipes, and connections (Table 2).

The studies show that failure indices depend on numerous factors and – for various materials and different water supply systems – may substantially differ in individual years. An average value of network failure intensity index for distribution system *A* in the analyzed years maintains within a range of 0.30–0.33 failure/(km y). According to more accurate data, in 2018, the average index for the total network length (without taking into account the type of material) was 0.25 and for connections 0.43 failure/(km y).

Instead, for system *B*, a clear downward trend from 2013 was stated, where the index ranged from 1.95 to 0.44 failure/(km y) in 2018. According to the data considering the type of material in 2018 (system *B*), an especially high index was recorded for gray cast iron and steel pipes, 2.00 and 1.78 failure/(km y), respectively. Low indices were found for PE and PVC pipes, 0.06 and 0.22 failure/(km y), respectively.

In accordance with the standard PN-EN 60300:–3–4:2008, the recommended failure intensity index for water mains should not exceed 0.3 failure/(km y), indices for distribution pipes, and water supply connections – 0.5

Table 1
Characteristics of the water supply network

Year	Length of the water supply network, L_m (km)	Length of private service pipes, L_p (km)	Number of service connections, N_c	Number of inhabitants using the water supply system, IN	Average pressure in the tested network, p (m H_2O)
			Company *A*		
2013	1,517.10	832.30	50,851	323,357	43
2014	1,529.70	845.60	51,537	321,726	43
2015	1,542.70	854.20	52,284	319,891	43
2016	1,562.30	867.20	53,093	318,393	43
2017	1,579.60	876.20	53,704	316,653	42
2018	1,588.80	884.40	54,238	315,033	40
			Company *B*		
2013	254.47	93.80	7,714	154,929	46
2014	254.58	94.20	7,750	153,082	46
2015	256.43	88.00	7,105	151,019	45
2016	256.88	95.40	7,171	148,533	43
2017	262.73	96.42	7,275	146,761	45
2018	265.37	94.95	7,282	145,700	43

Table 2
Mean values of unit intensity of water pipeline failures λ (failure/(km y))

Years	2013	2014	2015	2016	2017	2018
Company *A*						
Number of failures failure/y	731	708	793	746	747	777
Network length $L_m + L_p$, km	2,349.4	2,375.3	2,396.9	2,429.5	2,455.8	2,473.2
failure intensity index λ, failure/(km y)	0.31	0,30	0.33	0.31	0.30	0.31
Company *B*						
Number of failures failure/y	679	455	304	198	204	158
Network length $L_m + L_p$, km	348.2	348.7	343.4	352.2	359.0	360.3
failure intensity index λ, failure/(km y)	1.94	1.31	0.89	0.56	0.57	0.44

and 1.0 failure/(km y), respectively. Taking into consideration the analyzed companies in 2018 both systems show indices lower than the recommended values. It should be emphasized that company *B* does not operate a water mains network, and distribution networks and water supply connections are burdened with a higher failure risk due to their situation in the area of underground mining activities. The analysis of failure intensity for 72 polish water supply networks shows that failures of those systems depend primarily on the type of material used to build the water supply network, its age, and location. For cast iron pipes an average failure intensity index is 0.76 failure/(km y) and in the areas of underground mining impact – 0.82 failure/(km y); in a similar way for steel pipes on average 0.71 and 2.58 failure/(km y), for PE pipes – 0.39 and 0.77 failure/(km y), and for PVC pipes – on average 0.14 and 0.43 failure/(km y), respectively [29]. According to figures collected by the Chamber of Commerce of Polish Waterworks (IGWP) based on questionnaires comprising 145 enterprises an average failure intensity index in 2015 was 0.36 failure/(km y), and in 2014 an average for 151 enterprises was 0.39 failure/(km y) [30].

The survey presented in Benchmarking [30] shows diversification of failure intensity indices depending on the size of water supply companies. In the group of polish small enterprises (below 20,000 inhabitants using the water supply system) the failure intensity index was 0.32 failure/(km y) and in the group of big ones (over 100 thousand inhabitants using the water supply system) 0.46 failure/(km y).

A lower failure intensity index in small enterprises results from a more favorable age structure of the network. In enterprises audited by the Supreme Audit Office (NIK), an average failure intensity index in 2016 was 0.48 at a national average of 0.35 failure/(km y) [31]. For company *A*, the average failure intensity index is now much lower than the average for big enterprises. Also for company *B*, it is slightly lower than the average for big enterprises, although distribution system *B* is exposed to mining impacts. It is estimated that approximately 30%, and even 50% of water supply network failures may result from the impact of mining activities [32–34]. The number of failures and related failure intensity index proves the network condition, but not always the amount of lost water.

Water losses from the network depend not only on the number of failures but also on the rate of water outflow from the damaged pipe and the duration of this outflow. In turn, the outflow rate depends on the diameter of the hole and the pressure in the network.

This is shown inter alia by studies on water distribution systems for polish cities Końskie, Jasło, or Jarosław [35–38].

3.3. Water balance and indices characterizing water losses

The water balance and water loss indices were prepared based on the data received from companies operating the analyzed distribution systems (Table 3). The figures related to the amount of pumped water and water sales should be considered reliable. The water production in the Częstochowa company is entirely metered – each of intakes is equipped with a water consumption meter, while the Chorzów company purchases water based on the readings of water meters at metered points. It should be emphasized that all connections of both water supply systems in the studied period were metered. Only the water consumption for own needs is not metered and provided by both companies as estimates, but in relation to water pumped on a low level.

Company *A* showed the water consumption for own needs (network rinsing, technological needs, and social needs) from 0.9% to 1.0%, while company *B* from 1.1% to 1.5% of water produced in individual years (Figs. 1 and 2). Results of the Supreme Audit Office (NIK) inspection in 12 polish distribution systems show much higher, than in companies *A* and *B*, water consumption for own needs, on average 6% [31]. The non-revenue basic water loss index NRWB in accordance with the IWA recommendations is used for more reliable assessment of losses as compared with the WS. This index does not consider the volume of water used for own needs of the water supply company, which allows avoiding errors resulting from intentional overstating by some companies of the water volume used for own needs.

The analysis of WS for the system operated by company *A* in the years 2013–2018 indicates stabilization of those indices on a level of 11%–15%, lower than average values reported for polish systems (Fig. 1). The average WS reported by [38] for a few dozen polish water supply systems is approximately 21%, and according to surveys

Table 3
Summary of water balance for 2013–2018

Year	Water supplied to the network, SIV (thousand m^3/y)	Water sold, BAC (thousand m^3/y)	Water used for own needs of the company, UAC (thousand m^3/y)	Water loss in the distribution system, CARL (thousand m^3/y)
Company *A*				
2013	18,239.3	15,706.0	192.0	2,341.3
2014	20,444.3	17,610.0	212.0	2,622.3
2015	21,303.5	18,598.8	210.1	2,494.6
2016	19,398.3	17,056.1	184.5	2,157.8
2017	21,214.3	18,441.1	196.8	2,576.4
2018	17,838.2	14,974.2	169.9	2,694.1
Company *B*				
2013	7,686.7	6,939.3	115.2	632.2
2014	7,698.0	7,063.0	116.4	518.6
2015	7,662.5	7,051.4	115.0	496.1
2016	7,633.3	7,182.2	114.7	336.3
2017	7,619.2	7,110.4	114.4	394.4
2018	7,160.6	6,854.6	78.8	227.2

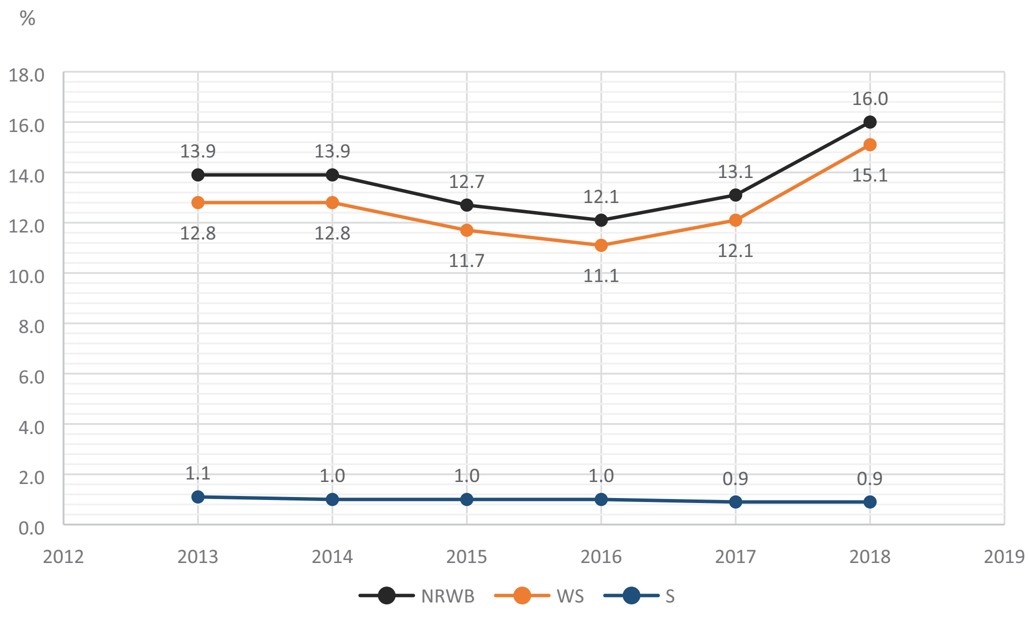

Fig. 1. Percentage water loss index (WS), non-revenue water basic index (NRWB), and percentage water used for own needs of the company (*S*) – company *A*.

carried out in 2015, presented in Benchmarking [30], approximately 15%–16%. In turn, the results of Supreme Audit Office (NIK) inspections in 12 polish distribution systems show high diversification of WS. In 2016, the highest water loss index of 21.2% occurred in the water supply network in Zduńska Wola, while the lowest, 4.15%, in Dębica, at a national average of 15.2% [31].

WS and NRWB values for the system operated by company *B* show serious reduction of water losses in the analyzed years. In 2018, the WS reached 3.2 %, and the NRWB a value of 4.3%, which shows an extremely low level as compared with polish and global systems (Fig. 2). It should be emphasized that both indices were reduced by more than 5% in the analyzed years. The WS value for this systems is now comparable with the level of leakages in the Netherlands (3%–7%) and much lower than mean values for the USA, Canada, Italy, or Greece, where average WS values, depending on the country, fall within the range of 13%–35% [39,40].

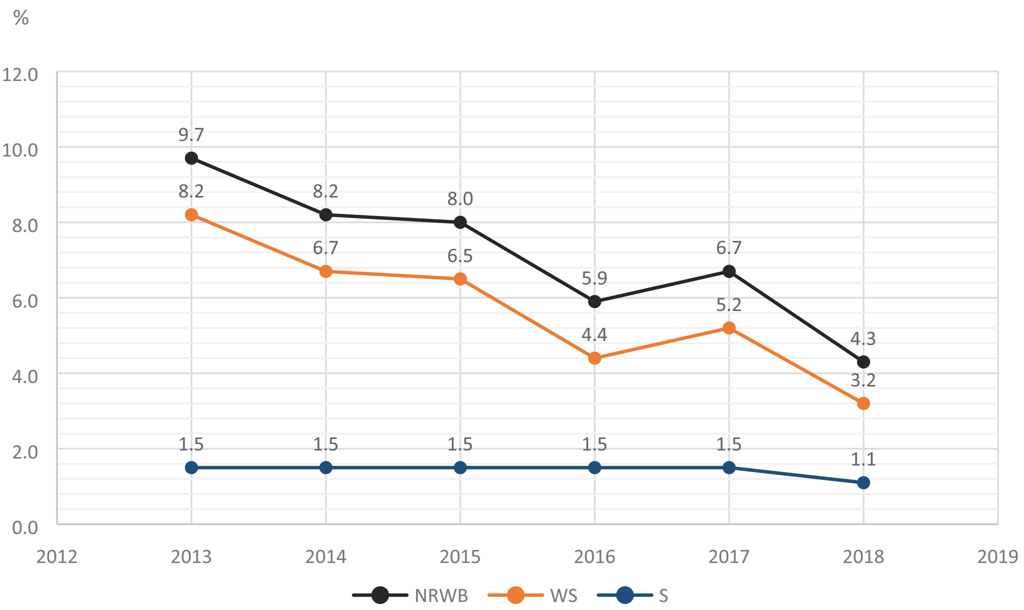

Fig. 2. Percentage water loss index (WS), non-revenue water basic index (NRWB), and percentage water used for own needs of the company (*S*) – company *B*.

Percentage indices allow to assess water losses in a specific network during many years, but are insufficient for a comprehensive analysis of water losses, in particular for comparison of different distribution systems. Distribution systems differ in the network length, number of connections, the number of served customers, the value of pressure, or hydraulic load of water supply networks. Such factors affect the amount of water losses and therefore other loss indices were determined, recommended by the IWA, allowing to assess the water distribution systems condition more precisely and objectively. Important indices reflecting water losses are the index referring to the amount of water loss per 1 km of network, and the index of losses per one water supply connection, RLB_1 and RLB_2, respectively (Table 4).

The unit water loss index per kilometer of water supply network RLB_1 for company *A* in the analyzed period was on a similar level, from 0.16 to 0.19 $m^3/(h\ km)$. For company *B*, the index was clearly decreasing from 0.28 m^3/h km in 2013 to 0.10 m^3/h km in 2018. In Poland, this index is systematically calculated and disclosed to the public in the benchmarking by the IGWP and in 2015, its average value for medium-size polish enterprises was 0.28 and for big water supply companies 0.29 m^3/h km [30]. Results of the NIK inspection in polish distribution systems show big diversification of RLB_1. In the examined companies this index in 2016 ranged from 0.08 m^3/h km in Stalowa Wola to 0.43 m^3/h km in Wałcz, at a national average of 0.28 m^3/h km [31]. Comparing RLB_1 values for both analyzed companies with Western and Polish standards, they should be considered lower than average. According to the German criteria, this index is at a recommended level below 0.20 $m^3/(km\ h)$.

The RLB_2 is another index recommended by the IWA for systems with connections density higher than 20/km of network. For the water supply network operated by company *A*, this index in the analyzed period was in a range of 111–139 dm^3/connection/d, which against a background of polish systems shows that losses are on a level lower than average. Average RLB_2 for polish systems was approximately 150 dm^3/(connection d) [38]. In countries of Western Europe, 100 dm^3/(connection d) is taken as the maximum permissible value of RLB_2. However, this index is frequently very diversified, broad-scale survey presented in the water use, and loss report shows that its value for networks in New Zealand ranges from 100 to 290 dm^3/(connection d) [41]. In the analyzed years in company *A*, this index was subject to certain fluctuations, but no clear downward trend was found for it. Instead, for the network operated by company *B*, the RLB_2 index in the years 2013–2015 was much higher than average values for polish systems. In the next years, it clearly decreased, down to a value of 86 dm^3/(connection d) considered low according to Western standards. In 2018, the value of RLB_2 was three times lower than in 2013.

A good condition of company *A* network is proved by a unit water loss per inhabitant index, Q_{los}, which value during the analyzed years ranged from 18.5 to 22.3 dm^3/(inhabitant d) (Table 4). The survey by Bergel of 334 polish group water supply systems shows an average range of 24.0–39.9 dm^3/inhabitant/d, while the analysis by Hotloś for 10 city water supply systems shows an average value of this index from 16 to 35 dm^3/inhabitant/d [7,38]. For company *B*, this index in 2018 reached a very low level of 4.3 dm^3/(inhabitant d), which indicates a very good condition of the network.

The network efficiency index (*D*) is interesting from the assessment point of view of the distribution management method and water supply networks maintenance. Because of its comparability with indices used in other European

Table 4
Water loss indices for the analyzed companies

Year	RLB_1, $m^3/(km\ h)$	RLB_2 $dm^3/(connection\ d)$	Q_{los} $dm^3/(inhabitant\ d)$	*D* (%)
		Company *A*		
2013	0.18	126	19.8	86.1
2014	0.20	139	22.3	86.2
2015	0.18	130	21.3	87.3
2016	0.16	111	18.5	88.0
2017	0.19	131	22.2	87.0
2018	0.19	135	23.0	84.0
		Company *B*		
2013	0.28	225	11.2	90.0
2014	0.23	183	9.3	91.7
2015	0.22	191	9.0	92.0
2016	0.15	128	6.2	94.1
2017	0.17	157	7.4	93.3
2018	0.10	86	4.3	95.7

countries it may be fully classified as a benchmarking index. For company, *A* values of this index in the analyzed period were pretty stable and ranged from 84 to 88%. In the case of company *B*, this index in consecutive analyzed years was growing from 90.0 in 2013 to 95.7 in 2018 (Table 4). In a questionnaire survey of 145 polish enterprises, an average network efficiency index for big companies (more than 100,000 inhabitants using the network) was 82.6% (median 86.18%). In the case of both analyzed companies, this index was higher than the average for big companies presented in a benchmarking survey [30].

The IWA recommends to determine for distribution systems, apart from total losses CARL, so-called unavoidable losses UARL, depending on the network length, the number, and length of connections, and on an average operational pressure. Losses unavoidable from technical point of view are very difficult to eliminate, and from economic point of view, their elimination is unprofitable. It is considered that the unavoidable losses show the minimum level of losses, which may be achieved in a properly operated water supply system [42]. The amounts of unavoidable losses for both systems in the analyzed period were relatively low as compared with other networks and constituted a few percent of pumped water. For water supply system *A*, the value of unavoidable losses index UARL in 2018 was 1,459,793 m^3/y, which was approximately 8% of the amount of water pumped into the network. Instead, for water supply system *B*, the value of unavoidable losses index UARL in 2018 was 203,658 m^3/y, which was approximately 3% of the amount of water pumped into the network. Figs. 3 and 4 present total and unavoidable losses for both companies in the years 2013–2018.

The comparison and analysis of total loss figures as against unavoidable losses presents water losses and the technical condition of the network (Figs. 3 and 4).

The analysis of the value of unavoidable losses and total losses for company *A* shows that it is advisable to further reduce losses, all the more that in 2017–2018 a fairly significant increase in CARL was found compared to 2016, with a relatively stable UARL in this period. The company is technically and organizationally prepared for further loss reduction, which according to the conducted analyses will bring the expected economic effects. In the case of company *B*, in 2018 total losses almost reached the level of unavoidable losses. The task for this company is to keep losses at such a low level.

The ILI index, being a quotient of total losses to unavoidable losses, is considered a reliable comparative index for various systems, and recommended by the IWA for the network assessment. Its use is recommended when the number of connections to a water distribution system exceeds 5,000, and their density is higher than 20/km of network, and at a pressure in the network of at least 0.25 MPa [43,44]. The evaluated water supply systems fulfill these criteria. Table 5 shows the criteria for evaluation the ILI according to IWA, World Bank Institute Banding System, and American Water Works Association.

The infrastructural leakage index in company *A* is relatively low and stable as compared with other polish distribution systems, in recent years it was 1.5–1.8. Instead, for the network operated by company *B*, the ILI index in the years 2013–2018 was decreasing to a very low value of 1.12 in 2018 (Fig. 5). The ILI value equal to 1.0 proves that the real losses reached the level of unavoidable losses, CARL = UARL. In accordance with rigorous IWA criteria, the value of ILI ≤ 1.5 shows a very good technical condition of the water distribution network (Table 5). Instead, according to the WBI Banding System criteria for developed countries and standards of the AWWA, the value of ILI ≤ 2.0 shows a very good technical condition of a water distribution network. It should be emphasized that this index value in 2013 for the system operated by company *B* was approximately 3.00, which according to IWA criteria was showing a poor network condition. Such a large reduction of

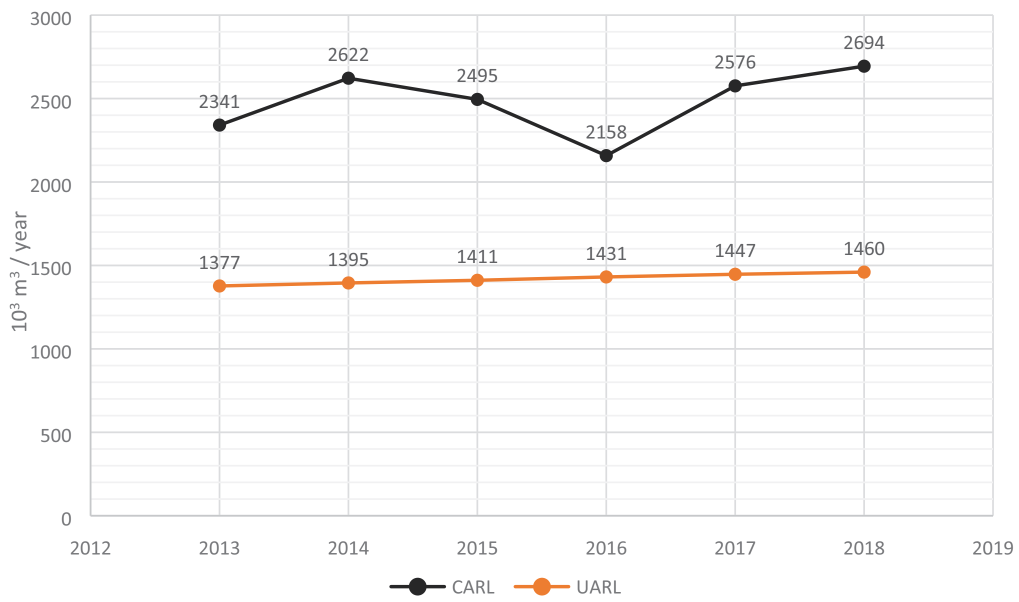

Fig. 3. Unavoidable losses in relation to total losses in the years 2013–2018 (company *A*).

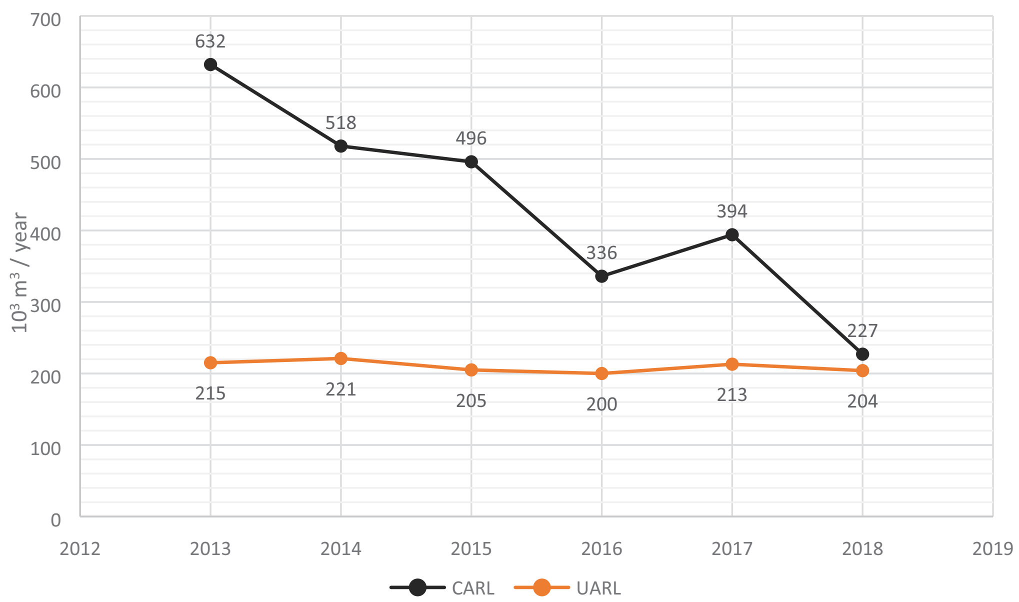

Fig. 4. Unavoidable losses in relation to total losses in the years 2013–2018 (system *B*).

the infrastructural leakage index in the considered period illustrates an effective fight against water losses. The Berger survey of 67 polish distribution systems serving 10/20 thousand inhabitants shows that an average ILI for those systems is 1.9 [38]. The ILI index for system *B* in 2018 was lower than presented by other polish authors [35,36,45–47]. The survey of 44 water distribution systems carried out by McKenzie and Lambert [44], including 22 from Europe, 17 from Australia, and 5 systems from New Zealand, shows a very wide ILI range from values below 1.0 for two studied systems to more than 5.0 for 11 systems. Then results of surveys of 16 European water supply systems in such countries as: Austria, Belgium, Bulgaria, Denmark, England, France, Germany, Italy, Malta, Portugal, Scotland, Serbia, and Croatia also confirm a very wide ILI range, from 0.7 to 5.8 [41,43,44]. A very low ILI equal to 0.3 was reported for some distribution systems in the Netherlands and Austria, which shows that the UARL is higher than the CARL [48]. It should be emphasized that at the ILI determination both real and apparent water losses are considered, e.g. inaccuracies of water meters readings. The ILI values in a range of 2–4 show advisability of introducing improvements to increase profitability through improvement in the network pressure management, AKW, and network maintenance [25,27].

Table 5
Categories of assessment of water supply systems according to ILI [26]

ILI scope and categories according to IWA (condition)	ILI categories	ILI scope according to WBI Banding System		ILI scope according to AWWA
		Developing countries	Developed countries	
ILI ≤ 1.5 (very good)	Very good	ILI ≤ 4.0	ILI ≤ 2.0	ILI ≤ 3.0
1.5 < ILI ≤ 2.0 (good)				
2.0 < ILI ≤ 2.5 (satisfactory)	Good	4.0 < ILI ≤ 8.0	2.0 < ILI ≤ 4.0	2.0 < ILI ≤ 2.5
2.5 < ILI ≤ 3.0 (poor)	Poor	8.0 < ILI ≤ 16.0	4.0 < ILI ≤ 8.0	5.0 < ILI ≤ 8.0
3.0 < ILI ≤ 3.5 (very poor)				
ILI ≥ 3.5 (inadmissible)	Inadmissible	ILI > 16.0	ILI > 8.0	ILI > 8.0

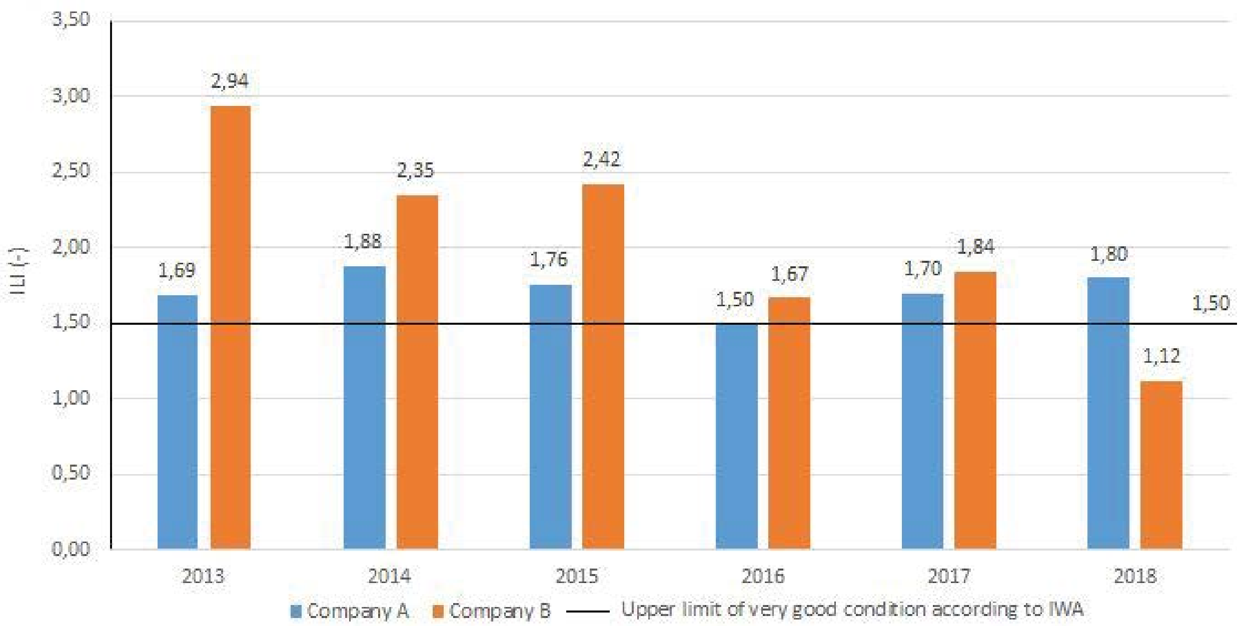

Fig. 5. Infrastructure leakage index – ILI.

The analysis of water loss took into account the hydraulic load index for the network q_0, m³/(km d) (Table 6).

Water losses in a distribution system are related to the hydraulic load of the network.

Therefore, in order to obtain reliable results, water loss analyses must take into account not only the amount of losses but also the hydraulic load of the network. In order to evaluate water losses in distribution systems, it is advisable to compare networks with the same or similar load.

In general, a reduction in the load to the network results in a decrease in water losses. It should be noted that the hydraulic load index for the network used by company *B* is significantly higher compared to those used by company *A* (Table 6). It is characteristic that despite of the higher hydraulic load of system *B*, lower loss rates were found there than for system *A*. On the other hand, the analysis of the hydraulic load indices of the water supply network in subsequent years for each system separately shows their slight changes and it is difficult to establish a clear relationship between the load and water losses.

Table 6
Summary of indices of hydraulic load of a water supply system (q_0) (m³/(km d)

Water supply companies	2013	2014	2015	2016	2017	2018
A	32.8	36.6	37.8	34.0	36.8	31.0
B	82.8	82.7	82.2	81.3	93.0	73.9

3.4. Description and assessment of loss reduction strategies applied by the analyses companies

The analysis of losses amount and variability over years in the analyzed distribution systems and of initiatives taken for their reduction shows great involvement of companies in the introduction of strategies for proper loss management. For a few years, the companies are carrying out active water losses management and broaden actions aimed at losses reduction. Because of distribution systems specificity and a wide range of available loss reduction possibilities each of companies prepared a plan of water losses reduction, in which it individually defined and implemented solutions matching the needs.

Company *A* for more than 10 y is implementing a plan for water losses reduction. In the years 2008–2009, the NRWB index was 20%, ILI more than 2.5, and Q_{los} approximately 28 dm^3/(inhabitant d) [49]. In recent years, these indices substantially decreased and stabilized. In the analyzed period, the NRWB was approximately 12%–15%, ILI approximately 1.5–1.7, and Q_{los} approximately 18–20 dm^3/(inhabitant d). The failure intensity of the entire operated water supply system is relatively low as for big distribution systems and is 0.30 failure/km/y.

This situation resulted primarily from implementation and systematic expansion of the water supply network monitoring. Pressure and flow parameters are permanently monitored in various objects, like wells or pumping stations, as well as by point measurements on the water supply network. Already approximately 50 supply zones are equipped with measuring equipment. The necessity to examine losses for separated sectors is indicated in numerous papers [50–55]. Now more than 75% of the area served by company *A* is subject to permanent control of night flows, which significantly shortens the time of failure detection and removal. The data obtained from the water supply network monitoring is compared with the calculated minimum volume of water, which should flow through the studied area, considering unavoidable losses existing in the studied zone. The studies on the water supply network carried out by a method of gradual testing consist in gradual closing the water inflow to the next sections of the water supply network at simultaneous analysis of those actions impact on the flow measured in the zone. The measurement is carried out to localize the area of the highest water losses, above the level of unavoidable losses. Early leakage detection with the contribution of network monitoring, via observations of the increase in minimum night flow, and AKW allows to shorten its duration. The company systematically improves the network monitoring by construction of new control and measuring points, which are aimed at separation of additional balance zones. The process of system expansion should be divided into three stages. The first consists in metering objects of strategic importance for the company, such as wells and intakes. The next stage comprises covering with monitoring the pumping stations and pressure reducing valves. The last, continuously implemented, is related to the construction of measuring points in important places of the water supply network. A zonal system of flows and pressures monitoring allows to indicate quickly zones and sections, in which parameters of network operation differ from the rights ones and require action starting.

The continuously performed pressure control and regulation is undoubtedly the factor that substantially resulted in losses reduction in the studied distribution system. The process of regulation consists in decreasing the pressure value in pipes to the minimum value, which ensures water supply to satisfy customer needs. The necessity of pressure monitoring and decreasing in the network to optimum values was emphasized in numerous papers [52,56,57]. The monitoring is carried out in the company based on a mathematical hydraulic model for the selected supply zone. Measuring equipment is situated in characteristic points of the network, used to determine the minimum and maximum pressure, calculated in a given measurements zone. This results in pressure reduction and stabilization improvement, reduction of failure intensity, and reduction of water losses. Moreover, periodical studies on pressure distribution are carried out in determined areas by means of portable recorders.

The implemented geographical information system (GIS) is invaluable support for the network monitoring. This system allows creating a number of valuable quantitative specifications related to the distribution system and its failure intensity. Apart from such pieces of information as the length, diameter, material, or the year of construction, in a short period of time, it is possible to obtain data characterizing the failure type and origin. This allows to analyze, the failure intensity for individual network sections or a supply zone. The division of the network into zones combined with failures geolocation in the GIS system allows to select both individual network sections, as well as a certain defined set of sections, which should be analyzed in terms, for example, the pressure value and fluctuations.

Expanded diagnostic actions have a significant impact on quick leakages localization. The company is equipped with electro-acoustic diagnostic devices, such as correlators, geophones, noise loggers, or a pipe tracker. The consistently carried out replacement of old damaged pipes with new ones and renewal and rehabilitation of many kilometers of water supply pipes had a very significant impact on the amount of water losses.

Company *B* prepared and for a few years is carrying out a program of quick leakages detection and water losses reduction. Effects of this activity over studied years are very well-visible. In 2009, the NRWB index was approximately 30%, ILI more than 2.5, and Q_{los} approximately 28 dm^3/(inhabitant d). These indices were systematically and dynamically decreasing. In 2018, the NRWB was 4.3%, ILI – 1.12, and Q_{los} approximately 4.0 dm^3/(inhabitant d). The failure intensity of the entire operated water supply system went down from 2.4 to 0.44 failures/km/y, which shows low failure intensity for the system operating in the area of underground mining impact.

The company, implementing active water loss management, carries out actions aiming at water losses reduction in four areas: AKW, pressure management, speed of repairs, and pipe materials management. They consider implementation of AKW, pressure, and flows monitoring in nearly the entire distribution system to be most significant actions to reduce water losses. Regular inspections of determined areas of the water supply network to detect and remove leakages existing in the network are carried out under AKW. Performing the AKW, the company can much more precisely determine the amount of real losses in various network zones and objects. The implemented and systematically carried out recording and analysis of data characterizing, the water supply network operation, such as: the number and size of leakages, frequency, and sites of failure origination, type and age of fittings and pipes, parameters of network operation resulting from the observation of the minimum night flow, etc. enable early leakage detection in the network and hence reduction of water losses. The flows and pressure monitoring in separate parts of the water supply network, so-called measuring zones, allows to notice leakages almost immediately and to start repair actions.

The monitoring system covers twenty water supply zones and allows for measuring and monitoring about 78% of the amount of water consumed by a company. The remaining amount of water is determined by using the traditional water meter readings taken once a month. After entering the data into the system and comparing the indications, it is possible to detect possible irregularities related to the increased water consumption of a given zone.

Unexpectedly, high night flows provide a signal to search for and localize leakages. The measurement of minimum night flow is taken at most reliable time, usually between 1 and 3 a.m., when the water consumption by customers is the lowest. Numerous studies prove that it is a very important action to detect network failures [54,55]. The night flows analysis allows to identify areas, in which leakages or uncontrolled consumption occur.

The company uses electroacoustic diagnostic devices, applying a system for acoustic leakages detection by means of loggers, correlators, geophones, or modern stethoscopes. Sensors of the system for acoustic leakages detection record noises originating from water supply networks at night hours, which allows to localize failures.

Also company *B* utilizes the GIS system, which allows to create maps of the managed area, to collect, store, and process the data. Just by its use, it is possible to acquire quickly and precisely characteristic network data, including information about pipe diameters and their course, fittings location, type of materials, and their failure intensity, etc. The data analysis allows to diagnose the network condition. A few pressure regulation points are working in the area of company operations. The pressure in the network is regulated by setting the output pressure. However, its disadvantage consists in the lack of pressure regulation possibility during night hours, when it is highest, and possibility to experience its fluctuations caused by the water consumption during the day.

For many years, the company performs a broad scope of repairs and replaces water supply pipes every year. Sections are qualified for replacement based on the failure intensity index values. In 2013–2018, approximately 25.0 km of the water supply network were modernized and replaced, which accounts for nearly 10% of the operated distribution network.

The company is also carrying out for many years actions aimed at reducing apparent losses through replacement of water meters or radio readings. Many authors emphasize the necessity to analyze and assess the share of apparent losses in total water losses [28,58].

4. Summary and conclusions

A significant part of polish water supply companies operate distribution networks, in which an average age of pipes exceeds a few dozen years. The reconstruction of the entire infrastructure and immediate reduction of failure intensity and water loss indices is usually beyond the reach of companies investment budgets. The experience of companies analyzed in the paper shows that to reduce water losses to the planned minimum losses it is necessary to carry out comprehensive interrelated organizational and technological actions.

Within active loss management the analyzed waterworks for more than 10 y are implementing actions in the field of AKW, proper pressure management in water supply networks, speed and quality of repairs, and also systematically carry out the pipe materials management. Because of specific nature of water supply systems operation each company developed an own action program for losses reduction. The scope and schedule of work were adapted to local conditions of operation and to companies possibilities.

Company *A* operates a big and complicated distribution system, where approximately 50% of pipes are made of cast iron and steel, and only because of comprehensive and systematic actions carried out for a few years the company reached a satisfactory level of water losses. A low, as for such a big and complicated system, and stable level of losses was found in the considered period. Company *B* operates in the area of underground mining impact, where maintaining the failure frequency low is especially difficult. A low water loss level in both systems is the effect of adopted programs for water losses reduction, consistently implemented for many years.

Both companies indicate the implementation of pressure and flows monitoring, pressure regulation, and reduction, as well as systematic replacements of most failure intensive pipes as the most important actions resulting in water losses reduction. The introduction of a modern monitoring system allows in a precise way to supervise the network operation, and primarily to shorten the time from the moment of failure occurrence to the moment of its removal start. The network division into metered sectors and studying losses for individual sectors are of crucial importance. The division into zones provides a possibility to narrow the search area, which accelerates leakage localization and reduces the amount of lost water. Flow measurements in separate zones, carried out by both companies during night hours, are a very effective action to detect leakages. It allows detecting excessive flows, which can result from a failure or uncontrolled water consumption. Continuous pressure control in specified areas and its reduction to optimum levels is a good and very effective practice applied in the studied companies. Consistently carried out renewal and replacement of damaged pipes has a significant impact on reduction of water losses. The analyzed companies for many years carry out also actions aimed at apparent losses reduction, which according to the literature data may be a few percent. They result from metrological properties of water meters (flows below the starting level) and from difficulties in simultaneous measurement of water supply and consumption. The lump-sum settlements were canceled in the analyzed companies by metering all customers. Water meters of higher measurement accuracy class are installed and verification periods are observed. Radio readings of water meters are implemented on a large scale.

The examinations review leads to the following conclusions:

- The analysis of water balance and numerous water loss indices from the period of 6 y allowed to learn fuller the trends and tendencies in the field of water lost in the assessed systems. The results show that water losses in both systems are lower than average for polish and numerous global systems of water supply. The obtained effects confirm the effectiveness of actions taken to reduce losses.

- For a reliable and credible assessment of water losses level, it is necessary to analyze the balance and numerous water loss indices during a longer period of time. Assessments based on single results may be misleading. Not always low NRWB and WS indicate a good condition of the network. For example, in the years 2013–2015 for system *B* at low NRWB and WS the ILI or RLB_2 indices were high.
- Dynamic reduction of failure intensity and water losses in system *B* in the analyzed period shows that it is possible to reduce losses to a much lower level as compared with other systems operating in the areas of underground mining impact, and even to a level lower than in systems not exposed to such an impact.
- For system *A*, the failure intensity and all studied loss indices during the analyzed period were changing within a narrow range. This proves stabilization of water losses on a relatively low level as compared with similar big and complicated distribution systems.
- The failure intensity index is important for the assessment of the technical condition of the network. It should be emphasized, however, that the problem of the influence of the system failure rate on the amount of lost water is quite complicated, it requires testing not only the damage intensity indicator but also other factors characterizing failures and affecting water leakages from the network.
- In accordance with rigorous IWA criteria, the ILI value shows a very good technical condition of distribution system *B* and a good one of system *A*. According to the WBI Banding System for developed countries and standards of the AWWA, the ILI index for both systems shows a very good technical condition of both network. Particular dynamics of this index reduction was found for company *B*, where the ILI value is now close to 1.
- It is recommended that companies continue reduction of water losses to so-called economic level of leakages. The limit value of losses and hence the ILI value that should be pursued by companies must take into account economic factors such as production costs, treatment, and distribution costs of the treated water, or implementation costs of solutions reducing water losses.
- Because of carried out continuous actions in the field of losses reduction and the operators potential, including strategic planning, possessed equipment, laboratories, monitoring, implemented GIS systems, plans of further network modernization, ISO systems used, or additionally the EMAS (company *A*), it is possible to further improve the technical condition of distribution systems. As a result, it will be possible to keep losses on a low level or to reduce them more.
- It is advisable that companies meter the water consumption for their own needs. Such figures are given as estimates. It is also advisable to continue implementation of remote reading of all meters.

The examinations review lead to the following conclusions: BS/PB – BS/PB-400-301/19.

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