water

MDPI

Article

Evaluation and Management of Water Losses in Water Distribution Systems: Towards the Implementation of Directive (EU) 2020/2184

Iwona Deska [1,*], Urszula Kępa [1] and Agnieszka Ociepa-Kubicka [2]

[1] Department of Sanitary Networks and Installations, Faculty of Infrastructure and Environment, Czestochowa University of Technology, Brzeźnicka 60 A, 42-215 Czestochowa, Poland; urszula.kepa@pcz.pl
[2] Entrepreneurship Centre, Faculty of Management, Czestochowa University of Technology, Armii Krajowej 19 B, 42-218 Czestochowa, Poland; a.ociepa-kubicka@pcz.pl
* Correspondence: iwona.deska@pcz.pl; Tel.: +48-343-250-917

Abstract

In accordance with the provisions of Directive (EU) 2020/2184, the largest water supply companies in the European Union (EU) will be required to report real water losses starting from 2026. The recommended water loss performance indicators (PIs) are the infrastructure leakage index (ILI) rating method or "another appropriate method". The article presents results of research aimed at examining the relationship between the ILI and other selected PIs for water losses in selected Polish water distribution systems (WDSs) located in southern Poland. The highest values of determination coefficients for the linear relationships between the ILI and PIs were obtained in the case of intermediate normalized PIs for real losses expressed both as a volume of water per km of mains per 1 m H_2O of pressure (R^2 = 0.951) and as a volume of water per service connection per 1 m H_2O of pressure (R^2 = 0.9365). A very strong linear correlation with the ILI was also obtained in the case of basic normalized PIs for real losses, expressed as the volume of water per service connection (R^2 = 0.7336). The moderate linear correlation was detected in the case of the percentage PIs for water losses. Results show that the recommended indicators, which can be used when the ILI cannot be calculated, should be the intermediate or basic operational normalized indicators.

Keywords: water losses; real losses; infrastructure leakage index (ILI); directive (EU) 2020/2184; water distribution network (WDN); linear relationship

Check for updates

Academic Editors: Dariusz Kowalski and Paweł Suchorab

Received: 17 December 2025
Revised: 11 February 2026
Accepted: 16 February 2026
Published: 24 February 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

The urbanization and excessive exploitation of freshwater resources contribute to water scarcity and stress [1–3]. Seasonal water scarcity is a common problem in the hot regions of the Earth, such as in East Asia and Central Africa. Still, it also occurs in some parts of South America and southern Europe [1,4]. The deteriorating surface and groundwater quality is an additional problem many countries face [3,5]. Unfortunately, due to climate change, water scarcity and degrading water quality issues may increase, especially in river basins that are currently very vulnerable to water stress [5].

According to the Special Edition of the Sustainable Development Goals (SDGs) Report from 2023 [4], in 2020, as many as 2.4 billion people lived in areas at risk of water scarcity. According to SDGs Report from 2025 [6], in 2024, 2.2 billion people still did not have access to safely managed drinking water. Strategies for improving water security include improving the efficiency of water use, taking into account changes in water availability

over time. In regions affected by water scarcity, supply-driven planning is a much better solution than demand-driven planning [3].

Water losses in distribution systems are a serious global problem affecting developed countries [7,8]. For example, the average non-revenue water (NRW) level in European countries remains at 25%, while globally this figure is 30% [7–9]. However, NRW values may vary significantly across the EU countries. Taking into account the data for 2021, NRW expressed as a percentage of water supplied (WS) to the network in the Netherlands was approximately 5%, while in Poland it was 25%, and in Bulgaria this value reached as much as approximately 60% [9,10].

The water collection, treatment, and transport require significant energy inputs; for example, the entire water and wastewater sector in the EU accounts for 3.5% of electricity consumption [11]. Therefore, water losses are also inextricably linked to energy losses and additional greenhouse gas (GHG) emissions [12]. Water losses, therefore, negatively affect the environment, lead to waste of resources and energy [13], and thus generate additional, unnecessary costs for water supply companies [14]. Therefore, high energy efficiency of water supply systems (WSSs) is a priority in water sector management [11,15]. Regular inspection of pump systems, pressure management, and even energy recovery through pumps as turbines (PATs) [16–18] significantly increases the energy efficiency of water supply systems. Additionally, good results are achieved through effective monitoring, automation, and proper asset management [7,18].

Monitoring and reporting water losses and implementing strategies to counteract leakages are essential elements of caring for the environment, promoting the sustainable use of water resources, and maintaining the company's income and image. Water losses in the water distribution network (WDN) are determined based on a water balance (WB) prepared for a specific period of time (e.g., monthly or annually) [19]. The WB was first proposed and published in 2000 by the International Water Association (IWA) and is widely used by consultants and water supply companies [20,21]. Since its first publication, it has undergone modifications. The most significant change from the original version of WB is the inclusion of water imported (WI) and water exported (WE). The updated WB diagram is shown in Figure 1. Components of water losses and NRW are marked in red and orange colors.

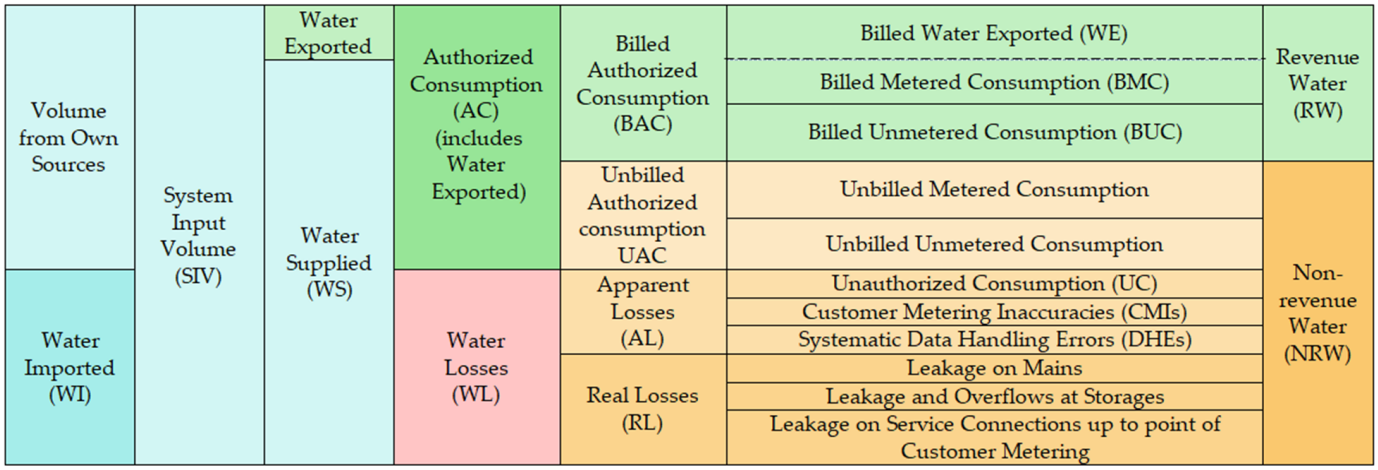


Figure 1. The water balance (prepared based on [20–22]).

The supplemented WB considers that the total volume of water produced by the company, referred to as system input volume (SIV), may come from its own sources or can be imported from other WSSs [20–22]. SIV is divided into WS, which is supplied to the WDN, and WE, which is sold to other WSSs. The WB presented in Figure 1 shows

that total water losses are divided into apparent losses (AL) and real losses (RL) [23–25]. AL are caused by measurement inaccuracies as well as water theft [26,27]. The real losses depend on the volume of leaks caused by bursts and failures (in the water supply network, connections, and water tanks). Following the principles of the SDGs, to improve resource efficiency and water supply services, water supply companies should strive to reduce water losses caused by leaks [28].

Strategies aimed at preventing and minimizing real water losses include [17,18,28,29]:

- the active leakage control to locate unreported leaks;
- the pressure management;
- the pipeline and asset management;
- the speed and quality of repairs.

Real losses cannot be completely eliminated and, in theory, should not be reduced below the unavoidable level, e.g., unavoidable annual real losses (UARL). Reducing annual leakages to the UARL is not always economically justified, as the cost of measures aimed at minimizing such significant losses may be higher than the potential profit associated with water savings. Therefore, it is considered that water losses should primarily be reduced to the so-called Economic Leakage Level (ELL), which is higher than UARL [30–33].

In order to estimate water losses, various water loss performance indicators (WLPIs) have been developed by the IWA [23,24] and the American Water Works Association (AWWA) [34] and are used by water utilities. These indicators are divided into several categories, including percentage indicators, basic and intermediate operational normalized indicators, and detailed indicators. The examples of detailed indicators are the infrastructure leakage index (ILI), also known as Op29 and UARL [19,35,36]. The ILI was designed by the IWA Task Force in 1999 and is recommended for comparing leakage rates between different WSSs with diverse infrastructure characteristics, such as the length of mains, the length and density of service connections, and average operating pressures [24,37,38]. The ILI is considered one of the most effective and commonly used WLPIs for assessing RL [19,23,24,39]. This dimensionless index is derived from both the structural and operational characteristics of the WDN [40] and is calculated as the quotient of current annual real losses (CARL) and UARL (detailed equations are provided in Section 2) [39,41,42]. The ILI enables a reliable and credible assessment of the WSS condition and, in addition, is the only indicator that allows for comparison of different systems [19,39]. The ILI evaluation facilitates the development of potential action plans and measures [40,43]. Many companies believe that ILI can also be used in relation to separate district metered areas (DMAs) or pressure management areas (PMAs), allowing corrective strategies to be implemented in those parts of the WDNs that most require intervention. Nevertheless, there was also an ongoing debate about the ILI, with critical opinions regarding its use [42,44,45]. According to Alegre et al. [42], criticism of the ILI stems from the fact that, as the only indicator developed by the IWA, it is based on an empirical expression. Another problem associated with the ILI is the significant impact of operating pressure and the length of service connections on its value [42]. Giustolisi et al. [44,45] have emphasized that the ILI primarily applies to systems with 5000 or more service connections. They have proposed the use of the asset management support indicator (AMSI) in relation to smaller WDSs and DMAs.

However, it should be emphasized that the IWA Water Loss Specialists Group (WLSG) is constantly working on adapting the methodology for calculating ILI and UARL in order to extend their applicability to smaller WDSs (or DMAs) with fewer than 5000 service connections. Specialists from IWA WLSG recommend multiplying UARL by the system correction factor (SCF) to calculate ILI for smaller systems, zones, or DMAs with a number of service connections less than 5000, and/or average pressures less than 45 m H_2O or higher than 60 m H_2O [46–48]. The design of DMAs is an essential element

for active leakage control, which aims to detect and eliminate unreported leaks, as well as to implement pressure management strategies [49]. Therefore, the ability to estimate the ILI for separate DMAs is crucial for the proper implementation of strategies aimed at reducing real water losses.

Reducing water and energy losses in WDNs is part of SDG 6.4, which is scheduled for implementation in 2030 [33,50]. The Directive (EU) 2020/2184 of the European Parliament and of the Council on the quality of drinking water, also known as the Drinking Water Directive (DWD) [51], is a regulation that requires operators of larger water supply networks in the EU to report water losses caused by leaks. Broadly understood initiatives and activities aimed at reducing water losses in water supply systems, as well as related water loss reporting, are part of ESG strategies in the water supply and sewage sector [52].

The Directive (EU) 2020/2184 entered into force on 25 December 1998 as the Council Directive 98/83/EC [53]. The European Commission announced the review of DWD in March 2014 as a follow-up to the Right2Water European Citizens' Initiative [54]. The revised DWD (Directive (EU) 2020/2184 recast) [51] was formally adopted by the European Parliament (EP) on 16 December 2020 and entered into force in January 2021. Until 12 January 2023, the Directive (EU) 2020/2184 was to be transposed into national legislation in EU Member States [51,54].

The implementation of Directive (EU) 2020/2184 will require, among other things, the development of effective methods for assessing water losses and reducing leakages. According to the Directive, by 12 January 2026, EU Member States shall declare the use of the ILI rating method or other appropriate method to assess water leakage levels within their territories [51]. However, in accordance with the provisions of the Directive, the obligation to report WL applies to utilities supplying at least 10,000 m^3 of water per day to consumers or serving at least 50,000 people [55].

By 12 January 2028, the Directive (EU) 2020/2184 should be supplemented by a delegated act [54,56] specifying detailed reporting guidelines. In accordance with Article 21 of the Directive, the European Commission should determine the threshold value (based on the ILI or another appropriate method) above which Member States are required to present an action plan. The threshold value should be determined based on both Member States' assessments and the average leakage rate in the EU [57].

The Commission Delegated Regulation (EU) 2023/2486 of 27 June 2023 [45,46] specifies requirements for the ILI value for three distinct cases of the WDN operation [51,56,57]:

- For the existing WDN, the leakage level should be calculated using the ILI (the threshold value in this case should be equal to or lower than 2.0) or using another appropriate method (the threshold value should be determined in accordance with Article 4 of Directive (EU) 2020/2184);
- For the construction and operation of a new WDN, or an extension of an existing WDN, the requirements are similar to those for the existing WDN, but in this case the threshold value of the ILI should be equal to or lower than 1.5;
- For the renewal of existing WDN, the activities undertaken shall reduce by at least 20 percent the gap between the current averaged three-year ILI value and a value of 1.5 (or the gap between the current leakage level averaged over three years, calculated using another appropriate method, and the threshold value established in accordance with Article 4 of Directive (EU) 2020/2184).

All of the above-described leakage rate calculations should be applied to both the entire WDN and the specified part of the system, where the works are carried out, e.g., at the water supply zone level, and at both DMAs and PMAs [51,56,57].

Previous studies show that not all water supply companies are ready to implement the requirements of Directive (EU) 2020/2184. Utilities are not always able to determine all

the data necessary to calculate the ILI. For example, some companies struggle to determine the correct value of average operating pressure [37,58]. Therefore, the provisions of the Directive anticipate this situation and stipulate that the ILI or "another appropriate method" can be used for calculating water losses. However, neither the Directive [51] nor the Delegated Regulation [56] specifies which methods can be used when the ILI cannot be applied. It should be emphasized that the ILI is currently considered the most reliable indicator. By relating CARL to UARL, the ILI provides quick and reliable information on the WDS condition in terms of the volume of leaks that can be avoided by implementing corrective measures [19,59]. When it is not possible to calculate the ILI due to the lack of one or more parameters (e.g., the operating pressure, the length of mains, length and number of service connections), another optimal WLPI should be selected that allows the condition of the WDN to be estimated with a reliability similar to that provided by the ILI. Many indicators have been developed to estimate water losses. However, their accuracy and reliability vary significantly depending on the characteristics of the WDN, the volume of water produced and transported, and the purpose of the calculations [23,24,37,38]. Few studies in scientific publications have analyzed the correlation among different water loss indicators, including ILI. In addition, these studies usually focus on a limited number of indicators or on indicators other than those recommended by the IWA [44,60]. Giustolisi et al. (2024) [44] described a linear relationship between actual water losses and normalized WLPIs (defined as leakage density, expressed as the volume of leakage per unit length of the network per day). In their research, they also demonstrated a nonlinear relationship between leakage density and the percentage WLPI. In addition, they found that the water consumption density (consumption per unit length of network per day) significantly affects this relationship. Giustolisi et al. (2024) [44,45] proposed the use of the asset management support indicator (AMSI) that they developed. For several WSSs (and DMA zones), they compared the calculated AMSI and ILI values. Based on the results obtained, they concluded that the ILI values are several times higher than the AMSI values. In addition, they found that AMSI depends on operating pressure. Based on the calculation models presented in the publication, the AMSI formulas may be more complex for network operators than the ILI formulas [44].

In another publication, Oberascher et al. (2020) [60] analyzed the relationship between ILI and water demand, percentage indicator, and normalized WLPIs. They reported a very high Pearson's correlation coefficient (r = 0.952) between the ILI and the percentage indicator. However, they emphasized that, according to Austrian law, percentage WLPIs (defined as volume-related indicators) are calculated as the percentage volume of water loss in relation to water demand, rather than as the volume of water loss in relation to SIV. Therefore, the percentage indicators calculated in [60] may differ from those determined using the methods proposed by the IWA. Oberascher et al. [60] also analyzed the correlation between the ILI and normalized WLPIs estimated as: (a) leakage volume in m^3 per km of mains per hour, and (b) leakage volume in dm^3 per service connection per day. Their results show a very strong correlation between ILI and the normalized WLPIs expressed per length of mains. However, they emphasized that such a strong correlation may result from relatively low levels of water losses in Austria, due to high standards and significant reductions in leaks, often even below the expected UARL value. Therefore, the results obtained by Oberascher et al. may be limited and applicable mainly to WDSs in Austria or to very well-managed WSSs with very low water losses [60].

Given that the results available in the literature may be limited and that there is still a gap in the current knowledge on this issue, it can be concluded that there is a need to continue and expand the analysis and research on the correlation between ILI and other water loss indicators recommended by the IWA.

In view of the above, the following research questions were formulated: (1) Can all water loss performance indicators be equally valuable for estimating the WDS condition for reporting purposes as a part of the implementation of the Directive (EU) 2020/2184? (2) Based on correlation analysis, is it possible to identify types of indicators that could be used when it is problematic to determine the ILI? (3) Is there a need to clarify which WLPIs should be used for reporting water losses in order to enable the comparison of the condition of different WDNs in the EU?

Taking into account these questions, the study's primary objective was to analyze the correlation between the ILI and other PIs to identify groups of indices that could be recommended for reporting purposes related to the implementation of the Directive (EU) 2020/2184. The research results can be used by engineers and policy makers in preparing and implementing more detailed water loss reporting requirements.

2. Materials and Methods

The research described in the paper was conducted based on annual WBs covering the years 2017 and 2021, carried out for 12 Polish Water Supply and Sewerage Companies (analyzed in previously published papers [58,61]). Information regarding the location and names of plants is not publicly available. All analyzed companies are located in the EU, in southern Poland. Data no. 1, 2, and 3 refer to annual WBs for three water supply companies for 2017. Data numbered from 4 to 12 refer to the WBs for 2021 for nine water supply companies. Data initially obtained from companies (described in [58,61]) included WS, which in this case was equivalent to SIV due to the lack of exported or imported water. The following data included billed authorized consumption (BAC), unbilled authorized consumption (UAC), the average operating pressure (P), the length of mains (L_m), as well as the number and the total length of service connections (N_c and L_t, respectively). The characteristics of the WDNs and the data used to prepare the WBs are presented in Section 3.

WLPIs calculated based on data have been classified into the following groups (subscripts have been introduced to water loss labels in order to distinguish between different types of losses, e.g., %—percentage index, b—basic index, i—intermediate index, 1—losses per km of the network, 2—losses per service connection):

1. Annual water loss volumes, expressed in m^3/year (marked as NRW, WL, RL, and AL);
2. Annual WLPIs expressed as percentages of SIV (marked as: $NRW_{\%}$, $WL_{\%}$, $RL_{\%}$, and $AL_{\%}$, respectively);
3. Annual basic operational normalized WLPIs expressed in m^3 per km of mains per day (marked as NRW_{b1}, WL_{b1}, RL_{b1}, and AL_{b1});
4. Annual basic operational normalized WLPIs expressed in dm^3 per service connection per day (marked as NRW_{b2}, WL_{b2}, RL_{b2}, and AL_{b2});
5. Annual intermediate operational normalized WLPIs expressed in m^3 per km of mains per day per 1 m H_2O of pressure (marked as NRW_{i1}, WL_{i1}, RL_{i1}, and AL_{i1});
6. Annual intermediate operational normalized WLPIs expressed in dm^3 per service connection per day per 1 m H_2O of pressure (marked as NRW_{i2}, WL_{i2}, RL_{i2}, and AL_{i2}).

The volume of NRW is calculated from Equation (1) as the difference between the water supplied to the network WS (in this case, the volume of SIV) and BAC [23,24,35].

$$NRW = SIV - BAC \quad (1)$$

where NRW is the volume of non-revenue water (m^3/year), SIV is a system input volume (m^3/year), and BAC is the billed authorized consumption (m^3/year).

NRW as a percentage of SIV is calculated from Equation (2):

$$NRW_{\%} = \frac{NRW}{SIV} \cdot 100\% \quad (2)$$

where $NRW_{\%}$ is the volume of non-revenue water expressed as a percentage of SIV (%), SIV, BAC, and NRW—as above.

The volume of total water loss (WL) is calculated using Equation (3) [23,35,62]:

$$WL = SIV - BAC - UAC \quad (3)$$

where WL is the total water loss (m^3/year), UAC is unbilled authorized consumption (m^3/year), and BAC is as above.

The total water loss as a percentage of SIV is calculated using Equation (4):

$$WL_{\%} = \frac{WL}{SIV} \cdot 100\% \quad (4)$$

where $WL_{\%}$ is the total water loss as a percentage of SIV (%), SIV and WL—as above.

CARL are the physical water losses (RL) that occurred during the balance year. In order to calculate RL and CARL, AL must first be estimated for the same period as RL. The AL depends on both customer meter inaccuracies (CMIs), data handling errors (DHEs), and unauthorized consumption (UC). The approximated value of AL can be calculated as the sum of 0.2% of billed metered consumption (BMC) (which corresponds to UC) and 2% of BMC (which corresponds to the sum of CMIs and DHEs) [38]. Considering that 100% of the water sold was metered, it can be assumed that BMC = BAC. Therefore, the following Equations (5) and (6) are used to calculate the above-mentioned RL and AL [36,62]:

$$CARL = RL = WL - AL \quad (5)$$

$$AL = 0.02 \cdot BMC + 0.002 \cdot BMC = 0.022 \cdot BMC \quad (6)$$

where RL is real water loss in m^3/year, CARL is current annual real loss in m^3/year (in this case CARL = RL), AL is apparent water loss in m^3/year, BMC is billed metered consumption in m^3/year (in this case BMC = BAC).

The annual percentage indicators $RL_{\%}$ and $AL_{\%}$ were calculated in a similar manner as shown in Equation (4), replacing WL with CARL or AL (in m^3/year), respectively.

The ILI was calculated based on Equation (7) [19,23,24]:

$$ILI = \frac{CARL}{UARL} \quad (7)$$

where ILI is infrastructure leakage index (−), UARL are unavoidable annual real losses in m^3/year, CARL—as above in m^3/year.

The UARL is calculated from Equations (8) or (9). Equation (8) is used if the service connection length is measured as a distance from the property line to the meter. Equation (9) is used if the service connection length is calculated as a distance from the main to the meter [39]. In this case, Equation (9) was used for the calculation of UARL:

$$UARL = \left(6.57 \cdot L_m + 0.292 \cdot N_c + 9.132 \cdot L_p\right) \cdot P \quad (8)$$

$$UARL = \left(6.57 \cdot L_m + 0.256 \cdot N_c + 9.13 \cdot L_t\right) \cdot P \quad (9)$$

where UARL—as above in m^3/year, L_m is the length of mains in km, L_p is the total length of service connections (from property lines to meters) in km, L_t is the total length of service connections (from mains to meters) in km, N_c is the number of service connections, P is the average operating pressure in m.

The basic operational normalized PIs for real losses expressed per km of mains per day (RL_{b1}) were calculated from Equation (10) [23]:

$$RL_{b1} = \frac{CARL}{365 \cdot L_m} \quad (10)$$

where RL_{b1} is the basic operational water loss indicator in m^3/(km·d), CARL—as above (m^3/year), L_m is the total length of mains (km).

The other basic operational PIs (NRW_{b1}, WL_{b1}, and AL_{b1}) were calculated in a similar manner as in Equation (10) by replacing CARL with NRW, WL, and AL (in m^3/year), respectively.

Basic operational normalized PIs for real losses (RL_{b2}) expressed per service connection per day were calculated from Equation (11) [23,63]:

$$RL_{b2} = \frac{CARL}{0.365 \cdot N_c} \quad (11)$$

where RL_{b2} is the real water loss in dm^3/(connection·d), N_c is the number of service connections (pcs), CARL—as above in m^3/year.

Other basic operational indicators, NRW_{b2}, WL_{b2}, and AL_{b2}, were calculated in a similar manner as in Equation (11) by replacing CARL with NRW, WL, or AL, respectively.

The intermediate operational normalized PIs for real losses (RL_{i1}) expressed per km of mains per day per 1 m H_2O of pressure were calculated from Equation (12) [23,63]:

$$RL_{i1} = \frac{CARL}{365 \cdot L_m \cdot P} \quad (12)$$

where RL_{i1} is the real water loss in m^3/(km·d·1mH_2O), P is the average operating pressure in m H_2O, CARL—as above (m^3/year), L_m—as above (km).

The other intermediate operational PIs (NRW_{i1}, WL_{i1}, and AL_{i1}) were calculated in a similar manner as in Equation (12) by replacing CARL with NRW, WL, and AL (in m^3/year), respectively.

The intermediate operational normalized PIs for real losses (RL_{i2}), expressed per service connection per day per 1 m H_2O of pressure, were calculated from Equation (13) [23,63]:

$$RL_{i2} = \frac{CARL}{0.365 \cdot N_c \cdot P} \quad (13)$$

where RL_{i2} is the real water loss in dm^3/(conn.·d·1mH_2O), CARL—as above in m^3/year, P—as above in m H_2O, and N_c—as above.

Other intermediate operational PIs (NRW_{i2}, WL_{i2}, and AL_{i2}) were calculated in a similar manner to Equation (13) by replacing CARL with NRW, W, or AL, respectively.

As part of the research described in this article, an analysis of the correlation between the ILI and all estimated PIs was carried out. Based on the results obtained, linear, logarithmic, power, and exponential regression relationships between values of ILI and other

PIs were analyzed. Correlation between each independent and dependent variable was estimated using Pearson's correlation coefficient r (Equation (14)):

$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt[2]{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}} \quad (14)$$

where r is Pearson's correlation coefficient, n is the number of data points, x_i is the x (independent) variable, $\overline{x}_i$ is the mean of the x variables, y_i is the y (dependent) variable, and the $\overline{y}_i$ is the mean of the y variables.

Linear regression models were evaluated based on determination coefficients (R^2) and the root mean squared errors RMSE (Equation (15)):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_i - \widehat{y}_i\right)^2} \quad (15)$$

where n is the number of data points, y_i is the i-th measurement, and $\widehat{y}_i$ is the i-th (corresponding) prediction.

Appropriate WLPIs were selected based on r, R^2, and RMSE values, which can be used to reliably determine the water losses in WDS when ILI cannot be used.

3. Results

This section contains the results of WBs for analyzed WDNs and calculations of diverse WLPIs, including the ILI. The second part of the section presents an analysis of the correlation between the ILI and other calculated WLPIs.

3.1. The Annual Water Balances and the Calculation of Water Loss Performance Indicators

The data for the preparation of annual WBs, including the geometry and basic parameters of analyzed WDNs, are presented in Table 1. Values of average operating pressures in the case of WBs no. 1–7, 9, and 10 are provided by water supply companies. Average operating pressures in the case of WBs no. 8, 11, and 12 are calculated based on the range of maximal and minimal pressures provided by companies. The random uncertainties of average pressures were assumed as ±5% at 95% confidence limits. The uncertainties of L_m, L_p, and N_c were assumed as 1% and the calculated uncertainties of service connection densities (D) amounted to 2%.

Annual WBs for analyzed WDNs prepared based on [58,61] are presented in Table 2. The table contains data on: SIV, BAC, and UAC. Other table components: NRW and WL, expressed as both volume per year and percentage of SIV, were calculated based on Equations (1)–(4). For each component of WBs, the random uncertainties were calculated at 95% confidence limits. The maximum values of uncertainties for measured SIV (where water was supplied only from own sources) were assumed as less than ±2% due to the high resolution of main flow meters, which are used in Polish water utilities. These values were adopted based on the information provided in [35,64]. Random uncertainties of BAC and UAC volumes were set at 2% and 20%, respectively. Other uncertainties included in Table 2 were determined in accordance with the methodology given in [35,36,38,64,65] based on uncertainties for SIV, BAC, and UAC.

Table 1. The characteristics of analyzed WDSs (based on [58,61]).

No. of WB	Length of Mains, L_m (km)	Length of Service Connections, L_p (km)	Number of Service Connections, N_c	Service Connections Density, D (conn./km)	Average Operating Pressure, p (m H_2O)
1	332.3 ± 3.4	112.1 ± 1.2	9565 ± 95.7	28.8 ± 0.6	38.0 ± 1.9
2	250.3 ± 2.5	113.5 ± 1.2	10,067 ± 100.7	40.2 ± 0.8	40.0 ± 2.0
3	262.7 ± 2.7	96.4 ± 1.0	7273 ± 72.8	27.7 ± 0.6	43.0 ± 2.2
4	1587.8 ± 15.9	905.2 ± 9.1	55,287 ± 552.9	34.8 ± 0.7	40.8 ± 2.1
5	191.3 ± 2.0	172.6 ± 1.8	6321 ± 63.3	33.0 ± 0.7	50.0 ± 2.5
6	376.5 ± 3.8	243.7 ± 2.5	15,812 ± 158.2	42.0 ± 0.9	55.0 ± 2.8
7	411.6 ± 4.2	153.3 ± 1.6	14,163 ± 141.7	34.4 ± 0.7	30.0 ± 1.5
8	141.5 ± 1.5	80.3 ± 0.8	6118 ± 61.2	43.2 ± 0.9	33.0 ± 1.7
9	268.4 ± 2.7	96.0 ± 1.0	7365 ± 73.7	27.4 ± 0.6	45.0 ± 2.3
10	193.1 ± 2.0	184.7 ± 1.9	6922 ± 69.3	35.9 ± 0.8	40.7 ± 2.1
11	155.7 ± 1.6	98.4 ± 1.0	4920 ± 49.2	31.6 ± 0.7	32.5 ± 1.7
12	269.5 ± 2.7	179.2 ± 1.8	6690 ± 66.9	24.8 ± 0.6	37.5 ± 1.9

Table 2. Data on system input volume (SIV), billed authorized consumption (BAC), unbilled authorized consumption (UAC), non-revenue water (NRW), and total losses for analyzed WDSs (on the basis of [58,61]). The random uncertainties were calculated at 95% confidence limits.

No. of WB	SIV (10^3 m^3/year)	BAC (10^3 m^3/year)	UAC (10^3 m^3/year)	NRW (10^3 m^3/year)	$NRW_{\%}$ (%)	WL (10^3 m^3/year)	WL% (%)
1	5825.9 ± 116.6	5362.4 ± 107.3	37.4 ± 7.5	463.5 ± 158.4	8.0 ± 2.8	426.1 ± 158.6	7.3 ± 2.8
2	6488.1 ± 129.8	5729.0 ± 114.6	150.9 ± 30.2	759.1 ± 173.2	11.7 ± 2.7	608.2 ± 175.8	9.4 ± 2.8
3	7619.1 ± 152.4	7110.3 ± 142.3	114.3 ± 22.9	508.8 ± 208.5	6.7 ± 2.8	394.5 ± 209.7	5.2 ± 2.8
4	16,563.4 ± 331.3	14,483.7 ± 289.7	178.8 ± 35.8	2079.7 ± 440.1	12.6 ± 2.7	1900.9 ± 441.6	11.5 ± 2.7
5	1539.3 ± 30.8	1327.6 ± 26.6	16.8 ± 3.4	211.7 ± 40.7	13.8 ± 2.7	1945.0 ± 40.8	12.7 ± 2.7
6	5864.8 ± 117.3	4546.8 ± 91.0	109.1 ± 21.9	1318.0 ± 148.5	22.5 ± 2.6	1208.8 ± 150.1	20.6 ± 2.6
7	3566.0 ± 71.4	2803.0 ± 56.1	53.0 ± 10.6	763.0 ± 90.8	21.4 ± 2.6	710.0 ± 91.4	19.9 ± 2.6
8	2415.3 ± 48.4	2074.6 ± 41.5	64.9 ± 13.0	340.6 ± 63.7	14.1 ± 2.7	275.8 ± 65.0	11.4 ± 2.7
9	6988.5 ± 139.8	6536.1 ± 130.8	78.6 ± 15.8	452.3 ± 191.4	6.5 ± 2.8	373.7 ± 192.1	5.4 ± 2.8
10	1517.4 ± 30.4	1332.1 ± 26.7	8.0 ± 1.6	185.2 ± 40.4	12.2 ± 2.7	177.2 ± 40.5	11.7 ± 2.7
11	1462.7 ± 29.3	1085.8 ± 21.8	15.5 ± 3.1	376.9 ± 36.5	25.8 ± 2.5	361.4 ± 36.6	24.7 ± 2.5
12	1684.4 ± 33.7	1374.9 ± 27.5	28.6 ± 5.8	309.5 ± 43.5	18.4 ± 2.6	280.9 ± 43.9	16.7 ± 2.7

Table 3 presents calculated annual volumes and percentage values of RL and AL, as well as detailed WLPIs: UARL and ILI. The annual volume of RL (also referred to as CARL) was calculated based on Equation (5). Real losses were also calculated as a percentage of SIV ($RL_{\%}$). Apparent losses were estimated based on Equation (6) as volume of water lost per year (AL) and as a percentage of SIV ($AL_{\%}$). Table 3 also presents calculations of the components of AL: CMIs, DHEs, and UC. Assumed values of random uncertainties for RL and AL were equal to 20% (at 95% confidence limits). The random uncertainties for the ILI were estimated at 95% confidence limits in accordance with the methodology presented in [35,65].

Table 4 presents values of basic operational normalized WLPIs (also referred to as basic unit indicators), derived from Equations (10) and (11). The units of these indicators can be divided into two groups, marked with subscripts 1 and 2, respectively: (1) the volume of water lost per km of mains per day, and (2) the volume of water lost per service connection per day. Within the scope of the examination, calculations were performed for four types of PIs: NRW, WL, RL, and AL. In the case of each calculated indicator, the random inaccuracy was estimated at 95% confidence limits (in accordance with the methodology described in [35,65]).

Table 3. Calculated values of real losses (RL and $RL_{\%}$), apparent losses (AL and $AL_{\%}$), unavoidable annual real losses (UARL), the infrastructure leakage index (ILI), and two components of apparent losses: the unauthorized consumption (UC) calculated as 0.2% of BAC, and sum of the water lost due to customer meter inaccuracies (CMIs) and data handling errors (DHEs), calculated as 2% of BAC. The random uncertainties were calculated at 95% confidence limits.

No. of WB	RL = CARL (10^3 m^3/year)	$RL_{\%}$ (%)	UC (10^3 m^3/year)	CMIs + DHEs (10^3 m^3/year)	AL (10^3 m^3/year)	$AL_{\%}$ (%)	UARL (10^3 m^3/year)	ILI (−)
1	308.2 ± 160.0	5.3 ± 2.8	10.7 ± 2.2	107.3 ± 21.5	118.0 ± 21.6	2.0 ± 0.4	214.9 ± 12.9	1.43 ± 0.84
2	482.2 ± 177.3	7.4 ± 2.8	11.5 ± 2.3	114.6 ± 23.0	126.0 ± 23.1	2.0 ± 0.4	210.3 ± 12.7	2.29 ± 0.99
3	238.1 ± 211.7	3.1 ± 2.8	14.2 ± 2.9	142.2 ± 28.5	156.4 ± 28.6	2.1 ± 0.4	192.1 ± 11.6	1.24 ± 1.18
4	1582.3 ± 445.4	9.6 ± 2.7	29.0 ± 5.8	289.7 ± 58.0	318.6 ± 58.3	1.9 ± 0.4	1340.3 ± 80.5	1.18 ± 0.41
5	165.8 ± 41.2	10.8 ± 2.7	2.7 ± 0.6	26.6 ± 5.4	29.2 ± 5.4	1.9 ± 0.4	222.5 ± 13.4	0.74 ± 0.23
6	1108.8 ± 151.2	18.9 ± 2.6	9.1 ± 1.9	90.9 ± 18.2	100.0 ± 18.3	1.7 ± 0.4	481.1 ± 28.9	2.30 ± 0.46
7	648.3 ± 92.1	18.2 ± 2.6	5.6 ± 1.2	56.1 ± 11.3	61.7 ± 11.3	1.7 ± 0.4	231.9 ± 14.0	2.80 ± 0.57
8	230.1 ± 65.6	9.5 ± 2.8	4.2 ± 0.9	41.5 ± 8.3	45.6 ± 8.4	1.9 ± 0.4	106.6 ± 6.4	2.16 ± 0.75
9	229.9 ± 193.9	3.3 ± 2.8	13.1 ± 2.7	130.7 ± 26.2	143.8 ± 26.3	2.1 ± 0.4	203.6 ± 12.3	1.13 ± 1.02
10	147.9 ± 40.8	9.8 ± 2.7	2.7 ± 0.6	26.6 ± 5.4	29.3 ± 5.4	1.9 ± 0.4	192.4 ± 11.6	0.77 ± 0.26
11	337.5 ± 36.9	23.1 ± 2.6	2.2 ± 0.5	21.7 ± 4.4	23.9 ± 4.4	1.6 ± 0.3	103.4 ± 6.2	3.26 ± 0.56
12	250.6 ± 44.3	14.9 ± 2.7	2.8 ± 0.6	27.5 ± 5.5	30.3 ± 5.6	1.8 ± 0.4	192.0 ± 11.6	1.31 ± 0.31

Table 4. Calculated values of basic operational normalized (unit) water loss performance indicators. Denotations: NRW—non-revenue water, WL—total losses, RL—real losses, AL—apparent losses; denotations of subscripts: b—basic index; 1, 2—the unit type. The random uncertainties were calculated at 95% confidence limits.

No. of WB	NRW_{b1} (m^3/(km mains·d))	NRW_{b2} (dm^3/(conn. ·d))	WL_{b1} (m^3/(km mains·d))	WL_{b2} (dm^3/(conn. ·d))	RL_{b1} (m^3/(km mains·d))	RL_{b2} (dm^3/(conn. ·d))	AL_{b1} (m^3/(km mains·d))	AL_{b2} (dm^3/(conn. ·d))
1	3.8 ± 1.4	132.8 ± 45.4	3.51 ± 1.31	122.6 ± 45.5	2.54 ± 1.32	88.3 ± 45.9	0.97 ± 0.18	33.79 ± 6.18
2	8.3 ± 1.9	206.6 ± 47.2	6.66 ± 1.93	165.5 ± 47.9	5.28 ± 1.94	131.2 ± 48.3	1.38 ± 0.26	34.30 ± 6.27
3	5.3 ± 2.2	191.7 ± 78.6	4.11 ± 2.19	148.6 ± 79.0	2.48 ± 2.21	89.7 ± 79.8	1.63 ± 0.30	58.93 ± 10.77
4	3.6 ± 0.8	103.1 ± 21.9	3.28 ± 0.77	94.2 ± 21.9	2.73 ± 0.77	78.4 ± 22.1	0.55 ± 0.10	15.79 ± 2.89
5	3.0 ± 0.6	91.8 ± 17.7	2.79 ± 0.59	84.5 ± 17.7	2.37 ± 0.59	71.8 ± 17.9	0.42 ± 0.08	12.66 ± 2.32
6	9.6 ± 1.1	228.4 ± 25.8	8.80 ± 1.10	209.5 ± 26.0	8.07 ± 1.10	192.1 ± 26.2	0.73 ± 0.14	17.33 ± 3.17
7	5.1 ± 0.7	147.6 ± 17.6	4.73 ± 0.61	137.3 ± 17.7	4.32 ± 0.62	125.4 ± 17.9	0.41 ± 0.08	11.93 ± 2.18
8	6.6 ± 1.3	152.5 ± 28.6	5.34 ± 1.26	123.5 ± 29.2	4.46 ± 1.27	103.1 ± 29.4	0.88 ± 0.17	20.44 ± 3.74
9	4.6 ± 2.0	168.3 ± 71.2	3.81 ± 1.97	139.0 ± 71.5	2.35 ± 1.98	85.5 ± 72.1	1.47 ± 0.27	53.49 ± 9.78
10	2.6 ± 0.6	73.3 ± 16.0	2.51 ± 0.58	70.1 ± 16.0	2.10 ± 0.58	58.5 ± 16.2	0.42 ± 0.08	11.60 ± 2.12
11	6.6 ± 0.7	209.9 ± 20.3	6.36 ± 0.65	201.3 ± 20.4	5.94 ± 0.65	188.0 ± 20.6	0.42 ± 0.08	13.30 ± 2.43
12	3.2 ± 0.5	126.8 ± 17.9	2.86 ± 0.45	115.0 ± 18.0	2.55 ± 0.45	102.6 ± 18.2	0.31 ± 0.06	12.39 ± 2.27

Table 5 presents intermediate operational normalized WLPIs. Values of these indicators were calculated based on the basic operational unit indicators (presented in Table 4) by dividing their values by the operating pressure expressed in m H_2O. Taking into account the units, these intermediate PIs can be divided into two groups, marked with subscripts 1 and 2, respectively: (1) the volume of water lost per km of mains per day per 1 m H_2O, and (2) the volume of water lost per service connection per day per 1 m H_2O. As part of the analysis, calculations were performed for four types of indicators: NRW, WL, RL, and AL. Calculations were performed based on Equations (12) and (13). Random inaccuracies were calculated at 95% confidence limits (in accordance with the methodology described in [35]).

3.2. Analysis of the Linear Correlation Between the ILI and Other Water Loss Indicators

Based on the calculated WLPIs shown in Tables 2–5, a correlation analysis was performed between various PIs and the ILI. Various types of relationships were examined as part of the analysis. Results presented in Sections 3.2.1–3.2.6 show linear, logarithmic, power, and exponential relationships between the ILI and:

- annual volumes of NRW, WL, RL, and AL, expressed in 10^3 m^3/year;
- annual percentage WLPIs: $NRW_{\%}$, $WL_{\%}$, $RL_{\%}$, and $AL_{\%}$;

- basic operational normalized WLPIs: NRW_{b1}, WL_{b1}, RL_{b1}, AL_{b1}, expressed in m^3 of water lost per kilometer of mains per day, and NRW_{b2}, WL_{b2}, RL_{b2}, AL_{b2}, expressed in dm^3 of water lost per service connection per day;
- intermediate operational normalized WLPIs: NRW_{i1}, WL_{i1}, RL_{i1}, and AL_{i1}, expressed in m^3 of water lost per kilometer of mains per day per 1 m H_2O of pressure, as well as: NRW_{i2}, WL_{i2}, RL_{i2}, and AL_{i2}, expressed in dm^3 of water lost per service connection per day per 1 m H_2O of pressure.

Table 5. Calculated values of intermediate operational normalized (unit) water loss performance indicators. Denotations: NRW—non-revenue water, WL—total losses, RL—real losses, AL—apparent losses; denotations of subscripts: i—intermediate index; 1, 2—the unit type. The random uncertainties were calculated at 95% confidence limits.

No. of WB	NRW_{i1} (m^3/(km mains·d·1mH_2O))	NRW_{i2} (dm^3/(conn.·d·1mH_2O))	WL_{i1} (m^3/(km mains·d·1mH_2O))	WL_{i2} (dm^3/(conn.·d·1mH_2O))	RL_{i1} (m^3/(km mains·d·1mH_2O))	RL_{i2} (dm^3/(conn.·d·1mH_2O))	AL_{i1} (m^3/(km mains·d·1mH_2O))	AL_{i2} (dm^3/(conn.·d·1mH_2O))
1	0.101 ± 0.035	3.49 ± 1.20	0.092 ± 0.035	3.21 ± 1.20	0.067 ± 0.035	2.32 ± 1.21	0.026 ± 0.005	0.89 ± 0.17
2	0.208 ± 0.048	5.16 ± 1.18	0.166 ± 0.049	4.14 ± 1.20	0.132 ± 0.049	3.28 ± 1.21	0.034 ± 0.007	0.86 ± 0.16
3	0.123 ± 0.051	4.46 ± 1.83	0.096 ± 0.051	3.46 ± 1.84	0.058 ± 0.052	2.09 ± 1.86	0.038 ± 0.007	1.37 ± 0.26
4	0.088 ± 0.019	2.53 ± 0.54	0.080 ± 0.019	2.31 ± 0.54	0.067 ± 0.019	1.92 ± 0.55	0.013 ± 0.003	0.39 ± 0.08
5	0.061 ± 0.012	1.84 ± 0.36	0.056 ± 0.012	1.69 ± 0.36	0.047 ± 0.012	1.44 ± 0.36	0.008 ± 0.002	0.25 ± 0.05
6	0.174 ± 0.020	4.15 ± 0.47	0.160 ± 0.020	3.81 ± 0.48	0.147 ± 0.020	3.49 ± 0.48	0.013 ± 0.003	0.32 ± 0.06
7	0.169 ± 0.021	4.92 ± 0.59	0.158 ± 0.021	4.58 ± 0.59	0.144 ± 0.021	4.18 ± 0.60	0.014 ± 0.003	0.40 ± 0.08
8	0.200 ± 0.038	4.62 ± 0.87	0.162 ± 0.039	3.74 ± 0.89	0.135 ± 0.039	3.12 ± 0.89	0.027 ± 0.005	0.62 ± 0.12
9	0.103 ± 0.044	3.74 ± 1.59	0.085 ± 0.044	3.09 ± 1.59	0.052 ± 0.044	1.90 ± 1.61	0.033 ± 0.006	1.19 ± 0.22
10	0.065 ± 0.015	1.80 ± 0.40	0.062 ± 0.015	1.72 ± 0.40	0.052 ± 0.015	1.44 ± 0.40	0.010 ± 0.002	0.29 ± 0.06
11	0.204 ± 0.020	6.46 ± 0.63	0.196 ± 0.020	6.19 ± 0.63	0.183 ± 0.020	5.78 ± 0.64	0.013 ± 0.003	0.41 ± 0.08
12	0.084 ± 0.012	3.38 ± 0.48	0.076 ± 0.012	3.07 ± 0.48	0.068 ± 0.012	2.74 ± 0.49	0.008 ± 0.002	0.33 ± 0.07

Tables S1–S4 in the Supplementary Materials show the values of regression coefficients and determination coefficients for linear, exponential, logarithmic and power relationships between the ILI and other WLPIs.

3.2.1. The Correlation Between the ILI and Annual Volumes of Water Losses

Figure 2 shows relationships between the ILI and calculated volumes of NRW, WL, RL, and AL (estimated based on data presented in Tables 2 and 3).

Results presented in Figure 2 indicate that the correlation between the ILI and annual volumes of water losses is very weak (in this case, there is essentially no correlation). R^2 for linear relationships ranged from 0.01 (for NRW) to 0.0547 (for AL). In the case of relationships between the ILI and NRW, WL, or RL, a weak positive correlation was observed, while in the case of AL, the observed weak correlation was negative. Obtained results confirm that data showing the volume of water losses or the volume of NRW, without additional information on the WDS's size and the volume of WS, cannot be used as reliable PIs either to assess the condition of the WDN or for reporting purposes.

3.2.2. The Correlation Between the ILI and Percentage WLPIs

Figure 3 presents different kinds of relationships between the ILI and annual percentage WLPIs: $NRW_{\%}$, $WL_{\%}$, $RL_{\%}$, and $AL_{\%}$ (also known as an indicator Op26). These plots were prepared based on the results presented in Tables 2 and 3.

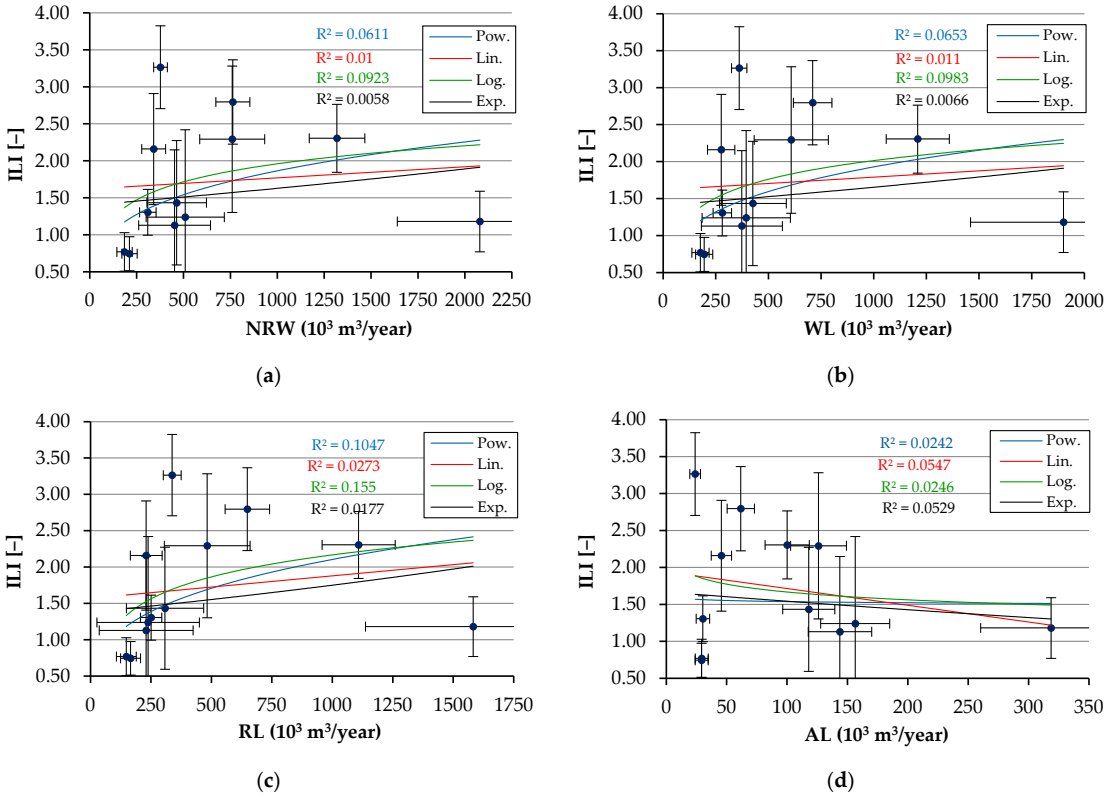


Figure 2. The linear (red line), logarithmic (green), power (blue), and exponential (black) relationships between values of the ILI and calculated annual volumes of: (**a**) NRW; (**b**) WL; (**c**) RL (CARL); (**d**) AL.

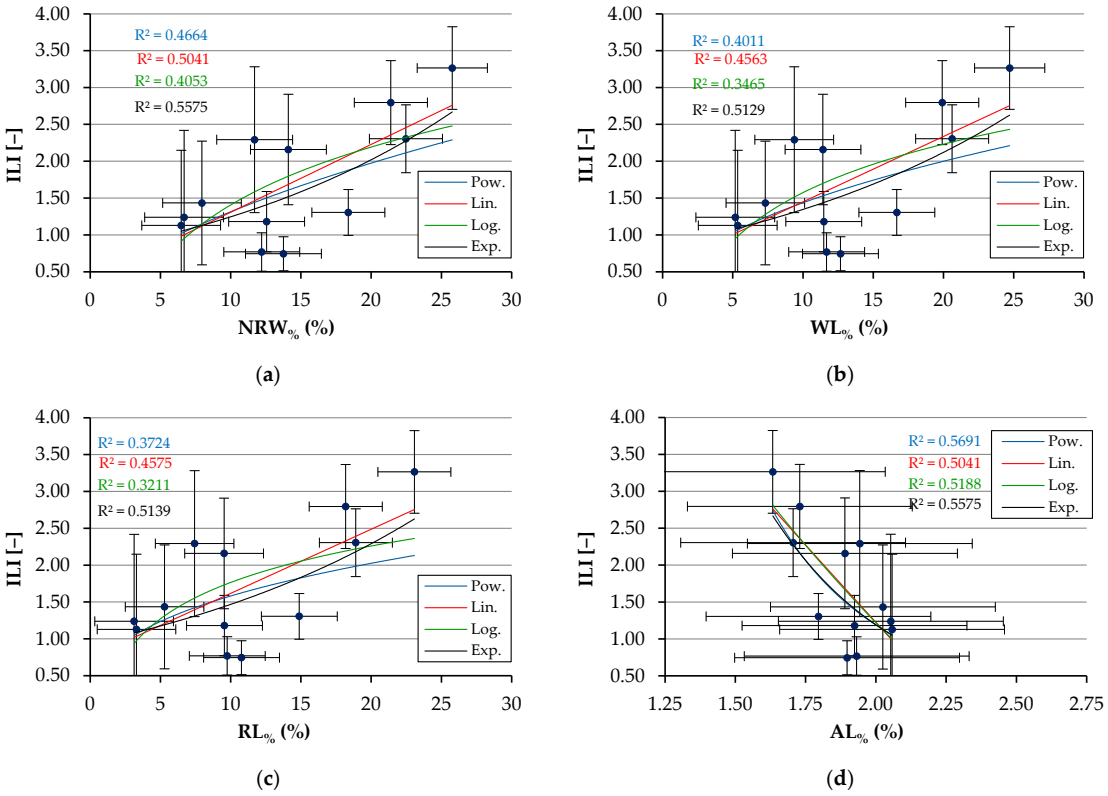


Figure 3. The linear (red line), logarithmic (green), exponential (black), and power (blue) relationships between values of the ILI and percentage WLPIs: (**a**) non-revenue water (NRW%); (**b**) total water losses (WL%); (**c**) real water losses (RL%); (**d**) apparent water losses (AL%).

Results presented in Figure 3 indicate the existence of a moderate to strong correlation between the ILI and percentage PIs for water losses. The highest values of R^2, ranging from 0.4563 (for $WL_{\%}$) to 0.5041 for both the $NRW_{\%}$ (also known as an indicator Fi36) and $AL_{\%}$, were obtained for linear relationships. A positive correlation was obtained in the case of the dependence of ILI on the three analyzed indices: $NRW_{\%}$, $WL_{\%}$, and $RL_{\%}$ (plots a, b, and c), while a negative correlation was obtained in the case of the relationship between ILI and $AL_{\%}$. Medium to strong negative correlation was also obtained for the logarithmic relationship between the ILI and AL% (R^2 = 0.5188).

3.2.3. The Correlation Between the ILI and Basic Normalized WLPIs per Length of Mains

Figure 4 shows the linear relationships between the ILI and basic operational normalized WLPIs expressed as volume of water lost (in m^3) per kilometer of mains per day. In order to properly distinguish between the analyzed coefficients presented in Figure 4, as well as in Figures 5–7 in this section, different subscripts have been added to the indicator designations. The symbol "b" stands for basic index, while "i" stands for intermediate index. Additionally, symbols 1 and 2 indicate that water losses are related either to the length of mains or to the number of service connections, respectively. For the purposes of the analysis, typical and commonly used operational normalized basic real and total water loss indicators were calculated, marked as RL_{b1} (also known as Op28) and WL_{b1} (also known as Op24), respectively. Analysis also included non-revenue water (NRW_{b1}) and apparent losses (AL_{b1}), expressed in the same units. Calculated values of the above-mentioned indicators are included in Table 4.

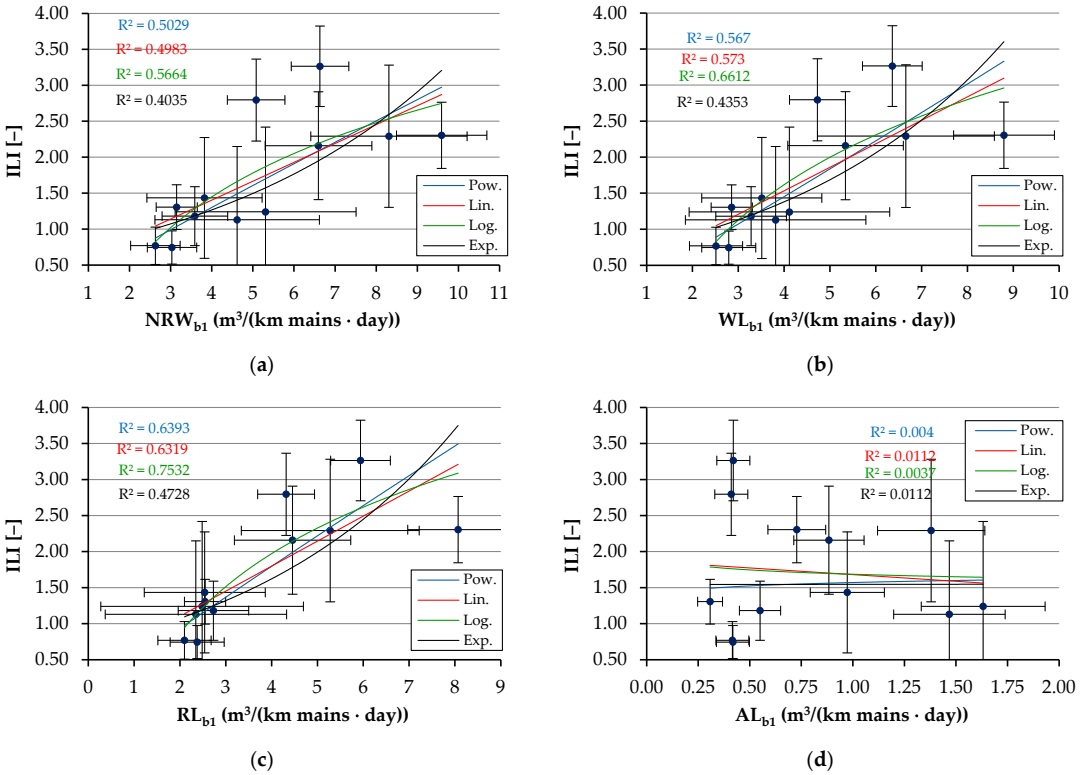


Figure 4. The linear (red line), logarithmic (green), exponential (black), and power (blue) relationships between ILI indexes and operational normalized basic WLPIs expressed in dm^3 of water lost per kilometer of mains per day: (**a**) the non-revenue water (NRW_{b1}); (**b**) the total water loss indicator (WL_{b1}); (**c**) the real water loss indicator (RL_{b1}); (**d**) the apparent water loss indicator (AL_{b1}).

The results presented in Figure 4 indicate a very strong positive correlation between the ILI and the basic operational indicator RL_{b1}. The highest value of R^2 was in this case

obtained for both the power and logarithmic relationships (0.7561 and 0.7532, respectively). The strong positive correlation in the case of RL_{b1} was also obtained for linear and exponential relationships (R^2 = 0.6319 and 0.6299, respectively). The strong positive correlations were also identified for both NRW_{b1} and WL_{b1}. A very weak negative correlation (or no correlation) was observed for AL_{b1} (for the linear relationship, the R^2 = 0.0112). The obtained results indicate that operational normalized WLPIs expressed as volume of water per km of mains per day (except for AL_{b1}) are strongly correlated with the ILI than previously analyzed both volumes of water lost per year and percentages of SIV (presented in Figures 2 and 3, respectively). The advantage of the discussed normalized indicators compared to those discussed earlier is that their values are determined taking into account the length of mains. Nevertheless, it should be noted that the commonly used basic operational real loss PI (in this analysis marked as RL_{b1}), calculated per km of mains per day, is only recommended for water supply networks with a service connection density (D) less than 20 conn./km. Meanwhile, the current analysis covers WBs for WDNs whose D was mostly greater than 20 conn./km (only in one case D < 20 conn./km).

3.2.4. The Correlation Between the ILI and Basic Normalized WLPIs per Number of Service Connections

Figure 5 shows the linear dependence of the ILI on basic operational normalized WLPIs expressed as volume of water lost (in dm^3) per service connection per day. For the purpose of the analysis, typical operational normalized basic WLPIs, referred to in this case as RL_{b2} (also known as Op27), AL_{b2}, and WL_{b2} (also known as Op23), were calculated. The non-revenue water, which is rather the typical financial indicator, was also calculated and expressed in the same units as NRW_{b2}. The calculations of these indicators are available in Table 4.

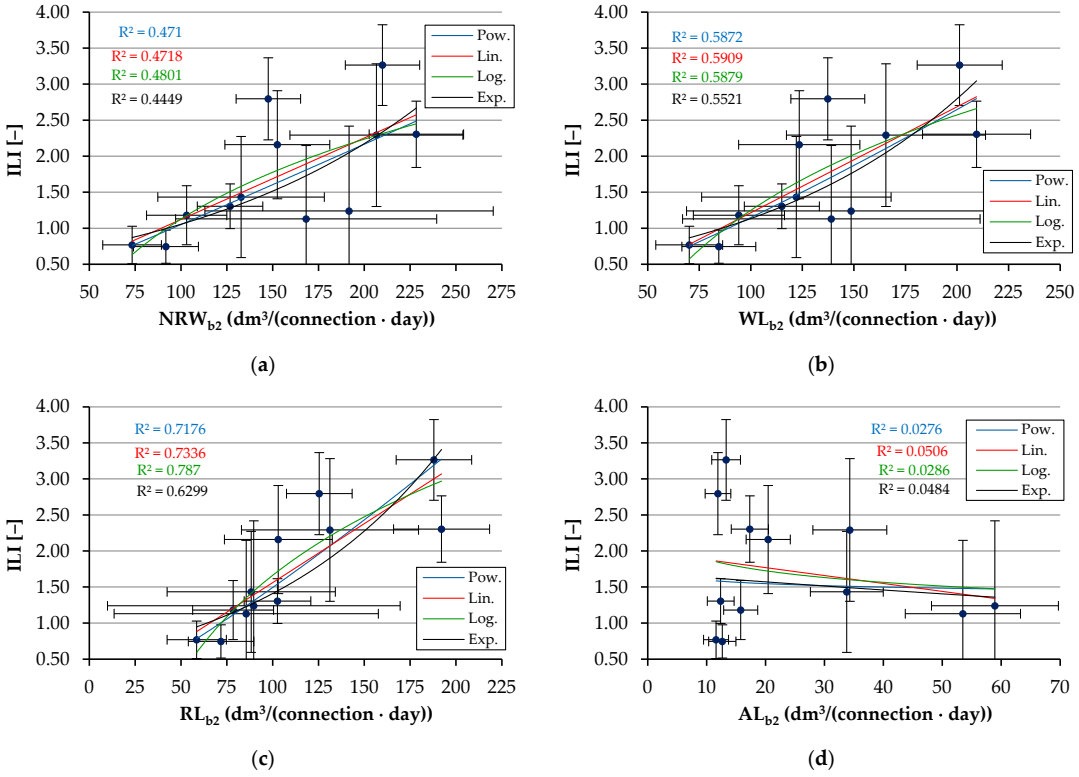


Figure 5. The linear (red line), logarithmic (green), exponential (black), and power (blue) relationships between ILI indexes and operational normalized basic WLPIs expressed in dm^3 of water lost per service connection per day: (**a**) the non-revenue water (NRW_{b2}); (**b**) the total water loss indicator (WL_{b2}); (**c**) the real water loss indicator (RL_{b2}); (**d**) the apparent water loss indicator (AL_{b2}).

Results presented in Figure 5 indicate that a very strong positive correlation was obtained for the relationship between the ILI and RL_{b2} (R^2 for all types of relationships ranged from 0.7108 (the exponential function) to 0.8031 (the power function). The R^2 for the linear relationship is 0.7336. The correlation obtained for RL_{b2} in the case of all types of dependencies is higher than that for RL_{b1}, which may be due to the fact that connection densities in the analyzed WDNs were mostly higher than 20 conn./km. A strong positive correlation is also obtained for WL_{b2} (R^2 = 0.5879–0.6619) and NRW_{b2} (R^2 = 0.4718–0.5785). A very weak negative correlation was observed for AL_{b2} (R^2 = 0.0165–0.0506).

3.2.5. The Correlation Between the ILI and Intermediate Normalized WLPIs per Length of Mains

Figure 6 shows the linear relationships between the ILI and intermediate operational normalized WLPIs expressed as volume of water lost (in m^3) per km of mains per day per 1 m H_2O of pressure. These PIs are marked in Figure 6 as: NRW_{i1}, WL_{i1}, RL_{i1}, and Al_{i1}. Plots presented in Figure 6 are prepared based on calculated values of PIs included in Table 5.

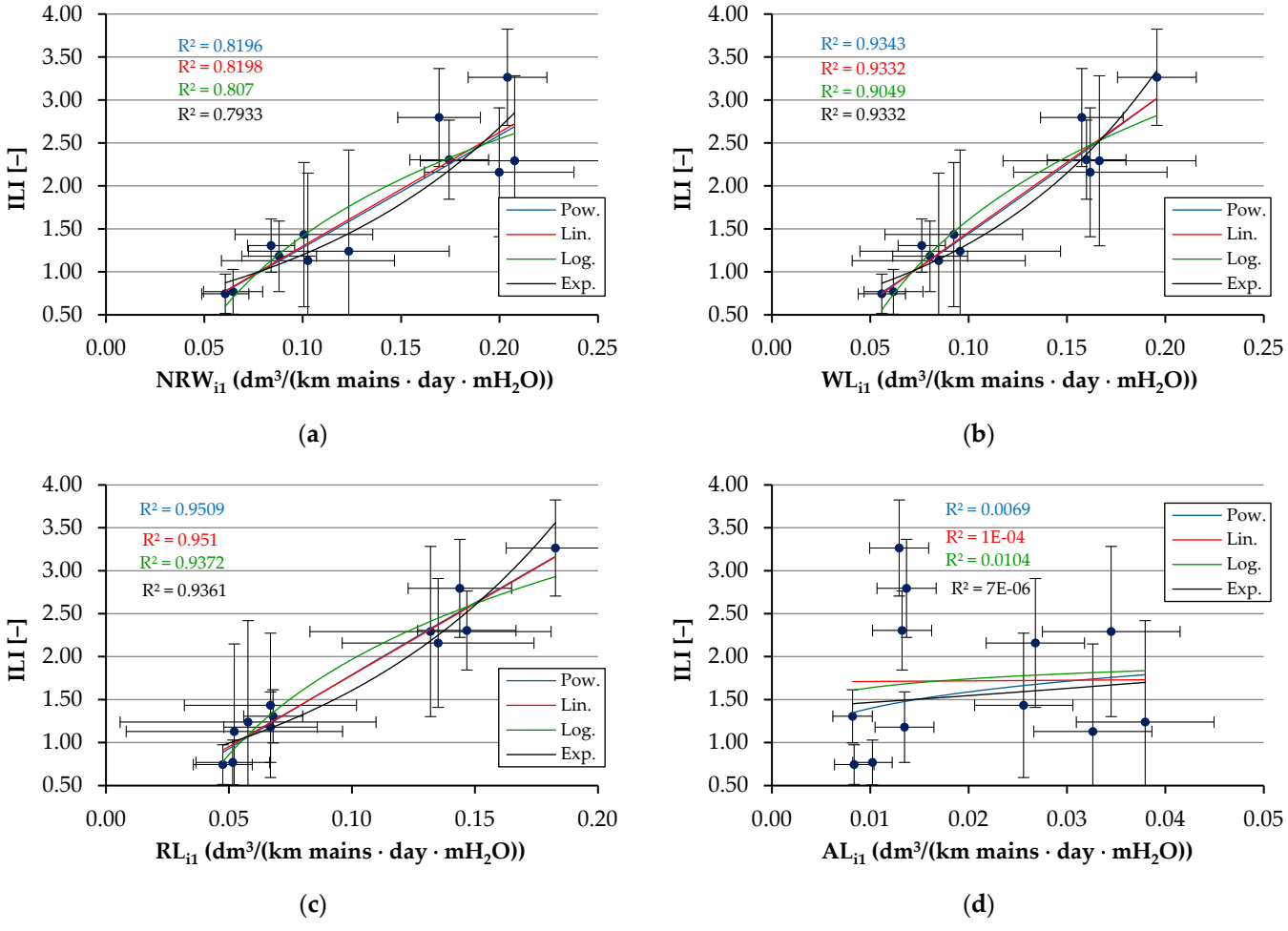


Figure 6. The linear (red line), logarithmic (green), exponential (black), and power (blue) relationships between ILI indexes and operational normalized intermediate WLPIs expressed in m^3 of water lost per kilometer of mains per day per 1 m H_2O of pressure: (**a**) the non-revenue water (NRW_{i1}); (**b**) the total water loss indicator (WL_{i1}); (**c**) the real water loss indicator (RL_{i1}); (**d**) the apparent water loss indicator (AL_{i1}).

The results presented in Figure 6 indicate that the highest and a very strong positive correlation was obtained for RL_{i1}. The R^2 for the linear relationship is 0.9510, and the R^2 for

the logarithmic relationship is 0.9372. In regard to RL_{i1}, very strong positive correlations were also obtained in the case of power and exponential relationships (R^2 = 0.9287 and 0.8985, respectively). Very strong positive correlations were also obtained in the case of WL_{i1} (the maximal value of R^2 = 0.9332 for the linear function) and in the case of NRW_{i1} (the maximal value of R^2 = 0.8827 for the power function). The weakest linear correlation among all analyzed cases was recorded for the linear relationship between the ILI and AL_{i1}. In fact, in this case, no correlation was found ($R^2 = 1 \times 10^{-4}$).

3.2.6. The Correlation Between the ILI and Intermediate Normalized WLPIs per Number of Service Connections

Figure 7 shows different kinds of relationships between the ILI and intermediate operational normalized WLPIs expressed as volume of water lost (in dm^3) per service connection per day per 1 m H_2O of pressure. These indices are marked as: NRW_{i2}, WL_{i2}, RL_{i2}, Al_{i2}. Plots in Figure 7 were prepared based on the values presented in Table 5.

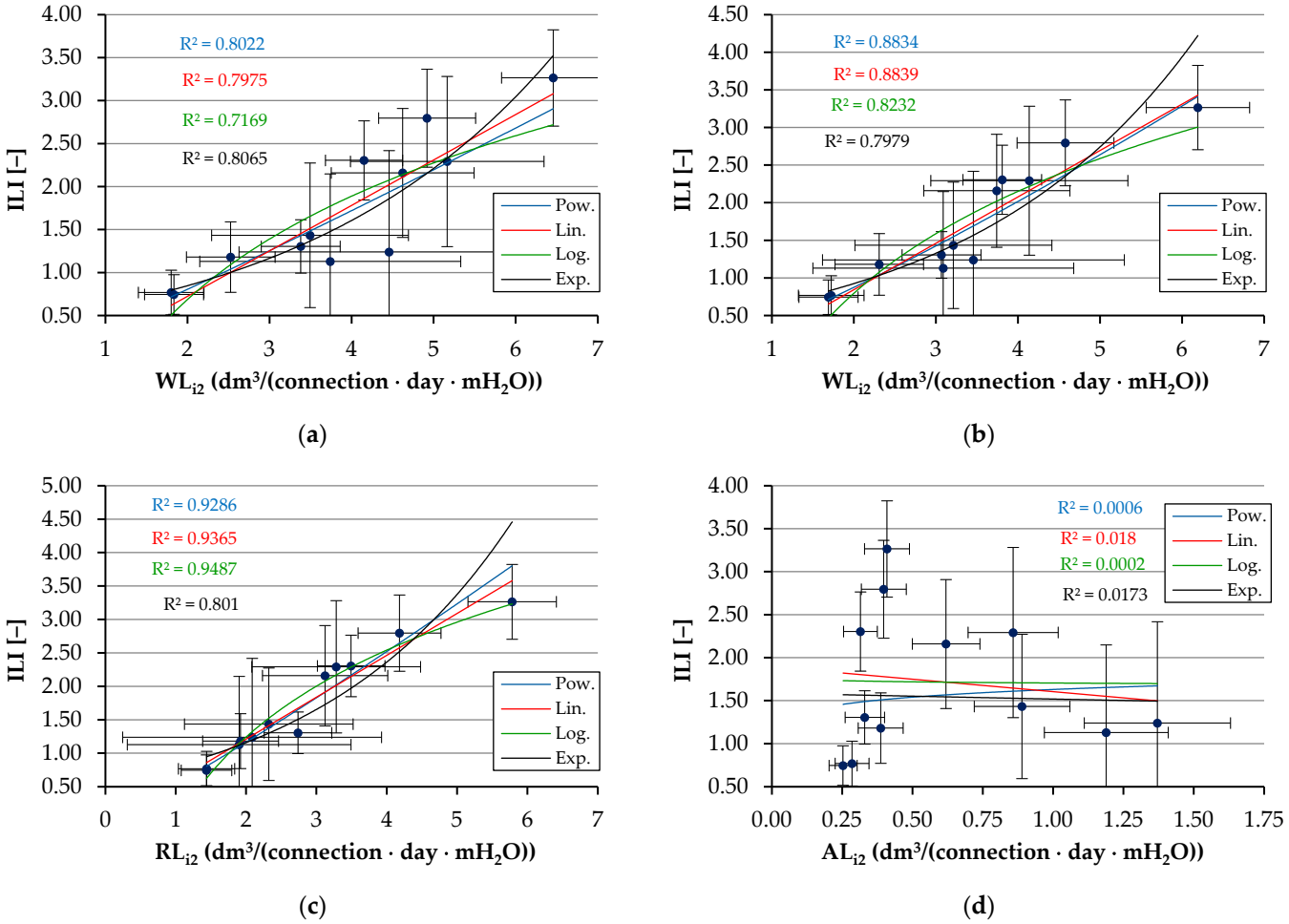


Figure 7. The linear (red line), logarithmic (green), exponential (black), and power (blue) relationships between ILI indexes and operational normalized intermediate water loss performance indicators expressed in dm^3 of water lost per service connection per day per 1 m H_2O of pressure: (**a**) non-revenue water (NRW_{i2}); (**b**) the total water loss indicator (WL_{i2}); (**c**) the real water loss indicator (RL_{i2}); (**d**) the apparent water loss indicator (AL_{i2}).

The results presented in Figure 7 indicate that a very strong, and at the same time, the strongest positive correlation among all analyzed sets of scores was obtained for the power relationship between the ILI and RL_{i2} (R^2 = 0.9502). In regard to RL_{i2}, very strong correlations were also obtained for logarithmic and linear functions (0.9487 and 0.9365,

respectively). It should be noted that the curves of the linear and power functions were very similar in this case. The second strongest correlation among the results presented in Figure 7 was obtained for the relationship between the ILI and WL_{i2} in the case of both linear and power functions (R^2 = 0.8839 and 0.8836, respectively). The linear positive correlation obtained for the relationship between ILI and NRW_{i2} was slightly lower but also classified as very strong (R^2 = 0.8262 for the exponential function, R^2 = 0.8089 for the power function, and R^2 = 0.7975 for the linear function). A very weak linear correlation (in fact, no correlation) was recorded for the relationship between ILI and AL_{i2} (R^2 = 0.018 for the linear relationship).

4. Discussion

The results described in Section 3 indicate that in many cases the determination coefficients (R^2) obtained for linear relationships between the ILI and other WLPIs were similar to values of R^2 calculated for non-linear functions (power, logarithmic, or exponential). The graphs for non-linear relationships (especially for power functions) were also very similar to those for linear functions. This may indicate the existence of linear relationships between the ILI and other analyzed WLPIs. Therefore, further considerations focus primarily on the linear correlation between all analyzed indicators.

Table 6 presents a summary of statistical calculations for the linear correlation between the ILI and other WLPIs analyzed in the research. The table lists values of determination coefficients (R^2), Pearson's correlation coefficients (r) (calculated from Equation (14)), and root mean squared errors (RMSE) (calculated based on Equation (15)).

Table 6. The summary of coefficients describing the correlation between ILI indexes and all water loss performance indicators (WLPIs): Pearson's correlation coefficients (r), determination coefficients (R^2), and root mean squared errors (RMSE).

WLPI	Unit	r	R^2	RMSE	WLPI	Unit	r	R^2	RMSE
Volume of Water Lost per Year					Basic Water Loss Performance Indicators as a Percentage of SIV				
NRW	10^3 m^3/year	0.1000	0.0100	0.7818	$NRW_{\%}$	%	0.7100	0.5041	0.5526
WL		0.1049	0.0110	0.7806	$WL_{\%}$		0.6755	0.4563	0.5785
RL		0.1652	0.0273	0.7739	$RL_{\%}$		0.6764	0.4575	0.5780
AL		−0.2339	0.0547	0.7629	$AL_{\%}$		−0.7100	0.5041	0.5526
Operational basic water loss indicators in water volume per km of mains per day					Operational basic water loss indicators in water volume per connection per day				
NRW_{b1}	m^3/(km mains·d)	0.7059	0.4983	0.5558	NRW_{b2}	dm^3/(conn.·d)	0.6869	0.4718	0.6517
WL_{b1}		0.7570	0.5730	0.5127	WL_{b2}		0.7687	0.5909	0.5019
RL_{b1}		0.7949	0.6319	0.4761	RL_{b2}		0.8565	0.7336	0.4050
AL_{b1}		−0.1058	0.0112	0.7802	AL_{b2}		−0.2249	0.0506	0.7645
Operational intermediate water loss indicators in water volume per km of mains per day per mH_2O					Operational intermediate water loss indicators in water volume per connection per day per mH_2O				
NRW_{i1}	m^3/(km mains·d·mH_2O)	0.9054	0.8198	0.3331	NRW_{i2}	dm^3/(conn.·d·mH_2O)	0.8930	0.7975	0.3531
WL_{i1}		0.9660	0.9332	0.2028	WL_{i2}		0.9402	0.8839	0.2673
RL_{i1}		0.9752	0.9510	0.1737	RL_{i2}		0.9677	0.9365	0.1976
AL_{i1}		0.0100	1E-04	0.7846	AL_{i2}		−0.1342	0.0180	0.7775

4.1. The Analysis of the Correlation Between the ILI and Annual Volumes of Water Losses

The results presented in Table 6 indicate that the weakest correlation was found for the relationship between the ILI and volumes of water loss per year (in 10^3 m^3/year). The

results confirm that water loss volumes cannot be classified as WLPIs and are not suitable for comparing the condition of different WDNs. The volume of water loss depends strongly on the network geometry and the amount of water produced, rather than on the condition of the WDN. However, this parameter plays an important role in the preparation of WB. On the other hand, the volume of water loss per unit of time can play a role in the evaluation of a particular WDS condition over different balance periods provided that the geometry of the system and the operating pressure remain relatively constant.

4.2. The Analysis of the Correlation Between the ILI and Percentage WLPIs

The second type of relationships discussed were correlations between ILI and WLPIs expressed as percentages of SIV. Among the analyzed indexes, $WL_{\%}$, $RL_{\%}$, and $AL_{\%}$ are categorized as basic operational indicators, while $NRW_{\%}$ is categorized as a basic financial indicator, according to the classification developed by the IWA [23,24] and AWWA [34]. Based on results obtained, a moderate correlation was found between the ILI and percentage WLPIs (in the case of $AL_{\%}$, this correlation was negative). The highest positive Pearson correlation coefficient (r) was recorded for $NRW_{\%}$ (0.7100), while the highest negative r value was recorded for $AL_{\%}$ (–0.7100). It is worth noting that the absolute values of r for the two linear functions mentioned above were identical (the same applies to R^2 and RMSE), which resulted from the adopted methodology for calculating $AL_{\%}$. The values of RMSE ranged from 0.5526 to 0.5785. A higher correlation between the ILI and percentage WLPIs was found by Oberascher et al. (2020) [60] in the research conducted in Austria, but these results have limited applicability due to a different methodology for determining such indicators (in accordance with Austrian water law). But they have underlined that, according to recommendations of the IWA, this index is not suitable for determining the efficiency of measures regarding real losses of water.

Percentage indicators are, to some extent, better for comparing water losses in distribution systems than the previously described annual loss volumes, as they relate water losses to SIV. These PIs are commonly used by water supply companies to report water losses due to their simplicity, ease of use, and good availability of data necessary for their calculation [37]. Nevertheless, they are not recommended for comparing water losses in different WSSs [38]. Percentage indicators have many disadvantages: their reliability is limited, they do not directly relate to the geometry of WSS (e.g., the length of mains, length and number of service connections), and they are widely criticized by scientists and practitioners [66]. Lambert (2002) [67] has stated that the percentage of SIV is too strongly influenced by consumption, as well as changes in consumption, and therefore it is unsuitable for operational management of real losses. Giustolisi et al. (2024) [45] also concluded that the percentage of SIV is a very weak indicator at the DMA level due to its dependency on the density of consumption. These recommendations agree with the results of research conducted by Winarni in 2008 [19], where a weak correlation was found between the ILI and real losses expressed as a percentage of SIV. Winarni has concluded that the comparison of leakages between water supply companies should not be based on percentage indicators [19]. Giustolisi et al. (2024) [44] have emphasized that the weakness of the percentage PIs relies on their non-linear formulation (the volume of water losses appears not only in the numerator but also in the denominator).

The percentage indicators also do not take into account the operational parameters of the network, such as operating pressure [66,67]. Therefore, it is often suggested that they should be replaced with normalized indicators, which are more accurate and take into account the geometry of WDSs [66,68,69]. An additional problem associated with the use of percentage indicators, as pointed out by Lambert [20], is that the division of SIV into WS and WE is not taken into account in the calculation of these indicators (if the company

exports water). If WE is relatively large in relation to SIV, the percentage loss indicator may be underestimated and will not reflect the actual condition of the system [20,24].

In view of the above issues and results of the analysis carried out, it can be concluded that percentage indicators should be considered inadvisable for the purpose of reporting water losses in connection with the implementation of the Directive (EU) 2020/2184. Both WI and WE play a significant role in WBs and should be reported in future investigations, according to expanded WB schemes [20].

4.3. The Analysis of the Correlation Between the ILI and Basic Normalized WLPIs

The next two groups of indicators discussed (Figures 4 and 5) are basic normalized operational WLPIs, expressed using two different units: m^3 of water per km of mains per day, as well as dm^3 of water per service connection per day. The obtained results presented in Figures 4 and 5, as well as in Table 6, confirm that in the case of both real and total losses, as well as NRW, their correlation with the ILI was very strong or strong. The highest positive very strong linear correlation (r = 0.8565) was obtained for the relationship between the ILI and RL_{b2} expressed as volume of water loss per service connection per day. A slightly lower very strong positive linear correlation (r = 0.7949) was recorded for the relationship between the ILI and RL_{b1} expressed as the water loss per km of mains per day. Also noteworthy are the relatively high values of r for the linear relationship between the ILI and total loss indicators WL_{1b} and WL_{2b} (0.7570 and 0.7687, respectively), referring to both the mains' length and number of service connections. The results obtained are consistent with the findings of Liemberger et al. (2007) [24]. In their research they have stated that the most appropriate traditional operational PIs for real losses are normalized indicators expressed per length of mains (so-called indicator Op28), or per number of service connections (so-called indicator Op27) [24]. Wyatt, in his article published in 2020 [68], has stated that normalized (unit) PIs for both real and apparent losses, expressed in terms of volume, per connection per day, appear to be the key performance indicators (KPIs). He has concluded that the advantages of these indicators are their simplicity, ease of calculation, broad understandability, as well as high technical rigor, usefulness in planning interventions for control and reduction in water losses. Wyatt has underlined that the IWA also recommends these indicators [68].

According to available knowledge [38,70], the choice of one of these two types of indicators (e.g., RL_{b1} or RL_{b2}) should be determined by the density of service connections (D). When D is higher than 20 connections per km, then the calculation of RL_{b2} is recommended (see Equation (11)). If D is less than 20 per km, it is recommended to use RL_{b1} (see Equation (10)). In the case of all the WBs analyzed in the current research, the connections' densities D were greater than 20 per km, and the best correlation, among basic normalized PIs, was identified for RL_{b2} (expressed per number of service connections). The analysis confirmed that the results presented in the current article are consistent with the findings and results available in the literature [24,38,70]. Lambert has concluded in articles published in both 2002 [69] and in 2019 [71] that the IWA recommends the use of an operational real loss performance indicator expressed as a volume of water per connection per day as the 'Best Practice' basic PI for systems with a service connections density D greater than 20 per km (when the system is pressurized). He emphasizes that in large water supply systems with high D, most real losses are related to leaks occurring at service connections [69,71]. In turn, Oberascher et al. [60] also found a strong correlation between the ILI and the basic operational normalized WLPIs, but he found a better correlation for the indicator related to network length. It should be emphasized that basic operational normalized WLPIs, especially those calculated based on real water losses (also known as Op27 and Op28), can be recommended and used as a good alternative if there are insufficient data to

determine the ILI. These indicators are very easy to calculate and, on the other hand, more accurate than percentage indicators, as they are determined based on data dependent on the characteristics of the water supply system [24,38,70,71].

4.4. The Analysis of the Correlation Between the ILI and Intermediate Normalized WLPIs

The intermediate operational normalized WLPIs are the last group of analyzed indices. They are expressed as both the volume of water lost per km of mains per day per 1 m H_2O of pressure and the volume of water lost per service connection per day per 1 m H_2O of pressure. Taking into account the results presented in Figures 6 and 7, as well as in Table 6, the correlations between the ILI and these PIs (excluding apparent loss indices AL_{i1} and AL_{i2}) were the strongest among all the indicators analyzed. The highest Pearson correlation coefficient for a linear function (r = 0.9752) was detected in the case of the relationship between the ILI and RL_{i1} (PI for real water loss expressed in volume per km of mains per day per 1 mH_2O of pressure). A very high Pearson's correlation coefficient (r = 0.9677), indicating a very strong correlation, was also obtained for the linear relationship between the ILI and RL_{i1} (expressed in volume per service connection per day per 1 mH_2O of pressure). It should be emphasized that in the case of the correlation between the ILI and RL_{i1}, as well as the correlation of the ILI and RL_{i2}, the lowest RMSE values (0.1737 and 0.1976, respectively) were also obtained. The high RMSE values were also obtained for the total WLPIs: WL_{i1} (RMSE = 0.2028) and WL_{i2} (RMSE = 0.2673). These RMSE values also indicated a strong linear correlation between each of these two indicators and the ILI. When analyzing the results presented in Table 6, it should be noted that, unlike basic normalized indicators, in the case of intermediate indicators, no impact of service connection density on the correlation between specified real loss indicators and ILI was observed. Despite D > 20 connections per km (for all WBs), a higher correlation coefficient was obtained in this case for the RL_{i1}, expressed in water volume per km of mains per day per 1 m H_2O. Future research should therefore analyze whether this relationship applies only to these specific data or to a wider population of results. It can be concluded that intermediate operational normalized indices are more accurate and better correlated with the ILI than the basic ones, because they take into account not only the size of the water supply system but also the operating pressure in the network. They can be an alternative solution for estimating WLPIs when the ILI cannot be estimated, but it should be emphasized that the data required to calculate them are almost identical to those used to calculate the ILI.

Therefore, their use instead of the ILI may be only justified when, for example, the data on either the length of mains or the number of service connections are incomplete. Use of these indicators is very simple because their calculation does not require the determination of UARL. On the other hand, however, the inability to compare real losses (CARL) with UARL means that normalized indicators, both basic and intermediate, do not allow for a relatively quick and in-depth assessment of the condition of the WDN, which is currently possible thanks to the ILI (classified together with UARL as detailed WLPIs).

The use of the ILI allows for comparing the condition of different WDSs with each other, but also allows for estimating changes in the condition of a particular WDN (e.g., year-on-year), which helps in making decisions about the possible implementation of rehabilitation plans. Taking into account the reporting related to the implementation of the Directive (EU) 2020/2184, it can therefore be concluded that although normalized indices are good and relatively accurate indicators, they should only be used in situations where it is impossible to determine the ILI.

As part of the analysis, random uncertainties were also calculated (see Tables 1–5 and Figures 2–7). In practice, uncertainties are rarely presented in WBs, but they provide valuable information on the accuracy of determining individual balance compo-

nents and estimated PIs. Performing such analyses is recommended, among others, by Lambert [38,65], AL Washali et al. (2020) [35], AL Washali et al. (2019) [36], and Babić et al. (2014) [64]. The results presented in Tables 2–5 and in Figures 2–7 show that determined values of both the NRW and WLPIs (including the ILI) may be subject to considerable random uncertainties. Increasing the accuracy class of water meters used in water supply companies can significantly improve the precision of measurements and, therefore, diminish the random uncertainties and, additionally, diminish apparent water losses.

It should also be emphasized that environmental reporting can play a very important role in the pursuit of sustainable development of water supply companies [52]. van Thienen et al. (2025) [9] have underlined that Directive (EU) 2020/2184 focuses on larger utilities serving at least 50,000 people. On the other hand, they have concluded that smaller WDNs experience a higher percentage of water losses due to limited resources and aging infrastructure. Therefore, van Thienen et al. have recommended that small water supply companies (serving under 50,000 people) should also be included in water loss management initiatives [9]. Sakai (2024) [72] has emphasized that performance indicators used in the water supply industry can be very useful tools for assessing the operational, financial, environmental, and social aspects of WDSs. He has underlined the need to strive for improvement in the standardization of data collection and processing. According to Sakai, the carbon neutrality, as well as the material structure of the network and even soil properties, should be taken into account in future studies related to, among other things, water loss management [72]. Research conducted by Musz-Pomorska et al. (2017) [73] confirms the impact of soil and the material structure on the network failure rates. In their study, the authors have stated that real water losses in Polish cities are related to leaks caused by bursts. Other causes of failures include annual temperature fluctuations, ground freezing, and unstable foundations. Pipelines in areas affected by mining damage are particularly vulnerable to failures [73].

It should be underlined that both active leakage control and reporting of water losses should fulfill their role and lead to an improvement in the company's condition. For this to happen, public awareness needs to be raised so that reporting is not just seen as a burdensome obligation, but as an opportunity to accurately diagnose problems and take appropriate corrective action plans.

It should be emphasized that the results and conclusions of the research described in this article are limited, as the study only took into account WBs calculated for water supply companies from one region (southern Poland). Further research is planned, which will cover a larger number of water supply companies with more diverse amounts of water produced and sold, in which real losses are characterized by different values of the ILI indexes.

5. Conclusions

Conclusions formulated based on the results of the research and the literature review are presented below:

1. The results of the conducted research indicate that, in the case of analyzed WBs, the strongest linear correlation was obtained for the relationship between the ILI and the intermediate operational normalized PIs for real water losses RL_{i1} ($R^2 = 0.9510$). The results suggest that normalized intermediate PIs for real losses expressed as volume of water lost per time, per 1 m H_2O of pressure, and, respectively, per length of mains or number of service connections, may be an alternative to the ILI in situations where it is impossible to calculate the ILI. However, it should be emphasized that both the ILI and normalized average indices require determining almost the same

parameters, including operating pressure. Therefore, if a water supply company has all the necessary data, the ILI should be the index of the first choice.

2. The research results also suggest a very strong correlation for the linear relationship between the ILI and basic normalized operational PIs for real losses. The best results in this category of PIs were recorded for the relationship between the ILI and PIs for real losses, RL_{b2} (R^2 = 0.7336). The results indicate that basic unit operational PIs for real losses expressed as volume of water lost per time, per length of mains (or per the number of service connections) can be a very good alternative to the ILI indicator in situations where a company does not have all the data necessary to determine the ILI. Compared to intermediate normalized operational indicators, the advantage of basic indicators is that average pressure is not required for their calculation.
3. The results indicate a moderate linear correlation between the ILI and percentage indicators (calculated as a percentage of SIV). Based on the literature review and on the research, it can be concluded that results obtained using these indicators may not be reliable and should not be recommended as an alternative to the ILI for water loss reporting purposes in connection with the implementation of Directive (EU) 2020/2184.

The results of the study confirmed that not all water loss indicators can be reliable PIs used for the evaluation of water losses in WDSs and for reporting purposes within the framework of the implementation of the Directive (EU) 2020/2184. The correlation analysis conducted in this research enabled the identification of the most reliable and easily determined PIs for water losses, which can be used in situations where the ILI is not applicable. The authors postulate that the possibility of using water loss performance indicators other than the ILI should be defined more precisely, e.g., in a delegated act or other documents regulating the reporting process related to the implementation of Directive (EU) 2020/2184. Specifying which water loss indicators can be used if ILI cannot be estimated would increase the reliability and credibility of water network condition assessments. Authors propose that normalized operational indicators (basic and intermediate) should be the preferred PIs, and that the determination of the density of service connections should precede the choice of appropriate indicator type.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w18050527/s1, Table S1. The regression coefficients (a,b) and determination coefficients (R2) for linear relationships between the ILI and other WLPIs. Explanations (y = ILI, x = WLPI, a,b—regression coefficients). Table S2. The regression coefficients (a,b) and determination coefficients (R2) for exponential relationships between the ILI and other WLPIs. Explanations (y = ILI, x = WLPI, a,b—regression coefficients). Table S3. The regression coefficients (a,b) and determination coefficients (R2) for logarithmic relationships between the ILI and other WLPIs. Explanations (y = ILI, x = WLPI, a,b—regression coefficients). Table S4. The regression coefficients (a,b) and determination coefficients (R2) for power relationships between the ILI and other WLPIs. Explanations (y = ILI, x = WLPI, a,b—regression coefficients).

Author Contributions: Conceptualization, I.D., U.K. and A.O.-K.; methodology, I.D.; software, I.D. and U.K.; validation, I.D., U.K. and A.O.-K.; formal analysis, I.D.; investigation, I.D., U.K. and A.O.-K.; resources, I.D. and A.O.-K.; data curation, I.D., U.K. and A.O.-K.; writing—original draft preparation, I.D.; writing—review and editing, I.D., U.K. and A.O.-K.; visualization, I.D. and U.K.; supervision, I.D. All authors have read and agreed to the published version of the manuscript.

Funding: The scientific research was funded by the statutory subvention of Czestochowa University of Technology, Faculty of Infrastructure and Environment (BS/PB-400/301/26).

Data Availability Statement: Data are contained within the article. The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AL	Apparent losses
AMSI	Asset management support indicator
AWWA	American Water Works Association
BAC	Billed authorized consumption
BMC	Billed metered consumption
CARL	Current annual real losses
CMIs	Customer meter inaccuracies
DHEs	Data handling errors
DWD	Drinking Water Directive
ELL	Economic leakage level
EU	European Union
GHG	Greenhouse gas
ILI	Infrastructure leakage index
IWA	International Water Association
KPI	Key performance indicator
NRW	Non-revenue water
PAT	Pump as turbine
PI	Performance indicator
RL	Real losses
SCF	System correction factor
SDG	Sustainable Development Goal
SIV	System input volume
UAC	Unbilled authorized consumption
UARL	Unavoidable annual real losses
UC	Unauthorized consumption
WB	Water balance
WDN	Water distribution network
WDS	Water distribution system
WE	Water exported
WI	Water imported
WL	Water losses
WLPI	Water loss performance indicator
WLSG	Water Loss Specialists Group
WS	Water supplied
WSS	Water supply system

References

1. European Environment Agency (Ed.) *Water Resources Across Europe—Confronting Water Stress: An Updated Assessment*; EEA Report No 12/2021; Publications Office of the European Union: Luxembourg, 2021. Available online: https://www.eea.europa.eu/publications/water-resources-across-europe-confronting (accessed on 28 July 2025). [CrossRef]
2. Kummu, M.; Guillaume, J.H.A.; de Moel, H.; Eisner, S.; Flörke, M.; Porkka, M.; Siebert, S.; Veldkamp, T.I.E.; Ward, P.J. The world's road to water scarcity: Shortage and stress in the 20th century and pathways towards sustainability. *Sci. Rep.* **2016**, *6*, 38495. [CrossRef]
3. Amparo-Salcedo, M.; Pérez-Gimeno, A.; Navarro-Pedreño, J. Water Security Under Climate Change: Challenges and Solutions Across 43 Countries. *Water* **2025**, *17*, 633. [CrossRef]

4. United Nations. *The United Nations World Water Development Report 2023: Partnerships and Cooperation for Water*; UNESCO: Paris, France, 2023. Available online: https://www.unesco.org/reports/wwdr/2023/en/download (accessed on 25 July 2025).
5. Estrela-Segrelles, C.; Pérez-Martín, M.Á.; Wang, Q.J. Adapting Water Resources Management to Climate Change in Water-Stressed River Basins—Júcar River Basin Case. *Water* **2024**, *16*, 1004. [CrossRef]
6. UN DESA. *The Sustainable Development Goals Report 2025*; United Nations: New York, NY, USA, 2025. [CrossRef]
7. Sharif, M.N.; Haider, H.; Farahat, A.; Hewage, K.; Sadiq, R. Water–energy nexus for water distribution systems: A literature review. *Environ. Rev.* **2019**, *27*, 519–544. [CrossRef]
8. Barry, J.A. Watergy: Energy and Water Efficiency in Municipal Water Supply and Wastewater Treatment—Cost-Effective Savings of Water and Energy. The Alliance to Save Energy. 2007. Available online: https://www.ase.org/sites/ase.org/files/watergy_handbook.pdf (accessed on 20 September 2025).
9. van Thienen, P.; Steffelbauer, D.B.; Vertommen, I. Water loss management in Europe: Perceptions, drivers, responses/strategies, and results. *Water Pract. Technol.* **2025**, *20*, 1921–1938. [CrossRef]
10. EurEau. Europe's Water in Figures. An Overview of the European Drinking Water and Waste Water Sectors. 2021. Available online: https://www.eureau.org/resources/publications/eureau-publications/5824-europe-s-water-in-figures-2021/file (accessed on 25 August 2023).
11. Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on Energy Efficiency and Amending Regulation (EU) 2023/955. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023L1791&qid=1698344986352 (accessed on 20 July 2025).
12. United Nations. The Sustainable Development Goals Report 2023: Special Edition. 2023. Available online: https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pdf (accessed on 15 June 2025).
13. Choi, S.H.; Shin, B.; Shin, E. Managing Apparent Loss and Real Loss from the Nexus Perspective Using System Dynamics. *Water* **2022**, *14*, 231. [CrossRef]
14. Wilson, L.; Lichinga, K.N.; Kilindu, A.B.; Masse, A.A. Water utilities' improvement: The need for water and energy management techniques and skills. *Water Cycle* **2021**, *2*, 32–37. [CrossRef]
15. Andraka, D.; Kruszyński, W.; Tyniec, J.; Gwoździej-Mazur, J.; Kaźmierczak, B. Practical Aspects of the Energy Efficiency Evaluation of a Water Distribution Network Using Hydrodynamic Modeling—A Case Study. *Energies* **2023**, *16*, 3340. [CrossRef]
16. Ramos, H.M.; Mello, M.; De, P.K. Clean power in water supply systems as a sustainable solution: From planning to practical implementation. *Water Sci. Technol. Water Supply* **2010**, *10*, 39–49. [CrossRef]
17. Ávila, C.A.M.; Sánchez-Romero, F.-J.; López-Jiménez, P.A.; Pérez-Sánchez, M. Leakage Management and Pipe System Efficiency. Its Influence in the Improvement of the Efficiency Indexes. *Water* **2021**, *13*, 1909. [CrossRef]
18. Giudicianni, C.; Herrera, M.; Nardo, A.d.; Adeyeye, K.; Ramos, H.M. Overview of Energy Management and Leakage Control Systems for Smart Water Grids and Digital Water. *Modelling* **2020**, *1*, 134–155. [CrossRef]
19. Winarni, W. ILI as Water Losses Indicator. *Civ. Eng. Dimens.* **2009**, *11*, 126–134. Available online: https://api.semanticscholar.org/CorpusID:55039172 (accessed on 16 December 2025).
20. Lambert, A. IWA Water Balance. The LEAKSSuite Library. 2019. Available online: https://www.leakssuitelibrary.com/iwa-water-balance/ (accessed on 5 September 2025).
21. Kanakoudis, V.; Tsitsifli, S.; Samaras, P.; Zouboulis, A. Assessing the performance of urban water networks across the EU Mediterranean area: The paradox of high NRW levels and absence of respective reduction measures. *Water Supply* **2013**, *13*, 939–950. [CrossRef]
22. Lambert, A.; Hirner, W. Losses from Water Supply Systems: Standard Terminology and Recommended Performance Measures. IWA. Blue Pages. 2000. Available online: https://www.wes-med.eu/wp-content/uploads/2023/01/RW-6-REGST-2023.01.16-IWA-2000.pdf (accessed on 20 August 2025).
23. Lambert, A.; Charalambous, B.; Fantozzi, M.; Kovac, J.; Rizzo, A.; St John, S.G. 14 years' experience of using IWA best practice water balance and water loss performance indicators in Europe. In Proceedings of the Specialized Conference: Water Loss 2014, Vienna, Austria, 30 March–2 April 2014. Available online: https://www.semanticscholar.org/paper/14-Years-Experience-of-using-IWA-Best-Practice-and-Lambert-Charalambous/bed71a37d56e232a13847b52cf68a1d6affdb25c (accessed on 18 May 2025).
24. Liemberger, R.; Brothers, K.; Lambert, A.; McKenzie, R.; Rizzo, A.; Waldron, T. Water Loss Performance Indicators. 2007. Available online: https://www.miya-water.com/fotos/artigos/15_water_loss_performance_indicators_6560934665a32619c8808b.pdf (accessed on 14 April 2025).
25. Liemberger, R.; Wyatt, A. Quantifying the global non-revenue water problem. *Water Supply* **2019**, *19*, 831–837. [CrossRef]
26. Arregui, F.J.; Cobacho, R.; Soriano, J.; Jimenez-Redal, R. Calculation Proposal for the Economic Level of Apparent Losses (ELAL) in a Water Supply System. *Water* **2018**, *10*, 1809. [CrossRef]

27. Rizzo, A. Apparent Water Loss Control: Theory and Application. In Proceedings of the Water Conference, Ferrara, Italy, 17–19 May 2006. Available online: https://www.mcast.edu.mt/wp-content/uploads/2006-Apparent-Water-Loss-Control-Theory-and-Application-Rizzo-A-IWA-Ferrara-Italy-2006H_4-1.pdf (accessed on 20 June 2025).
28. Ahopelto, S.; Vahala, R. Cost–Benefit Analysis of Leakage Reduction Methods in Water Supply Networks. *Water* **2020**, *12*, 195. [CrossRef]
29. Gupta, A.; Kulat, K.D. A Selective Literature Review on Leak Management Techniques for Water Distribution System. *Water Resour. Manag.* **2018**, *32*, 3247–3269. [CrossRef]
30. Yilmaz, S.; Ateş, A.; Firat, M.; Özdemir, Ö.; Cinal, H. Determination of economic loss levels in water distribution systems with different network conditions by a district stochastic optimization algorithm. *Water Supply* **2023**, *23*, 1349–1361. [CrossRef]
31. Moslehi, M.I.; Jalili-Ghazizadeh, M.; Yousefi-Khoshqalb, E. Developing a framework for leakage target setting in water distribution networks from an economic perspective. *Struct. Infrastruct. Eng.* **2021**, *17*, 821–837. [CrossRef]
32. Haider, H.; Al-Salamah, I.S.; Ghazaw, Y.M.; Abdel-Maguid, R.H.; Shafiquzzaman, M.; Ghumman, A.R. Framework to establish economic level of leakage for intermittent water supplies in arid environments. *J. Water Resour. Plan. Manag.* **2018**, *145*, 05018018. [CrossRef]
33. Heryanto, T.; Sharma, S.K.; Daniel, D.; Kennedy, M. Estimating the Economic Level of Water Losses (ELWL) in the Water Distribution System of the City of Malang, Indonesia. *Sustainability* **2021**, *13*, 6604. [CrossRef]
34. AWWA. The State of Water Loss Control in Drinking Water Utilities. A White Paper From the American Water Works Association. 2016. Available online: https://www.awwa.org/Portals/0/AWWA/ETS/Resources/WLCWhitePaper.pdf?ver=2017-09-11-153507-487 (accessed on 14 August 2025).
35. AL-Washali, T.; Sharma, S.; Lupoja, R.; Al-Nozaily, F.; Haidera, M.; Kennedy, M. Assessment of water losses in distribution networks: Methods, applications, uncertainties, and implications in intermittent supply. *Resour. Conserv. Recycl.* **2020**, *152*, 104515. [CrossRef]
36. AL-Washali, T.; Sharma, S.; AL-Nozaily, F.; Haidera, M.; Kennedy, M. Monitoring Nonrevenue Water Performance in Intermittent Supply. *Water* **2019**, *11*, 1220. [CrossRef]
37. Ramm, K.; Bylka, J. Nowe wymagania w zakresie jakości usług wodociągowych dotyczące strat wody (New Requirements for the Quality of Water Supply Services to Curb Water Loss). *Zesz. Nauk. Uniw. Ekon. Krakowie* **2021**, *4*, 47–65. (In Polish) [CrossRef]
38. European Commission, Directorate-General for Environment. *EU Reference Document Good Practices on Leakage Management WFD CIS WG PoM—Main Report*; Publications Office: Luxembourg, 2015. Available online: https://data.europa.eu/doi/10.2779/102151 (accessed on 2 September 2025). [CrossRef]
39. Lambert, A. UARL and ILI. The LEAKSSuite Library. 2020. Available online: https://www.leakssuitelibrary.com/uarl-and-ili/ (accessed on 3 September 2025).
40. Lenzi, C.; Bragalli, C.; Bolognesi, A.; Fortini, M. Infrastructure Leakage Index Assessment in Large Water Systems. *Procedia Eng.* **2014**, *70*, 1017–1026. [CrossRef]
41. Lambert, A.O.; Brown, T.G.; Takizawa, M.; Weimer, D. A review of performance indicators for real losses from water supply systems. *J. Water Supply Res. Technol.—AQUA* **1999**, *48*, 227–237. [CrossRef]
42. Alegre, H.; Baptista, J.M.; Cabrera, E., Jr.; Cubillo, F.; Duarte, P.; Hirner, W.; Merkel, W.; Parena, R. *Performance Indicators for Water Supply Services*, 3rd ed.; IWA Publishing: London, UK, 2017.
43. Berardi, L.; Laucelli, D.B.; Ripani, S.; Piazza, S.; Freni, G. Using water loss performance indicators to support regulation and planning in real water distribution systems. *Digit. Water* **2025**, *3*, 1–20. [CrossRef]
44. Giustolisi, O.; Ciliberti, F.G.; Mazzolani, G.; Laforgia, D. Effectiveness of water loss performance indicators for asset management. *Digit. Water* **2024**, *2*, 1–31. [CrossRef]
45. Giustolisi, O.; Mazzolani, G.; Berardi, L.; Laucelli, D.B. From advanced hydraulic modelling to performance indicator for the efficiency of investments in leakage management of pressurized water systems. *Water Res.* **2024**, *258*, 121765. [CrossRef] [PubMed]
46. Lambert, A. Low ILIs and Small Systems. The LEAKSSuite Library. 2020. Available online: https://www.leakssuitelibrary.com/low-ilis-and-small-systems/ (accessed on 19 November 2025).
47. Koelbl, J.; Lambert, A. Experiences in Real Loss Assessment 10-years after implementing the ILI as decisive Key-PI in Austria. In Proceedings of the Southeast Europe Regional Conference Water Loss 2019, Bucharest, Romania, 23 September 2019. Available online: https://www.bluenetworks.at/BlueNetworks/Pub-WL_files/WL23_WaterLoss2019-Bucharest_Koelbl_Lambert-final.pdf (accessed on 19 November 2025).
48. Stanton-Davies, K.; Shepherd, M. System Correction Factors—SCFs in Action in Europe, North America, UK and South Africa. In Proceedings of the Water Loss 2022 Conference, Prague, Czech Republic, 19–22 June 2022. Available online: https://www.wlranda.com/iwa-water-loss-2022-prague/ (accessed on 19 November 2025).
49. Kowalska, B.; Suchorab, P.; Kowalski, D. Division of district metered areas (DMAs) in a part of water supply network using WaterGEMS (Bentley) software: A case study. *Appl. Water Sci.* **2022**, *12*, 166. [CrossRef]

50. Ávila, C.A.M.; Sánchez-Romero, F.-J.; López-Jiménez, P.A.; Pérez-Sánchez, M. Improve leakage management to reach sustainable water supply networks through by green energy systems. Optimized case study. *Sustain. Cities Soc.* **2022**, *83*, 103994. [CrossRef]
51. Drinking Water Directive 2020/2184 (DWD). Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the Quality of Water Intended for Human Consumption. Document 32020L2184. Available online: https://eur-lex.europa.eu/eli/dir/2020/2184/oj (accessed on 18 July 2025).
52. Minea, G.; Lakatos, E.S.; Druta, R.M.; Moldovan, A.; Lupu, L.M.; Cioca, L.I. The Role of ESG in Driving Sustainable Innovation in Water Sector: From Gaps to Governance. *Water* **2025**, *17*, 2259. [CrossRef]
53. COUNCIL DIRECTIVE 98/83/EC of 3 November 1998 on the Quality of Water Intended for Human Consumption. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31998L0083 (accessed on 15 July 2025).
54. WAREG. European Water Regulators. Available online: https://www.wareg.org/articles/4-navigating-the-evolutions-of-the-eu-drinking-water-directive/ (accessed on 20 July 2025).
55. COMMISSION DELEGATED REGULATION (EU) 2021/2139 of 4 June 2021 Supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by Establishing the Technical Screening Criteria for Determining the Conditions Under Which an Economic Activity Qualifies as Contributing Substantially to Climate Change Mitigation or Climate Change Adaptation and for Determining Whether that Economic Activity Causes no Significant Harm to Any of the Other Environmental Objectives. Available online: https://eur-lex.europa.eu/eli/reg_del/2021/2139/oj/eng (accessed on 16 September 2025).
56. COMMISSION DELEGATED REGULATION (EU) 2023/2486 of 27 June 2023 Supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by Establishing the Technical Screening Criteria for Determining the Conditions Under Which an Economic Activity Qualifies as Contributing Substantially to the Sustainable Use and Protection of Water and Marine Resources, to the Transition to a Circular Economy, to Pollution Prevention and Control, or to the Protection and Restoration of Biodiversity and Ecosystems and for Determining Whether that Economic Activity Causes no Significant Harm to any of the Other Environmental Objectives and Amending Commission Delegated Regulation (EU) 2021/2178 as Regards Specific Public Disclosures for Those Economic Activities. Available online: https://eur-lex.europa.eu/eli/reg_del/2023/2486/oj/eng (accessed on 16 September 2025).
57. IWA Water Loss Specialist Group Position Statement. Use of the Infrastructure Leakage Index (ILI) in EU Directives and Regulations. 2022. Available online: https://iwa-website-assets.s3.eu-west-2.amazonaws.com/blogs_1750245155507_6757b78552.pdf (accessed on 10 August 2025).
58. Ociepa-Kubicka, A.; Deska, I.; Ociepa, E. Issues in Implementation of EU Regulations in Terms of Evaluation of Water Losses: Towards Energy Efficiency Optimization in Water Supply Systems. *Energies* **2024**, *17*, 633. [CrossRef]
59. Seago, C.J.; McKenzie, R.S.; Liemberger, R. International Benchmarking of Leakage from Water Reticulation Systems. In Proceedings of the IWA Leakage 2005 Conference, Halifax, NS, Canada, 12–14 September 2005. Available online: https://www.miya-water.com/fotos/artigos/06_international_benchmarking_of_leakage_from_water_reticulation_systems_1017893235a325e2b03b5c.pdf (accessed on 25 June 2025).
60. Oberascher, M.; Möderl, M.; Sitzenfrei, R. Water Loss Management in Small Municipalities: The Situation in Tyrol. *Water* **2020**, *12*, 3446. [CrossRef]
61. Ociepa, E.; Mrowiec, M.; Deska, I. Analysis of Water Losses and Assessment of Initiatives Aimed at Their Reduction in Selected Water Supply Systems. *Water* **2019**, *11*, 1037. [CrossRef]
62. Serafeim, A.V.; Fourniotis, N.T.; Deidda, R.; Kokosalakis, G.; Langousis, A. Leakages in Water Distribution Networks: Estimation Methods, Influential Factors, and Mitigation Strategies—A Comprehensive Review. *Water* **2024**, *16*, 1534. [CrossRef]
63. Kanakoudis, V.; Tsitsifli, S.; Samaras, P.; Zouboulis, A.; Banovec, P. A new set of water losses-related performance indicators focused on areas facing water scarcity conditions. *Desalin. Water Treat.* **2013**, *51*, 2994–3010. [CrossRef]
64. Babić, B.; Stanić, M.; Prodanović, D.; Džodanović, B.; Đukić, A. Reducing Uncertainty of Infrastructure Leakage Index—A Case Study. *Procedia Eng.* **2014**, *89*, 1577–1584. [CrossRef]
65. Lambert, A. Random Uncertainty in Water Balance. The LEAKSSuite Library. 2020. Available online: https://www.leakssuitelibrary.com/random-uncertainty-in-water-balance/ (accessed on 2 September 2025).
66. Lambert, A. Professionals Abandon %s of System Input Volume. The LEAKSSuite Library. 2019. Available online: https://www.leakssuitelibrary.com/pros-abandon-percents-of-siv/ (accessed on 2 September 2025).
67. Lambert, A.O. International Report on Water Losses Management and Techniques. In Proceedings of the IWA Berlin Congress, Berlin, Germany, 15–19 October 2001. Available online: http://www.studiomarcofantozzi.it/IntRepWaterLossesMan%26TechniquesBerlin.pdf (accessed on 25 September 2025).
68. Wyatt, A.S. The use of Frontier Analysis to assess the technical rigor of water loss performance indicators. *H_2Open J.* **2020**, *3*, 102. [CrossRef]
69. Kwietniewski, M. Application of Water Loss Indicators as a Measure of its Distribution Effectiveness in Water Supply Systems. *Environ. Prot.* **2013**, *35*, 9–16. Available online: http://www.os.not.pl/docs/czasopismo/2013/4-2013/Kwietniewski_4-2013.pdf (accessed on 20 August 2025). (In Polish)

70. Lambert, A.O.; McKenzie, R.D. Practical Experience in Using the Infrastructure Leakage Index. The International Water Association Conference 'Leakage Management: A Practical Approach' in Lemesos, Cyprus in November 2002. Available online: http://www.studiomarcofantozzi.it/IWACyprusNov2002Lambert&McKenziepaper.pdf (accessed on 2 September 2025).
71. Lambert, A. Reliable Operational PIs for Real Losses. The LEAKSSuite Library. 2019. Available online: https://www.leakssuitelibrary.com/reliable-operational-pis-for-real-losses/ (accessed on 2 September 2025).
72. Sakai, H. Review of research on performance indicators for water utilities. *AQUA—Water Infrastruct. Ecosyst. Soc.* **2024**, *73*, 168. [CrossRef]
73. Musz-Pomorska, A.; Iwanek, M.; Parafian, K.; Wójcik, K. Analysis of water losses in two selected water distribution systems. *E3S Web Conf.* **2017**, *17*, 00062. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.