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Issues in Implementation of EU Regulations in Terms of Evaluation of Water Losses: Towards Energy Efficiency Optimization in Water Supply Systems

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Abstract: The water and sewage sector is responsible for approximately 3.5% of energy consumption in the European Union (EU). Leaks causing water losses in water distribution systems (WDSs) are responsible for approximately 24% of water consumption in the EU, which contributes to additional energy losses and emissions of greenhouse gases (GHGs). The implementation of the Directive of the European Parliament and the EU Council on the quality of drinking water (Directive (EU) 2020/2184) introduces the obligation to report water losses by large water utilities in EU Member States. The reported indicator will be the infrastructure leakage index (ILI) which is the ratio between current annual real loss (CARL) and unavoidable annual real loss (UARL). The paper presents a comparative analysis of selected water loss performance indicators calculated for 12 Polish WDSs. Results show that values of calculated indicators were diverse. The overestimation of both the reported value of operating pressure and total length of service connections may lead to the overestimation of UARL and thus to the underestimation of ILI. Obtaining a satisfactory, but incorrect, value of ILI may result in the abandonment of activities aimed at water loss reduction. Water losses in water distribution systems (WDSs) contribute to a significant increase in both energy consumption and GHG emissions. Total approximated electrical energy related to CARL consumed in 2021 by eleven utilities (except for one company) amounted to 3.276 GWh and total approximated carbon emissions amounted to 2807.84 $MgCO_2$eq. In the case of four WDSs, reduction of ILI to the value of 1.5 may reduce GHG emissions by 31–54%. It can be concluded that the implementation of Directive (EU) 2020/2184 will require unification of methodology for calculation of parameters used in ILI evaluation in all EU Member States.

Keywords: water distribution system; water loss; water loss performance indicator; water loss management; infrastructure leakage index (ILI); drinking water directive; energy efficiency

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1. Introduction

Over the last 40 years, water use has been increasing globally by about 1% per year, and it is expected to grow in future at a similar rate. This increase in water use is driven by population growth and socio-economic development as well as changing consumption patterns [1]. Urbanization combined with high water consumption can create water scarcity [2]. Water scarcity occurs when insufficient water resources are available to satisfy annual requirements. It refers to a situation of unbalanced use of water, where water demand for human activities systematically exceeds the water supplied by the natural system [2]. Water scarcity is a result of the local impact of physical water stress and the acceleration and spreading of freshwater pollution [1,3,4]. Physical fresh surface water and groundwater scarcity can be divided into shortage and stress. Water shortage refers to the impact of low water availability per capita. Water stress refers to the impact of high water use (e.g., withdrawal or consumption) compared to water availability [4]. Water stress is an important environmental, economic, and societal challenge [5,6].

Seasonal water scarcity is also a result of climate change, and this problem increases in hot regions of the Earth, especially in Central Africa, East Asia and parts of South America. Water scarcity is also a problem in European countries, especially in southern Europe but also in other parts of the Old Continent [1,2]. Clean water resources are alarmingly low in nearly half of European Union (EU) countries (below 3000 m^3 per capita per year). According to the United Nations (UN), an annual level of water resources below 1700 m^3 per capita per year causes water stress, which means exceeding the water supply safety level. The United Nations, in the Special Edition of the Sustainable Development Goals Report, states that in 2020, about 2.4 billion people lived in water-stressed countries and 2.2 billion people still lacked safely managed drinking water. At the same time, in 2022 the water use efficiency rose by 9% [7]. In other regions of the world, drinking water resources are also decreasing. In turn, the energy consumption by water utilities and costs of water production are constantly increasing [8]. The water and wastewater sector in the EU is responsible for about 3.5% of electric energy consumption [9]. The production of water accounts for about 7–8% of global electricity consumption (e.g., for pumping, disinfection, and maintenance) [10,11]. The rational use of both water and energy is the basis for sustainable development. Therefore, one of the priorities for water sector management is the high energy efficiency of water supply systems [12,13].

Energy and water are interrelated [10]. The water–energy nexus in urban water supply systems varied in recent years due to climate change, population growth, and technological development. The new approach to the water–energy nexus in water supply takes into account the use of both renewable energy sources and alternative sources of water (e.g., rainwater harvesting and water reuse) [9,14]. The EU Directive on energy efficiency (Directive 2023/1791) [15] assumes that the energy efficiency should be increased by more than 32.5% by 2030. It requires a stronger promotion of cost-effective energy efficiency measures in all sectors, among other things, in the water sector, transport, and agriculture [15].

It is estimated that in EU countries about a quarter of drinking water (approximately 24%) never reaches consumers due to water losses [10,11]. Water losses not only cause additional, unnecessary costs for utilities and consumers but also cause adverse environmental effects such as resource waste [16], loss of treated water, and excessive energy consumption [17]. Choi et al. [16] suggest that water utilities should manage water losses from the water–energy nexus perspective. Energy is utilized during the extraction and treatment of water (e.g., disinfection) as well as during distribution in the water supply network. The energy intensity of water use is the total amount of energy required for the use of a specific amount of water in a certain location. This calculation can vary, and the most important factors are type and quality of water source, the pumping requirements, and the water system efficiency [18]. Each unit of distributed water results in the production and emission of a specified amount of greenhouse gases (GHGs), especially carbon dioxide (CO_2) [18,19]. GHG emissions caused by water supply companies are strongly influenced by energy sources used by electric utilities. Emissions will be lower when electricity for WDSs is generated from renewable energy sources [15]. Finding a balance between energy consumption and limits on GHG emissions should be an important step in WDS management [18]. It should be stressed that the water lost due to leakage contributes to additional carbon emissions that can be avoided by introducing strategies to prevent water losses [19]. Energy losses and GHG emissions associated with water leaks from WDSs result in an increase in costs incurred for water production. If larger leaks and failures occur, a significant amount of energy is also consumed during activities aimed at removing both failures and their consequences (energy utilized to locate leaks and to fix failures, keeping the water supply out of service, etc.). Energy efficiency in the WDS can be improved through regular checking of pumping systems, pressure management, management of leaks, energy recovery with use of pumps as turbines (PATs) [20,21], monitoring, automation, asset management, etc. [10]. The implementation of environmental management tools and standards may also contribute to improvement of sustainability and energy efficiency of water supply companies [22].

Reliable information about the amount of water lost from the distribution system provides a basis for renovation and modernization activities which aim to eliminate water leakages [23,24]. Numerous authors point to a difference in levels of water losses in various countries, ranging from very small to very high. The water losses in EU Member States are diverse. In the report from 2021 [25], the lowest average percentage of non-revenue water (NRW) is reported in the Netherlands (about 5%), in Germany (about 6%), and in Denmark (about 8%), while in many countries the NRW is higher, e.g., in France about 20%, in Belgium about 21%, in Poland about 25%, in Slovakia about 32%, in Italy about 41%, in Romania about 42%, and in Bulgaria about 60%. However, water losses vary greatly not only between the countries but, above all, between different WDSs in EU Member States. For example, from 2019–2021 the Supreme Audit Office (NIK) audited twenty water supply and sewage companies in several Polish rural communes. The report showed that more than half of the utilities recorded water losses of 30%. In 45% of enterprises, water losses accounted for more than half of the volume of water sold, while in six of them, they exceeded 60%. These losses significantly exceeded acceptable values and constituted a serious operational problem [26].

The total reduction of water losses in distribution systems is not technically possible or financially justified [27,28]. The further reduction of water losses (e.g., leak detection) is not profitable when the economic level of water losses (ELWL) is reached. The ELWL is the most economical value of total losses both real and apparent and is equal to the sum of the economic level of leakage (ELL) and the economic level of apparent losses (ELAL) [29]. The ELL determination contributes to better management of water distribution systems, but it requires specific knowledge of both the network structure and actual water leakage volumes and costs [30,31]. To determine the economic level of leakage, it is necessary to carry out an economic balance, which consists primarily of the costs of operation and removal of leaks, costs of collection and production of treated water, and its distribution including the energy costs [32,33]. It should be noted that drinking water requires special treatment to be usable and potable, which consumes a certain amount of energy [32] and emits a certain portion of GHGs [18]. The acceptable level of leakage should include both resource and environmental costs associated with water loss and other costs caused by leakage [23]. These additional costs can be caused by the subsidence of buildings, damage to roads, or even be related to traffic jams stemming from repairing water failures. Numerous authors emphasize that despite progress toward reducing water losses in distribution systems, losses still exceed economic levels [27,34].

Therefore, in increasing energy efficiency of WDSs, as a part of 2030 Sustainable Development Goal no. 6.4, the European Union puts extensive effort into improving the condition of the environment, including measures to reduce water losses [29]. A serious challenge for water companies in the EU is the implementation of the Directive of the European Parliament and of the Council (EU) on the quality of drinking water 2020/2184 (Directive (EU) 2020/2184) [35]. The provisions of this directive impose, for example, the obligation to apply and develop effective methods for assessing water losses and reducing leakages [35].

The article aims to analyze and assess the capabilities and readiness of 12 selected Polish water supply companies to implement the provisions of the Directive (EU) 2020/2184 in the field of water losses. Moreover, it indicates the advantages and disadvantages of water loss calculation methods and assesses their usefulness in the analyzed distribution systems. The research presented in the work refers to the current directions and world standards in the field of water distribution system management, recommended by the International Water Association (IWA), American Water Works Association (AWWA), and

World Bank Institute (WBI) Banding System. Conclusions from the article can be used to improve the assessment of water loss performance indicators and, thus, the condition of WDSs.

The article is composed of two parts: the literature review and the experimental section. The theoretical part consists of: (a) general information about water losses; (b) legal conditions regarding the reduction of leakages in the EU. The analysis included in the experimental section comprises: (i) calculations and assessment of water losses for 12 selected distribution systems; (ii) assessment of the usefulness and applicability of individual indicators to calculate water losses in the analyzed distribution systems; (iii) analysis of energy consumption and GHG emissions related to water losses in WDSs.

2. Legal Conditions Regarding the Reduction of Water Losses in the European Union Member States

2.1. The Implementation of Drinking Water Directive 2020/2184

The reduction of water losses has become a legal requirement due to the decreeing of the Directive of the European Parliament and the EU Council on the quality of drinking water (Directive (EU) 2020/2184) [35]. The directive entered into force in January 2021, and the EU Member States were obliged to transpose it within two years. The main objective of the document is to improve the technical condition of the water supply infrastructure, save energy and water resources, and protect drinking water from pollution, e.g., caused by leaks in the network. Directive (EU) 2020/2184 includes current and updated safety standards and a methodology used to identify and manage quality risks throughout the water supply chain, establishes a checklist of new substances, and introduces compliance provisions for products intended to come into contact with drinking water. New regulations also particularly address the problem of water leakages occurring during water distribution, which result in the loss of an average of 23% of treated water and, at the same time, the loss of energy [35–37]. Implementation of Directive (EU) 2020/2184 will require, among other things, the development of effective methods for assessing and reducing water leakages. By 12 January 2026, EU Member States shall ensure that the infrastructure leakage index (ILI) rating method or another appropriate method is used for assessment of water leakage levels within their territories. The assessment should cover WDSs providing at least 10,000 m^3 of water per day or servicing at least 50,000 people. The provisions of the Directive (EU) 2020/2184 state that by 12 January 2028, the European Commission (EC) shall adopt a delegated act in accordance with Article 21 in order to supplement the directive. The EC shall set out a threshold (based on ILI or another appropriate method) above which Member States shall present an action plan. The delegated act shall be prepared with use of the Member States' assessments and the average leakage rate in the EU determined on the basis of those assessments [35]. The requirement provided by the EC is that the leakage rate calculated using the ILI must not exceed 1.5. If the ILI value exceeds 1.5, it will be required to present a recovery plan by 12 January 2030. In order to restore WDSs, their efficiency should be improved by reducing the difference between the three-year average ILI value and the value of 1.5 by at least 20% [35,36].

Polish experts suggest that the provisions of the Directive (EU) 2020/2184, in the first place, will apply to large enterprises. For example, in Poland only 2% of water supply companies serve more than 100,000 inhabitants, 15% of companies serve between 20,000 and 100,000 inhabitants, and 83% of enterprises serve up to 20,000 inhabitants [37]. In the long term, in order to improve the efficiency of water supply networks (including the energy efficiency and reducing carbon emissions), this obligation should apply to all WDSs. Implementation of Directive (EU) 2020/2184 only for medium and large enterprises will result in the omission of most WDSs. Polish experts point out that, according to Art. 4.3 of the directive, Member States can decide how to implement these provisions. The implementation of Directive (EU) 2020/2184 will require development of effective and well-defined methods to assess and reduce the water losses [36,37].

The water loss performance indicator ILI recommended in Directive (EU) 2020/2184 was designed by an International Water Association (IWA) Task Force in 1999. This index is recommended by the IWA for comparison of leakage management performances between different WDSs with diverse infrastructure characteristics, such as: length of mains, length and density of service connections, and average operating pressures [36–38]. Currently, the ILI is considered as one of the most effective indicators for assessing the efficiency of WDSs. The ILI is calculated from Equation (1) (see Section 4) as a dimensionless ratio of current annual real loss (CARL) to unavoidable annual real loss (UARL) [39–42].

CARL is the real (physical) water loss occurring during a period of one year. It is the difference between total water losses (WLs) and apparent water losses (ALs). CARL is the volume of water lost as a result of leakage from the water supply network (from mains, service connections up to a customer's meter, and from storage facilities) [43,44]. The volume of CARL depends on the characteristics of the pipe network and the efficiency of the leak detection and repair policy practiced by the water supply company [45]. ALs, in turn, are water losses resulting from unauthorized consumption and the inaccuracy of water meters (see Equations (2) and (3) in Section 4) [41,44].

UARL is the volume of losses that can occur even in new and the best-managed WDSs with proper operation. Unavoidable losses are usually smaller than 0.5 m^3/h and very difficult to detect even via monitoring systems. They are unprofitable to remove, therefore they must be tolerated. The volume of unavoidable losses is calculated as the sum of three components: unavoidable leaks in mains (primary and secondary feeders), unavoidable leaks in service connections (both from mains to the property line (plot boundary) and from property line to first customer's meter). Unavoidable water losses are proportional to the length of mains, total length and number of service connections, and the operating pressure in the network [41]. It should be emphasized that, depending on the methodology for determining the length of service connections, different formulas are used to calculate UARL (see Equations (4) and (5) in Section 4) [46].

As the system ages, the rate of real losses increases due to new leaks and bursts. The difference between CARL and UARL is equal to the potentially recoverable real losses. However, in practice, reducing actual losses is economically justified and viable only up to the value of economic level of real losses (ELL) [45].

2.2. Strategies Aimed at the Reduction of Water Losses

Real losses in WDSs can be reduced by using the strategies such as (i) speed and quality of repairs, (ii) pressure management, (iii) pipeline and asset management, and (iv) active leakage control to locate unreported leaks [45].

To accurately determine both UARL and ILI and, above all, to effectively manage water losses, it is advisable to divide the network into district metered areas (DMAs) where the pressure values and parameters regarding the water balance can be indicated. The DMA consists of small clusters where both supplied and consumed water (water which enters and exits the DMA) are monitored remotely to evaluate the water balance. These small areas are created by boundary-isolating valves or by permanently disconnecting pipes to adjacent zones [47]. DMAs are widely used in some water supply networks to monitor unusual demands that are generally caused by leaks. If within a DMA the operating pressure is managed (decreased or increased, if needed), this zone is referred to as a pressure management area (PMA). Pressure management (PM) is the practice of managing pressures in a WDS to the optimum (minimum) levels of service and, at the same time, ensuring efficient and sufficient supply of water to consumers [48,49]. Generally, the minimum pressure in the water supply network is maintained during peak hours of consumption, but, on the other hand, it rises significantly during the off-peak hours (especially at night) and increases the frequency and volume of leaks [50]. PM is the most beneficial, energy efficient, and cost-effective leakage management method [51,52]. PM leads to a decrease in real water losses due to the reduction of excess pressures, pressure fluctuations, and transient flows [48]. The pressure in the WDS is generally managed with use of both pressure-reducing valves (PRVs) and variable speed pumps (VSPs). PRVs dissipate energy and thus reduce the operating pressure, but VSPs may reduce flow rate (when necessary) and thus reduce not only the pressure to avoid leakages and ruptures but also the energy consumption [20,53,54]. Variable speed drive changes the frequency of the input power and thus regulates the rotational speed of the VSP motor and changes the hydraulic performance of the pump. Monsef et al. (2018) [54] have confirmed that the simultaneous use of PRVs and VSPs to manage the pressure in a WDS have reduced the leakage rate and the energy consumption by 41.72% and 28.4%, respectively, in comparison with a non-management system. The creation of PMAs enables the reduction of leakages and the saving of energy due to the lowered pumping heads. PRVs used for pressure management within PMAs can be replaced by pumps as turbines (PATs). This strategy can be an alternative for production of clean renewable energy in WDSs. In addition to pumps, other small hydro-power systems, such as small turbines, micro-turbines, or pico-turbines, can be used for energy recovery [20,55]. PATs are easily available and installed and have relatively low costs compared with conventional hydraulic machines. PATs can be installed not only in urban WDSs but also in irrigation systems [21]. The main limitation of PATs is their lower efficiency when the velocity and the discharge of water flow vary [21,55]. In the case of variable operating conditions, an appropriate solution can be the hydraulic or electrical regulation of PATs [56]. The incorporation of this regulation into a pressurized water system results in an increase in energy production and thus the sustainability of the WDSs [57].

Active leakage control (ALC) is the continuous monitoring of flows in the network to identify and quantify existing unreported leaks or bursts immediately to start repairs as fast as possible. ALC consists of the following stages: (a) leak monitoring and localization, (b) leak location and pinpointing [58]. ALC is usually performed in DMAs or in PMAs and is carried out as acoustic and non-acoustic leak detection, or as a continuous monitoring of flow and pressures [58,59]. The effective pressure monitoring provides data for identification of pipe bursts and failures (e.g., pressure drops) [60,61]. According to the definition given by the American Water Works Association (AWWA), ALC can also include permanent flow monitoring in DMAs to infer changing leakage rates and identify emerging leakages [62]. ALC is a part of best management practices in WDSs to perform the fast detection and identification as well as repair of bursts in order to minimize the leakage volume and to avoid possible infrastructure damage which poses additional problems and generates energy losses [60,61].

Fast and high-quality repair is the strategy which aims to minimize the runtime of all leaks and breaks. The overall runtime of the leak consists of the awareness, location, and the duration of repair. Even in the case of relatively small leakages, their long runtimes will generate large amounts of water losses. Therefore, the runtimes of repairs should always be reduced to the economic minimum [48]. The speed of repairs strongly depends on the quality of the tools and methods used to detect leaks. Efficient and fast identification and location of leaks and the high quality of their repairs are critical for effective WDS management as well as water and energy conservation [48,63]. To meet the Sustainable Development Goals and to avoid the contamination of tap water, it is important to develop proper management procedures as well as decision-support tools [64].

Pipeline and asset management comprises, among other things, the selection, installation, maintenance, and renewal and replacement of old damaged and leaking mains and service connections. Proper asset management enables the prediction and prevention of events and reduces the risks associated with aging infrastructure [48].

3. Benchmarking Studies in the Water Supply Sector

Benchmarking is a crucial method of measuring and providing insights on performance. It is a useful tool for public authorities and regulators to learn best practices from each other to continuously improve services. Benchmarking can be used as an internal management tool for water and wastewater service providers [65]. In the mid-1990s, the

International Water Association (IWA) began work on a benchmarking project to compare strategies that control wastewater treatment processes. The definition of benchmarking applied by the IWA, accepted and commonly used by the water industry, is: "Benchmarking is a tool for performance improvement through systematic search and adaptation of leading practices" [65]. Due to the numerous problems of the water and wastewater sector, the IWA has expanded their subject of research and study to include other areas of water supply and sewage systems, including water losses. In 2010, the IWA created the Benchmarking and Performance Assessment Specialist Group (BPA SG) which is an international forum for discussing, promoting, creating networking opportunities, and improving the state of the art in all activities related to the performance assessment of water services [65,66]. The expert working group, which aims to optimize the management of the water and sewage sector, consists of scientists, consultants, and system operators. The result of their actions and activities is the publication of studies including performance indicators in the water and sewage sector and the assistance of enterprises in the execution and implementation of the benchmarking project [67–69].

In Poland, data on water losses are, among others, collected by the Central Statistical Office (GUS) as well as Chamber of Commerce "Polish Waterworks" (IGWP) [36]. Additionally, numerous Polish water supply companies and researchers present their own studies about water losses in the literature [70–72]. They often develop, recommend, and use various water loss performance indicators as well as energy and cost-efficiency indicators which may be calculated for the entire water supply system or for DMAs or PMAs.

4. Materials and Methods

The analysis covered the data from the year 2021, obtained via survey from 12 Polish water supply and sewerage companies, including quantity of the water supplied to the network (in the case of this investigation, this value is equal to system input volume (SIV) because the companies have not reported any imported or exported water). Water in the analyzed WDSs is used for human consumption, domestic purposes, social welfare purposes, as well as non-production and production purposes. In addition, the data on the water sold, water used for own purposes, length of mains and service connections, the number of service connections, number of inhabitants, and the average operating pressures in the tested networks were provided. The questionnaire sent to companies is included in the Supplementary Materials (File S1). The WDSs were named using letters from A to L. The names and exact locations of the water supply systems are not provided in the text. All of these systems are located in the Silesian voivodeship. In total, these WDSs supply water to more than 18.72% of the population in this province and, at the same time, more than 2.17% of population in Poland. Diverse water loss performance indicators were calculated on the basis of the provided data using Equations (1)–(10).

The infrastructure leakage index (ILI) was calculated on the basis of Equation (1).

$$\mathrm{ILI} = \frac{\mathrm{CARL}}{\mathrm{UARL}} \tag{1}$$

where CARL is current annual real loss in m^3/year, UARL is unavoidable annual real loss in m^3/year.

The current annual real loss (CARL) and total water loss (WL) were calculated from Equations (2) and (3) (all of the components in equations are established for the period of one year) [41].

$$\mathrm{CARL} = \mathrm{RL} = \mathrm{WL} - \mathrm{AL} \tag{2}$$

$$\mathrm{WL} = \mathrm{SIV} - \mathrm{UAC} - \mathrm{BAC} \tag{3}$$

where CARL is expressed in m^3/year, RL is real (physical) water loss (in this case equal to CARL) in m^3/year, WL is total water loss in m^3/year, AL is apparent (commercial) water loss calculated (as approximate value) as the sum of 0.1% of SIV and 2% of BAC (m^3/year), system input volume (SIV) in the absence of import and export of water is equal to the water supplied to the network (m^3/year), unbilled authorized consumption (UAC) is the water used for the needs of the company in m^3/year, and billed authorized consumption (BAC) is the water sold in m^3/year.

UARL can be calculated from Equations (4) and (5). In order to perform correct calculations, it should be checked if the service connection length provided by the water utility is measured from the property line to the meter (Equation (4)) or if it is measured from the mains to the meter (Equation (5)) [46]. In this case, Equation (5) was used for UARL calculation.

$$\mathrm{UARL} = \left(6.57 \cdot \mathrm{L_m} + 0.292 \cdot \mathrm{N_c} + 9.132 \cdot \mathrm{L_p}\right) \cdot \mathrm{P} \quad (4)$$

$$\mathrm{UARL} = (6.57 \cdot \mathrm{L_m} + 0.256 \cdot \mathrm{N_c} + 9.13 \cdot \mathrm{L_t}) \cdot \mathrm{P} \quad (5)$$

where L_m is the mains length in km, L_p is the total length of underground pipes (property line to meter) in km, L_t is the total length of underground pipes (service connections), from mains to meter in km, N_c is the number of service connections (mains to property line), P is the average operating pressure in m.

Other loss performance indicators were calculated as part of the analysis, such as: the percentage of water loss (WL%), the percentage of non-revenue water (NRW), as well as the normalized (unitary) indicators: the volume of physical water losses in m^3 per km of mains per hour (RLB_1), the volume of physical water losses in dm^3 per service connection per day (RLB_2), and the volume of physical water losses in dm^3 per inhabitant per day (Q_{los}). The formulas for calculation of these water loss performance indicators are given below (Equations (6)–(10)) [71–73].

Percentage of water loss (WL%), the total annual water loss expressed as a percentage of net water supplied, is calculated from Equation (6):

$$\mathrm{WL\%} = \frac{\mathrm{WL}}{\mathrm{SIV}} \cdot 100\% \quad (6)$$

where WL% is the total water loss as a percentage of water supplied to the network (%), WL is the volume of total water loss in m^3/year, SIV is the water supplied to the network in m^3/year.

Non-revenue water (NRW), the difference between water supplied to the network and water sold expressed as a percentage of net water supplied, is calculated from Equation (7):

$$\mathrm{NRW} = \frac{\mathrm{SIV} - \mathrm{BAC}}{\mathrm{SIV}} \cdot 100\% \quad (7)$$

where NRW is the non-revenue water as a percentage of water supplied (%), SIV is expressed in m^3/year, BAC is the water sold in m^3/year.

The volume of physical (real) water losses per km of mains per day (in Poland, it is also called real leakage balance (RLB_1)) is calculated from Equation (8). This indicator is applicable to WDSs with a density of service connections of fewer than 20 connections per km of network. This water loss performance indicator is used predominantly for rural areas.

$$\mathrm{RLB_1} = \frac{\mathrm{CARL}}{\mathrm{L_m} \cdot 365} \quad (8)$$

where RLB_1 is the volume of real water loss in m^3 per km of mains per day (m^3/(km·d)), CARL is current annual real loss in m^3/year, L_m is the length of mains in km.

The volume of physical (real) water losses in dm^3 per service connection per day (in Poland, it is also called real leakage balance (RLB_2) or RLL [44]) is calculated from Equation (9). This indicator is applicable to WDSs with a density of service connections higher than 20 connections per km of network. This water loss performance indicator is used predominantly for urban areas.

$$RLB_2 = \frac{CARL \cdot 1000}{N_c \cdot 365} \quad (9)$$

where RLB_2 is the volume of real water loss in dm^3 per service connection per day (dm^3/(connection·day), N_c is the number of service connections, CARL is given in m^3/year.

The volume of physical (real) water losses in dm^3 per inhabitant per day (in Poland, it is also called unitary loss per capita (Q_{los})) is calculated from Equation (10):

$$Q_{los} = \frac{CARL \cdot 1000}{IN \cdot 365} \quad (10)$$

where Q_{los} is the volume of real water loss in dm^3 per inhabitant per day (dm^3/(inhabitant·day), IN is the number of serviced inhabitants, CARL is in m^3/year.

It should be emphasized that the normalized real losses in this article were calculated for all companies as both RLB_1 and RLB_2, regardless on the density of service connections.

5. Results and Discussion

5.1. The Characteristics of the Water Distribution Systems

The data characteristics for the water distribution systems obtained in the survey from 12 water supply companies are presented in Table 1. Companies I and J did not keep records on the length of water supply connections, while companies G and H did not keep records on the number of serviced inhabitants. Companies H and K, on the other hand, did not specify the values of the average pressure in the network but presented the data as a pressure range.

Table 1. The characteristics of the water distribution systems.

Company	Length of Mains, L_m (km)	Length of Service Connections, L_p (km)	Network Length, $L_m + L_p$ (km)	Number of Service Connections, N_c	Density of Service Connections, D (con./km)	Average Pressure in the Network, p (m H_2O)	Number of Serviced Inhabitants, IN	Serviced Inhabitants as a Percentage of Population of Silesian Voivodeship (%)
A	1587.8	905.2	2493	55,287	34.8	40.8	311,400	7.07
B	191.30	172.57	363.87	6321	33.0	50	40,362	0.92
C	376.5	243.7	620.05	15,812	42.0	55	89,192	2.03
D	411.6	153.3	564.30	14,163	34.4	30	75,049	1.70
E	141.5	80.3	221.7	6118	43.2	33 (20–45) **	54,000	1.23
F	268.4	96.0	364.4	7365	27.4	45	148,000	3.36
G	193.1	184.7	377.8	6922	35.8	40.7 *	N.A.	N.A.
H	155.7	98.4	254.1	4920	31.6	32.5 * (20–45) **	N.A.	N.A.
I	238.4	N.A.	N.A.	4429	18.6	40	18,629	0.42
J	135.1	N.A.	N.A.	6476	47.9	30	30,912	0.70
K	114.7	N.A.	N.A.	4958	43.2	42.5 * (40–45) **	23,278	0.53
L	269.5	179.2	448.7	6690	24.8	37.5 * (35–40) **	33,360	0.76

*—The estimated value. **—The range of the water operating pressure in the water supply network. N.A.—Data not available.

5.2. Water Balance

Detailed data on water production and sales in 2021 in the analyzed companies are presented in Table 2. The preparation of the water balance requires data on the amount of water supplied to the network (in this case, the system input volume (SIV)), the unbilled authorized consumption which is the amount of water used for the needs of the water supply company (UAC), and the billed authorized consumption which is the amount of water sold to all customers (BAC). Current annual real loss in WDSs (CARL) was calculated from Equations (2) and (3). The water supply company K did not provide the data on unbilled authorized consumption. The uncertainty analysis was performed with 95% confidence limits for default uncertainties of SIV, BAC, UAC, and AL on the basis of [74].

Table 2. The summary of water balance for year 2021.

Company	System Input Volume, SIV (10^3 m^3/Year)	Billed Authorized Consumption, BAC (10^3 m^3/Year)	Unbilled Authorized Consumption, UAC (10^3 m^3/Year)	Water Loss, WL (10^3 m^3/Year)	Apparent Loss, AL (10^3 m^3/Year)	Real Loss, RL = CARL (10^3 m^3/Year)
A	16,563.400 ± 331.268	14,483.700 ± 289.674	178.800 ± 35.760	1900.900 ± 441.507	306.237 ± 58.029	1594.663 ± 445.304
B	1539.273 ± 30.785	1327.552 ± 26.551	16.766 ± 3.353	194.955 ± 40.791	28.090 ± 5.319	166.865 ± 41.136
C	5864.756 ± 117.295	4546.802 ± 90.936	109.134 ± 21.827	1208.820 ± 150.013	96.801 ± 18.225	1112.019 ± 151.116
D	3566.000 ± 71.320	2803,000 ± 56.060	53.000 ± 10.600	710.000 ± 91.333	59.626 ± 11.235	650.374 ± 92.021
E	2415.251 ± 48.305	2074.639 ± 41.493	64.858 ± 12.972	275.754 ± 64.987	43.908 ± 8.313	231.846 ± 65.516
F	6988.451 ± 139.769	6536.113 ± 130.722	78.612 ± 15.722	373.726 ± 192.018	137.711 ± 26.182	236.015 ± 193.795
G	1517.350 ± 30.347	1332.129 ± 26.643	8.014 ± 1.603	177.207 ± 40.415	28.160 ± 5.337	149.047 ± 40.765
H	1462.700 ± 29.254	1085.800 ± 21.716	15.500 ± 1.100	361.400 ± 36.565	23.179 ± 4.353	338.221 ± 36.823
I	800.268 ± 16.005	582.250 ± 11.645	23.584 ± 4.717	194.434 ± 20.348	12.445 ± 2.334	181.989 ± 20.481
J	1169.010 ± 23.380	981.488 ± 19.630	38.926 ± 7.785	148.596 ± 31.505	20.799 ± 3.933	127.797 ± 31.745
K	1275.000 ± 25.500	1201.452 ± 24.029	N.A.	N.A.	25.304 ± 4.813	N.A.
L	1684.364 ± 33.687	1374.868 ± 27.497	28.612 ± 5.722	280.884 ± 43.860	29.182 ± 5.510	251.702 ± 44.205

N.A.—Data not available.

5.3. Analysis of Water Loss Performance Indicators

Table 3 presents values of water loss performance indicators and unavoidable annual real loss (UARL) calculated for the 12 analyzed WDSs based on Equations (1)–(3) and (5)–(10). Values of water loss performance indicators can be calculated for an entire WDS or for separate DMAs. In this case, the companies provided data for the entire WDS.

Table 3. Water loss performance indicators for analyzed water distribution systems for year 2021.

Company	WL %	NRW %	RLB_1, m^3/(km·Day)	RLB_2, dm^3/(conn.·Day)	Q_{los}, dm^3/(inhab.·Day)	UARL (10^3 m^3/Year)	ILI (-)
A	11.5 ± 2.67	12.6 ± 2.67	2.75 ± 0.77 **	79.02 ± 22.06	14.03 ± 3.92	1340.272	1.19 ± 0.33
B	12.7 ± 2.66	13.8 ± 2.65	2.39 ± 0.59 **	72.32 ± 17.83	11.33 ± 2.79	222.529	0.75 ± 0.18
C	20.6 ± 2.56	22.5 ± 2.53	8.09 ± 1.10 **	192.68 ± 26.18	34.16 ± 4.64	481.055	2.31 ± 0.31
D	19.9 ± 2.56	21.4 ± 2.54	4.33 ± 0.61 **	125.81 ± 17.80	23.74 ± 3.36	231.887	2.80 ± 0.40
E	11.4 ± 2.69	14.1 ± 2.64	4.49 ± 1.27 **	103.82 ± 29.34	11.76 ± 3.32	106.557	2.18 ± 0.62
F	5.3 ± 2.72	6.5 ± 2.75	2.41 ± 1.98 **	87.80 ± 72.09	4.37 ± 3.58	203.639	1.16 ± 0.95
G	11.7 ± 2.67	12.2 ± 2.66	2.11 ± 0.58 **	58.99 ± 16.13	N.A.	192.389 *	0.77 ± 0.21 *
H	24.7 ± 2.50	25.8 ± 2.49	5.95 ± 0.64 **	188.34 ± 20.51	N.A.	103.378 *	3.27 ± 0.36 *
I	24.3 ± 2.54	27.2 ± 2.47	2.09 ± 0.24	112.58 ± 12.67 **	26.76 ± 3.01	N.A	N.A.
J	12.7 ± 2.69	16.0 ± 2.60	2.59 ± 0.64 **	54.07 ± 13.43	11.33 ± 2.81	N.A	N.A.
K	N.A.	5.8 ± 2.76	N.A.	N.A.	N.A.	N.A	N.A.
L	16.7 ± 2.61	18.4 ± 2.59	2.56 ± 0.44 **	103.08 ± 18.10	20.67 ± 3.63	191.976	1.31 ± 0.23 *

*—The approximate value. **—The indicator is not recommended due to the density of service connections per km of mains. N.A.—Data not available.

Obtained results show that water supply companies are not always able to estimate the unbilled authorized consumption. The percentages of water losses (WL%, also called WL) were calculated for 11 distribution systems (in the case of company K, calculation of WL was not possible due to the lack of data on UAC). The lowest value of WL, equal to 5.4%, was calculated for the company F, and the highest value, equal to 24.7%, was established for the system H. On the other hand, percentage values of NRW were calculated for all WDSs because their calculation did not require knowledge of UAC. Both WL and NRW values varied significantly between different WDSs. The analysis presented by Mutikanga in 2012 [75] for WDSs in different countries shows a very high variability in percentage of water loss performance indicators. The report EurEau (2021) [25] also shows that water losses expressed as an NRW percentage are diverse in EU Member States.

Values of NRW also comprise water used for the needs of the company (UAC) (e.g., the water used for maintenance, street cleaning, firefighting, in public buildings, etc.), therefore they are always higher than WL [76–78]. For this reason, the NRW percentage does not reflect the actual condition of WDSs. Lambert et al. (2014) [39] have emphasized that percentage indicators do not reflect the true condition of WDSs. Liemberger et al. (2007) [41] have pointed out that NRW as a percentage of SIV can be misleading as a water loss performance indicator and they recommend to express NRW in dm^3 per service connection per day (or in m^3 per km of mains per day for systems with service connection density lower than 20 per km of mains). Kwietniewski (2013) [71] has also concluded that both WL and NRW percentage indicators do not take into account factors which significantly affect water losses, such as the length of the water supply network (mains and service connections), the density of service connections per km of mains, and the average operating pressure in the WDS. Kwietniewski has postulated that percentage indices are not recommended for comparing water losses in different WDSs and they can only be used to compare the variability of water losses in a particular WDS over time [71].

Additionally, Liemberger et al. [41] have pointed out that it should be established whether the equation for the calculation of percentage indicators uses SIV as the denominator, which includes water exported, or water supplied into the network (WS), which does not. In the current paper, SIV is equal to WS, because companies have not reported any water import or export.

The normalized real loss performance indicators (called real loss balance—RLB — or RLL) were calculated as a part of the analysis described in the current paper. For 11 companies (except K) both RLB_1 and RLB_2 were calculated. But it should be expressed that for some WDSs either RLB_1 or RLB_2 should be calculated, depending on the density of service connections per km of mains (D) (see Tables 1 and 3). Only company I has D < 20 service connections per km of mains, therefore only in this case is the value of RLB_1 (in m^3 per m of mains per hour) reliable. For the remaining companies, the reliable water loss performance index is RLB_2 (expressed in m^3 per connection per day). The lowest values of RLB_2 were obtained for companies J and G, but good results were obtained for A, B, and F, too. According to reference values for retail systems in Portugal [79], the quality of services is good if $RLB_2 < 100$ $dm^3/(connection \cdot day)$. The calculated values of ILI as well as percentage indicators were also relatively low in the case of these companies. According to the same Portuguese guidelines, the services of companies D, E, I, and L have an average quality (RLB_2 = 100–150 $dm^3/(connection \cdot day)$). The values of RLB_2 indicate unsatisfactory quality of services for companies C and H ($RLB_2 > 150$ $dm^3/(connection \cdot day)$) [79]. The real losses expressed as RLB_2 for companies C and H are very high and equal to 192.68 and 188.34 $dm^3/(connection \cdot day)$, respectively. The values of ILI and percentage indicators calculated for these companies were also relatively high (but the calculation of ILI for company J was not possible).

The next calculated indicator was normalized real water loss per inhabitant per day (Q_{los}). In the case of the WDSs analyzed in the current paper, companies G and H did not keep records of the number of inhabitants, therefore Q_{los} was calculated for 10 utilities. The highest value of Q_{los} was calculated for company C for which the values of other loss performance indicators were also unfavorable.

Kwietniewski (2013) [71] recommends the use of normalized (unitary) indicators of water losses (RLB_1, RLB_2, or Q_{los}). The American Water Works Association (AWWA) in [78] also encourages drinking water industry stakeholders (water utilities, regulatory and financial rating agencies as well as water resource planning agencies) to discontinue the use of percentage loss performance indicators. At the same time, the AWWA recommends the use of normalized indicators which can be determined for a unit of time (e.g., for a day, for a unit of length of network, for one service connection, or per capita) [78].

The most important analyzed water loss performance indicator was the ILI, because this index is recommended for evaluation of WDSs' efficiency by Directive (EU) 2020/2184. The ILI was calculated for nine utilities. For companies I, J, and K, its calculation was not possible due to the lack of data on the length of service connections necessary for UARL estimation.

Table 4 shows comparison of the ILI with reference values for leakage performance categories (LPCs) for developed countries, recommended by the IWA, AWWA, and WBI Banding System. Each LPC is associated with an ILI range and a recommendation for activities aimed at leakage management [41,80]. In the case of category A, further loss reduction may not be economically viable (unless there are shortages). In the case of category B, there is the possibility of further improvement of infrastructure. In the case of category C, a high ILI can be tolerable if water resources are cheap and plentiful. In the case of category D, a high value of ILI shows inefficient use of resources and poor WDS condition.

Table 4. The comparison of ILI results with reference values for leakage performance categories (LPCs) for developed countries, recommended by IWA, AWWA, and WBI Banding System [41,80].

LPC	Description of LPC	ILI Range	Company/ILI Value											
			A	B	C	D	E	F	G	H	I	J	K	L
			1.19	0.75	2.31	2.80	2.18	1.16	0.77	3.27	N.A.	N.A.	N.A.	1.31
A1 *	Very low LPC	ILI ≤ 1.5	+	+				+	+					+
A2	Low LPC	1.5 ÷ 2.0												
B	Moderate LPC	2.0 ÷ 4.0			+	+	+			+				
C	High LPC	4.0 ÷ 8.0												
D	Very high LPC	ILI ≥ 8.0												

N.A.—Data not available. *—The target LPC according to Directive (EU) 2020/2184.

Data in Table 4 show that the target value of the ILI specified in Directive (EU) 2020/2184 corresponds to the A1 category (very low LPC), defined in world standards recommended by the IWA, AWWA, and WBI Banding System. Obtained results show that ILI values for five companies (A, B, F, G, and L) could be included in category A1 (ILI ≤ 1.5), and ILI values for four companies (C, D, E, and H) could be included in category B, characterized by moderate LPC (2.0 ≤ ILI ≤ 4.0).

According to Directive (EU) 2020/2184, there will be an obligation to determine leakages based on the ILI or another appropriate method. It should be emphasized that, depending on the indicator taken into account, the analyzed WDSs obtained different positions in the ranking on the evaluation of water losses. Therefore, the analysis of diversified water loss performance indicators can give a broader picture of water losses and the condition of a specified WDS.

Analyses available in the literature indicate greater usefulness of the ILI indicator to assess the level of water losses for well-managed systems with good infrastructure [45,71]. The obligation of ILI estimation applies to water supply systems serving at least 50,000 people. The ILI is dimensionless and technically applicable in the comparative analysis of different water systems around the world [71]. The advantage of this indicator is that its calculation is based on the assumption that water losses are inevitable, so a certain value of a loss should be accepted. Therefore, for ILI determination, it is necessary to calculate the UARL which is characteristic of a given water supply system and depends on the network's length, number and length of service connections, and pressure in the network.

It should be mentioned that the pressures reported by the surveyed companies were often approximate (company G), and in some cases only a range of pressure was provided (companies H, K, and L). Additionally, not all companies kept records of the length of service connections (companies I, J, and K). Utilities G and H indicated that the length of the service connections is approximate (therefore, values of UARL for these companies were marked as approximate—see Table 3).

Uncertainties in data provided (e.g., operating pressure and service connection length) significantly affect the accuracy of calculated ILI values. Figure 1 presents the influence of variable average operating pressures in networks on values of UARL (Figure 1a) and ILI (Figure 1b), taking into account actual values of current annual real loss (CARL).

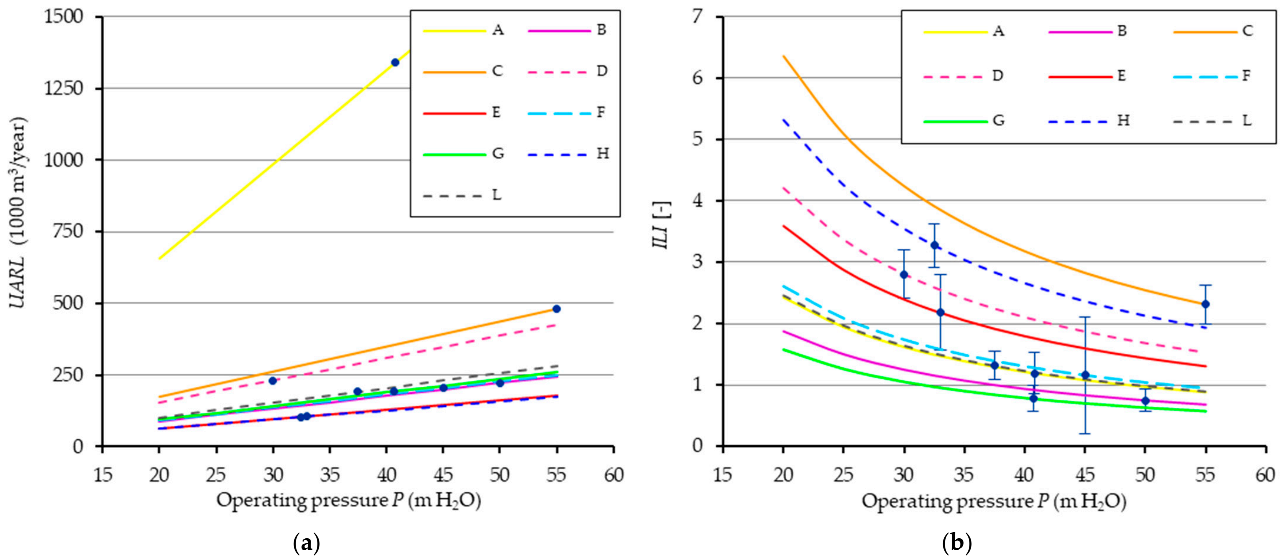

Figure 1. The influence of variable values of average operating pressures in the water supply networks on values of: (**a**) unavoidable annual real loss (UARL) and (**b**) infrastructure leakage index (ILI) calculated on the basis of actual values of CARL. Plotted data represented by points show actual relationships between P and UARL and between P and ILI (with error bars).

Figure 1 does not contain results for companies I, J, and K due to the lack of data required for calculation of UARL (and CARL in the case of company K). Results show that values of UARL rise with an increase in reported values of operating pressure, and these relationships are linear. On the other hand, with the rise of reported operating pressures, calculated values of ILI decrease. The relationship between the average operating pressure and ILI describes the power function. The results presented in Figure 1 show that inaccuracies in estimation of the average operating pressure can significantly influence the calculated value of UARL and thus the ILI. As a result, these inaccuracies may adversely affect the assessment of the technical condition of the WDS. Similar investigations were conducted in 2021 by Ramm and Bylka [36], who concluded that the change in operating pressure influences the ILI, and the underestimation of pressure in the network can increase ILI by several times. Therefore, changing the pressure value significantly influences the assessment of the technical condition and efficiency of the water distribution system [36]. Ramm and Bylka have concluded that, in Poland, the application of the ILI is limited to the local level. According to them, the implementation of Directive (EU) 2020/2184 will require methods for the collection and calculation of a large amount of data provided by water supply companies. Precise determination of ILI contributes to a better understanding and management of water losses [36].

The next analyzed parameter, whose estimation accuracy affects the accuracy of ILI determination, is the length of service connections. Calculated average lengths of service connections for analyzed WDSs, presented in Table 5, were calculated as a quotient of the total length of underground pipes between the main and customer meters to the number of service connections. These lengths ranged from approximately 10.82 m (company D) to 27.30 m (company B). It should be noted that some water supply companies have provided only approximate lengths of service connections and some companies (I, J, K) did not provide any information on these lengths.

Figure 2 presents the influence of variable average lengths of single service connections on values of UARL (Figure 2a) and ILI (Figure 2b), taking into account the actual values of: CARL, operating pressures in the network, and number of service connections.

Table 5. Average lengths of service connections.

Company	The Total Length of Service Connections (from the Mains to the Meter), L_t (km)	Number of Service Connections, N_c	The Average Length of Service Connections (from the Mains to the Meter, L_{tav} (m)
A	905.2	55,287	16.37
B	172.57	6321	27.30
C	243.72	15,812	15.41
D	153.30	14,163	10.82
E	80.31	6118	13.13
F	96.02	7365	13.04
G	184.70 *	6922	26.68 *
H	98.40 *	4920	20.00 *
I	N.A.	4429	N.A.
J	N.A.	6476	N.A.
K	N.A.	4958	N.A.
L	179.2	6690	26.79

*—The estimated value. N.A.—Data not available.

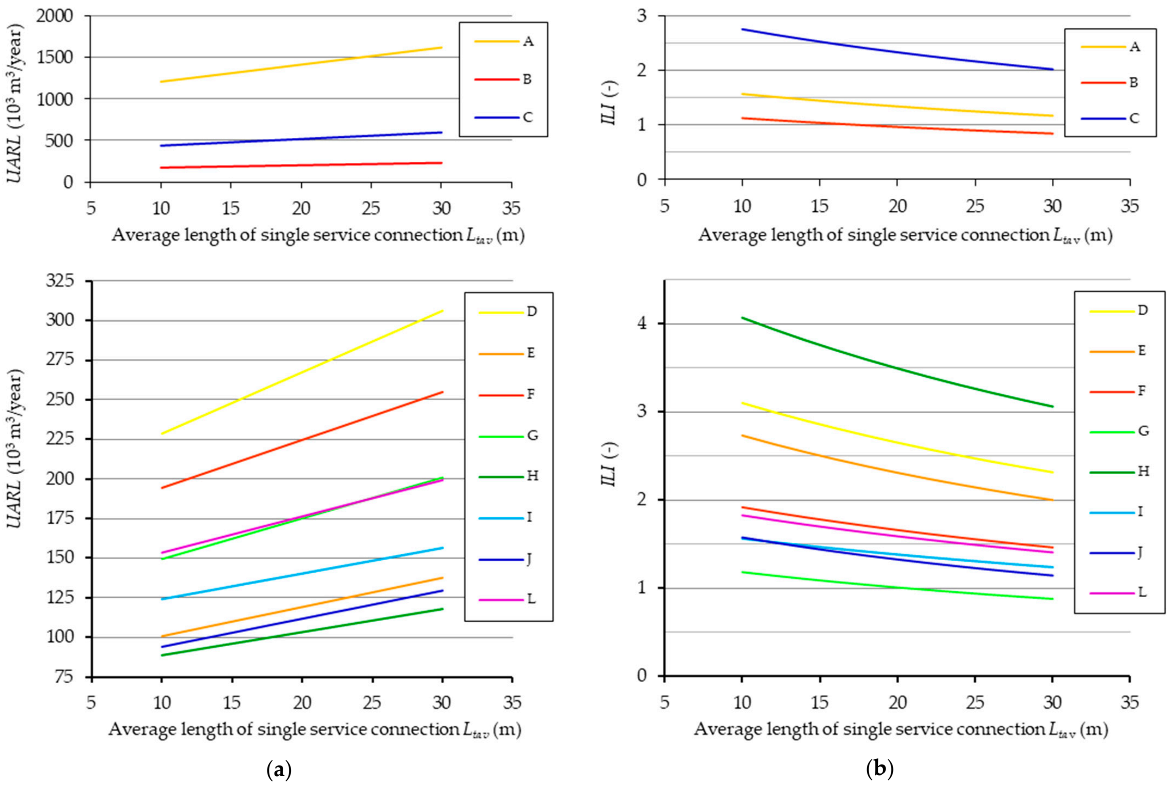

Figure 2. The influence of variable average lengths of single service connections on values of: (**a**) unavoidable annual real loss (UARL) and (**b**) infrastructure leakage index (ILI), calculated on the basis of actual values of CARL, actual number of service connections, and the average operational pressure.

Despite the lack of data on service connection lengths, graphs for companies I, J, and K are also presented. Values of UARL and ILI presented in Figure 2 were calculated based on hypothetical diverse service connection lengths. The results show the range in which UARL and ILI may vary in the case of imprecise estimation of the service connection lengths (in this case expressed as the average length of a single service connection). Results show that, in the case of company A, values of UARL are significantly higher than for other companies, but values of the ILI are relatively low and do not exceed 1.5. Taking into account the ILI and other loss performance indicators it can be concluded that company A administers a large WDS in which water losses are very well managed. The water distribution network A is divided into several PMAs. Additionally, the extensive area of the WDS is covered by active pressure control. Relatively high UARL values, compared to other companies, are observed in the case of company C. Values of the ILI calculated for diverse service connection lengths range from about 2.0 to 2.5, which is the third worst value (water losses in utility C are not well managed). However, the results obtained for company H deserve special attention. UARL values estimated for this company are very low due to the relatively small size of the water distribution network (short total lengths of mains and service connections and relatively small number of service connections). However, ILI values estimated for company H are the worst among the values calculated for all utilities (they range from about 2.8 to about 3.7). Other loss performance indicators estimated for company H are also high. Additionally, company H has not provided the precise value of operating pressure, only a wide range of pressures (20–45 m H_2O), and has provided only the estimated total length of service connections. Therefore, it can be concluded that company H is not well managed or provided data are imprecise. Results show that imprecise estimation of service connection lengths may have an impact on calculated values of both UARL and the ILI. The overestimation of the length of service connections may lead to overestimation of UARL and thus to underestimation of the ILI. Attention should also be paid to the correct reporting of service connection lengths, which has an impact on the selection of the appropriate equation for calculation of UARL (see Equations (4) and (5)). The length of service connections can be expressed in two ways: (a) as the length from the mains to customer meter or (b) as the length from the property line (the street edge) to the customer meter. It should also be mentioned that the obligation of ILI reporting will only apply to large water distribution systems. Such WDSs are usually located in larger cities with high-density housing and usually comprise zones with very old pipes and service connections. Probably, not all of these old service connections are inventoried correctly.

5.4. Analysis of the Energy Consumption and CO_2 Emissions

Each unit of water distributed by the water supply company results in the consumption of energy and emission of a certain amount of greenhouse gases. The energy plays an important role in every stage of water production, encompassing extraction, treatment, pumping, and distribution. The key part of GHG emissions occurs directly during water treatment and indirectly through the production of energy, as well as potential chemical additions. But it should be emphasized that in some countries (e.g., in the USA, in China, or in India) CO_2 (or CH_4) emissions released from groundwater due to groundwater table depletion could be significant [81,82]. Table 6 presents values of the energy consumption and CO_2 emissions related to CARL. The table also presents values of target annual real losses, electricity consumption, and GHG emissions corresponding to ILI = 1.5 (in this paper defined as $ARL_{ILI=1.5}$). This reduction of the ILI to 1.5 results from the application of Directive (EU) 2020/2184. The potential minimum target reduction of real losses was calculated as the difference between CARL and $ARL_{ILI=1.5}$. On the basis of these values, possible reductions of both electricity consumption and GHG emissions were established.

The annual energy consumption at individual water utilities was not made available, therefore, the energy consumption related to specific categories of water losses was estimated on the basis of averaged electricity consumption for 1 m^3 of produced water for Polish water supply companies. In the year 2021, this value (so-called utility energy intensity) was equal to 0.65 kWh/m^3 [83]. The CO_2 emissions were estimated on the basis of data available on the Electricity Maps website [19,84]. The average reference carbon intensity for Poland in the year 2021 amounted to 857 gCO_2eq/kWh. The utility carbon intensity calculated as a product of energy and reference carbon intensities amounted to 557.05 gCO_2eq/m^3. Such a high carbon intensity resulted from the large share of fossil fuels (coal) in Poland's energy mix. The share of coal in the electricity production and the emissions in 2021 amounted to 69.22% and 92.49%, respectively.

Table 6. The WDSs' electricity consumption and related CO_2 emissions for the year 2021.

Company	Current Annual Real Loss, CARL			Target Annual Real Losses Corresponding to ILI = 1.5, $ARL_{ILI=1.5}$			Potential Minimum Target Reduction of Real Losses According to Directive (EU) 2020/2184, $CARL-ARL_{ILI=1.5}$			
	Water Losses, 10^3 m^3/Year	Electricity Consumption, MWh	GHG Emission, $MgCO_2eq$/Year	Water Losses, 10^3 m^3/Year	Electricity Consumption, MWh	GHG Emission, $MgCO_2eq$/Year	Water Losses Reduction, 10^3 m^3/Year	Possible Reduction of Electricity Consumption, MWh	Possible Reduction of GHG Emission	
									$MgCO_2eq$/Year	%
A	1594.663	1036.53	888.31	2010.407	1306.765	1119.90	−415.74 *	**	**	**
B	166.865	108.46	92.95	333.794	216.966	185.94	−166.93 *	**	**	**
C	1112.019	722.81	619.45	721.583	469.029	401.96	390.44	253.78	217.49	35.11
D	650.374	422.74	362.29	347.831	226.090	193.76	302.54	196.65	168.53	46.52
E	231.846	150.70	129.15	159.836	103.893	89.04	72.01	46.81	40.11	31.06
F	236.015	153.41	131.47	305.458	198.548	170.16	−69.44 *	**	**	**
G	149.047	96.88	83.03	288.584	187.580	160.76	−139.54 *	**	**	**
H	338.221	219.84	188,41	155.067	100.794	86.38	183.15	119.05	102.03	54.15
I	181.989	118.29	101.38	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
J	127.797	83.07	71.19	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
K	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
L	251.702	163.61	140.21	287.963	187.176	160.41	−36.26 *	**	**	**

*—A negative value means that current annual real loss (CARL) is lower than the target annual real losses corresponding to ILI = 1.5 ($ARL_{ILI=1.5}$). **—ILI < 1.5, therefore, according to Directive (EU) 2020/2184, further water loss reduction is not obligatory. N.A.—Data not available.

Results presented in Table 6 show that water losses in WDSs contribute to a significant increase in both energy consumption and greenhouse gas emissions. In 2021, in all analyzed water supply companies (except K), the approximate total electricity consumption related to CARL amounted to 3.276 GWh and total carbon emissions amounted to 2807.84 $MgCO_2eq$. The target value of the ILI specified in Directive (EU) 2020/2184 amounts to 1.5. Therefore, the potential minimum reduction of real losses can be specified as the difference between current annual real losses and the annual real losses corresponding to ILI equal to 1.5 ($CARL - ARL_{ILI=1.5}$). For four utilities having an ILI higher than 1.5 (companies C, D, E, and H), the possible reductions of both electricity consumption and GHG emissions were calculated, whose sums amounted to 616.29 MWh and 528.16 $MgCO_2eq$, respectively. It should be emphasized that, in the case of five utilities (A, B, F, G, and L), ILI values were lower than 1.5, therefore, according to the Directive (EU) 2020/2184, further reduction of water losses was not required. Although in these cases water loss reduction is possible, it may not be economically viable. In practice, it is economically justified to reduce real losses to the economic level of leakage (ELL) which is estimated as the non-revenue water value corresponding to the economically recoverable losses. ELL is estimated on the basis of costs of water production and costs of initiatives aimed at reduction of water losses, e.g., creation of DMAs, active leakage control, pressure management, etc. [33].

The way to further reduce energy consumption is to invest in more sustainable and energy-efficient equipment and technologies. Additionally, the way to reduce GHG emissions is to use renewable energy sources (e.g., wind and solar power).

6. Summary and Conclusions

The aim of the article was to investigate issues and challenges concerning the implementation of the Directive of the European Parliament and of the Council (EU) on the quality of drinking water 2020/2184 regarding the evaluation of water loss performance indicators. By 12 January 2026, EU Member States shall ensure that the infrastructure leakage index (ILI) or another appropriate method is used for assessment of water leakages within their territories. However, the implementation of Directive (EU) 2020/2184 may encounter a number of problems and challenges that should be solved before the regulations enter into force. This article highlights several issues based on the analysis of water losses in 12 Polish water supply companies.

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

1. The significant limitation of the reliable assessment of water losses and, thus, the efficiency of analyzed WDSs is the lack and uncertainty of data. Results show that the use of the ILI is still limited in many water supply companies.
2. Imprecise determination of average operating pressure significantly affects calculated values of UARL and ILI. This leads to the overestimation of UARL and, thus, to the underestimation of ILI. The implementation of the directive will require the development of a unified methodology concerning the calculation of the average operating pressure.
3. The overestimation of the service connection length results in the overestimation of UARL and underestimation of the ILI. It is crucial to be aware of whether a water supply company has reported the length of service connections from the mains to the meter or the length from the property line to the meter. Each of these cases requires a different formula for calculating UARL.
4. The proper estimation of the service connection number and length in old and poorly inventoried networks can be difficult. For example, some mains can be incorrectly classified as service connections in the case of pipelines supplying water to buildings located far from the mains in the street.

5. The estimation of the average pressure can be difficult in large WDSs. Such networks should be divided into smaller district metered areas (DMAs) or pressure management areas (PMAs), and the ILI should be estimated for these separate zones. Further water loss management should be conducted in DMAs in which the ILI exceeds the value of 1.5.
6. The authors postulate that, for evaluation of WDSs, it may be necessary to consider the use of additional water loss performance indicators, e.g., the normalized real leakage balances expressed in m^3 per km of mains per day (if connection density is lower than 20) or expressed in dm^3 per connection per day (if connection density is greater than 20). These indicators can be determined on the basis of relatively easy to estimate parameters. The percentage water loss indicators are not recommended.
7. Water losses in WDSs contribute to a significant increase in both energy consumption and greenhouse gas emissions. Total approximated electricity (related to current annual real losses) consumed in 2021 by 11 out of 12 analyzed utilities amounted to 3.276 GWh and total approximated GHG emissions amounted to 2807.84 $MgCO_2eq$. In the case of four of the analyzed water supply companies, reduction of the ILI to the target value of 1.5 may reduce carbon emissions in these WDSs by values ranging from 31% to 54%.
8. The correct estimation of water loss performance indicators may influence possible actions to reduce water losses. The activity aimed at reduction of water losses allows for reducing the energy consumption in water distribution systems and for improving their energy efficiency. This will be a good step towards reducing GHG emissions and achieving Sustainable Development Goals concerning saving of both water and energy.
9. Further research should take into account analysis of water loss performance indicators for a longer period of time and the progress in implementing Directive (EU) 2020/2184.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17030633/s1, File S1: The questionnaire used in the survey with 12 Polish Water Supply and Sewage Companies.

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