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Water intake efficiency analysis in risk management of water supply systems - a case study of Głubczyce Collective Water Supply System, Poland

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ABSTRACT

In recent years, the onset of the summer season has inevitably been associated with external threats, such as hydrological drought. Prolonged dry weather conditions result in natural drought symptoms, including a decrease in both surface and groundwater levels, increased water evaporation, and the degradation of essential environmental, economic, and social functions. A negative water balance presents a challenge that, due to water scarcity, is likely to pose a threat not only to the continuity of safe drinking water supply but also to the health and lives of people. In these circumstances, the new directive on the quality of water intended for human consumption imposes on EU Member States the obligation to implement a risk management system throughout the entire water supply chain, from the water abstraction area to the consumer's tap. The paper presents tools and mechanisms employed in risk management for water supply systems and discusses their applicability within the framework of multi-protective barriers. Additionally, it delves into the construction of water supply infrastructure in the city of Głubczyce, located in the southwestern part of Poland. This discussion encompasses research results on the possibilities for diversifying and ensuring the safety of water supplies, with a particular emphasis on the operational reliability of critical infrastructure. The analysis is based on the Shannon–Weaver index and the Pielou dispersion index. The results of this analysis assess the potential for crisis situations in risk management. Taking into account the protection of critical infrastructure to ensure continuous water supplies under appropriate pressure for residents, the need to provide alternative water sources, such as tanks or packaged water, is demonstrated.

Keywords: Water supply system; Risk; Safety; Diversification; Critical infrastructure; Shannon–Weaver index; Pielou index

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1. Introduction

The primary objective of the Collective Water Supply System (CWSS) is to provide the population with safe drinking water. This system is a complex technical system consisting of two main subsystems: the Water Production Subsystem (WPSs) and the Water Distribution Subsystem (WDSs). The Water Production Subsystem comprises independent water abstraction areas, each responsible for the operation of individual intakes and water treatment plants. Meanwhile, the Water Distribution Subsystem includes a water supply network with pumping stations and network storage tanks. The CWSS operates in diverse and dynamically changing conditions, influenced by both internal and external factors. Variations in operational conditions and the numerous components of the water supply infrastructure can result in occasional malfunctions, which, in extreme cases or during severe weather events, may lead to a complete interruption of water supply to the population. On one hand, maintaining water supply to consumers relies

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on the efficiency and proper functioning of the water supply infrastructure, ensuring a high level of reliability and safety for the CWSS [1]. On the other hand, the continuity of water supply is contingent on having an ample supply of water resources to meet the current demand under all operating conditions [2]. However, in recent decades, in light of ongoing climate changes, a crucial factor determining the proper functioning of the water supply system is ensuring the appropriate quantity and quality of water extracted from the natural environment [3–7].

In recent years, the onset of the summer season has become inevitably associated with concerns about hydrological drought in many regions of the world. The persistence of dry weather contributes to the development of drought symptoms, including the lowering of both surface and groundwater levels, increased water evaporation, and the degradation of the environmental, economic, and social functions of individual natural elements. A negative water balance is a challenge that, depending on the degree of water deficit and other accompanying circumstances, may very likely lead to a threat not only to ensuring the continuity of safe drinking water supplies but also to human life, health, and the environment. According to data from the European Environment Agency, water scarcity lasting for at least one season in 2019 affected 29% of the EU territory (Table 1). Despite a recorded 15% reduction in water abstraction in EU countries between 2000 and 2019, there has been no overall reduction of the area affected by water scarcity. In fact, the situation has worsened since 2010. This, combined with the fact that climate change is expected to further increase the frequency, intensity, and impact of droughts, makes it unlikely that water scarcity will decrease by 2030 [8].

According to the Copernicus Climate Change Service (C3S) report [9], Europe experienced its hottest summer and the second warmest year on record in 2022, with 631,000 km^2 affected by drought. This represents an almost five-fold increase compared to the annual area affected by drought in the period 2000–2022 when approximately 167,000 km^2 of the EU (4.2%) were affected annually by droughts caused by low rainfall, high evaporation, and heatwaves resulting from climate change. The C3S report reveals that Europe has been warming twice as fast as the global average since the 1980s. This has far-reaching impacts on the socio-economic structure and ecosystems of the region, and it also creates risks in ensuring the provision of safe drinking water to the inhabitants of Europe [9,10].

Table 1
Distribution of water deficit in EU countries in 2019 [8]

No.	EU Country	WEI+	Annual quarters	No.	Countries outside the EU	WEI+	Annual quarters
1	Cyprus	124	III	1	Turkey	68.7	III
2	Malta	74.9	I	2	North Macedonia	9.0	III
3	Greece	70.2	III	3	Serbia	5.3	IV
4	Portugal	66.0	III	4	Kosovo	3.4	II
5	Italy	57.0	III	5	Albania	2.9	III
6	Spain	47.2	III	6	Switzerland	1.0	III
7	Romania	23.5	III	7	Bosnia and Herzegovina	0.5	III
8	Czechia	19.5	III	8	Norway	0.1	III
9	Poland	14.5	II	9	Iceland	0.0	II
10	Belgium	13.2	III				
11	Denmark	12.6	III				
12	Estonia	10.3	III				
13	Netherlands	6.3	III				
14	France	4.3	II				
15	Germany	2.9	III				
16	Bulgaria	2.5	I				
17	Hungary	2.0	IV				
18	Finland	2.0	III				
19	Lithuania	1.6	III				
20	Luxemburg	1.5	III				
21	Slovakia	1.2	2019 Annual				
22	Ireland	1.0	II				
23	Slovenia	0.6	II				
26	Sweden	0.4	III				
27	Latvia	0.3	III				
24	Croatia	0.2	III				
25	Austria	0.2	IV				

WEI+ - Water exploitation index plus.

In most EU Member States, the area affected by drought in 2022 was much larger than the average area affected by drought between 2000 and 2020 (Fig. 1). The most significant drought effects in 2022 were observed in Belgium, Luxembourg, and Slovenia. In 2022, drought impacted as much as 70% of Luxembourg's area, significantly surpassing the average annual area affected between 2000 and 2020, which was around 8.6% (Fig. 1). Drought affected over 50% of the territories of Belgium and Slovenia, much above the long-term average (which was less than 5% of the territory). Outside the EU region, the highest drought impact in 2022 was recorded in Bosnia and Herzegovina (47% of the country) and Montenegro (25% of the country). In Poland, the area affected by drought in 2022 more than doubled compared to the long-term average impact, covering 8.8% of the country's area [9,10].

Between 2010 and 2019, the 27 EU Member States abstracted approximately 38 billion·m^3 of groundwater per year, equivalent to 65% of total water abstraction for public water supplies. Surface water sources covered 25% of water demand, and the remaining 10% of water intended for human consumption comes from other sources, such as water desalination [11]. Climate change affects both the quantity and quality of groundwater through the interplay between pollution and excessive water abstraction. According to Eurostat data [12], renewable freshwater resources in EU countries decreased by 289,607.0 million·m^3 (8%) in the period 2020–2022 compared to the average value from 2013–2019. The deepening impact of climate change includes an increase in mean sea level and storm surges, leading to seawater intrusion into coastal groundwater aquifers [13]. Additionally, it is estimated that climate change will not only increase the demand for water for crop irrigation in Europe but also lead to an increased demand for drinking water. Water shortages in Europe are a reality, with intense droughts causing economic damage worth up to EUR 9 billion per year and additional immeasurable damage to ecosystems [11]. Therefore, if long-term droughts persist, the continuity of water supplies intended for human consumption may be particularly exposed to fluctuations in the water balance.

The reports from the Institute of Meteorology and Water Management - National Research Institute indicated any issues of hydrogeological drought in Poland since 2015 [14]. According to the Plan for Mitigating the Effects of Drought [15], there is an increasing risk of drought in Poland, primarily driven by rising daily temperatures and a higher frequency of heavy rainfall events. The climatic water balance for the summer and autumn seasons has deteriorated. From a spatial perspective, at the national level, a decrease in the risk of atmospheric and agricultural drought is anticipated in some mountainous regions, while an increase in drought risk is expected in other parts of the country. In 38.95% of river basin areas, the utilization of surface water resources can be considered normal, in 37.50% of river basin areas, this utilization is intensive, and in 23.55%, it is very intense. Analyses of the effects of climate change conducted in 2021 revealed that in Poland, 37.80% of agricultural and forest areas face an extremely high risk of agricultural drought. When combined with areas at moderate risk (7.72%), as much as 45.52% of agricultural and forest areas are significantly threatened by agricultural drought. This could exert

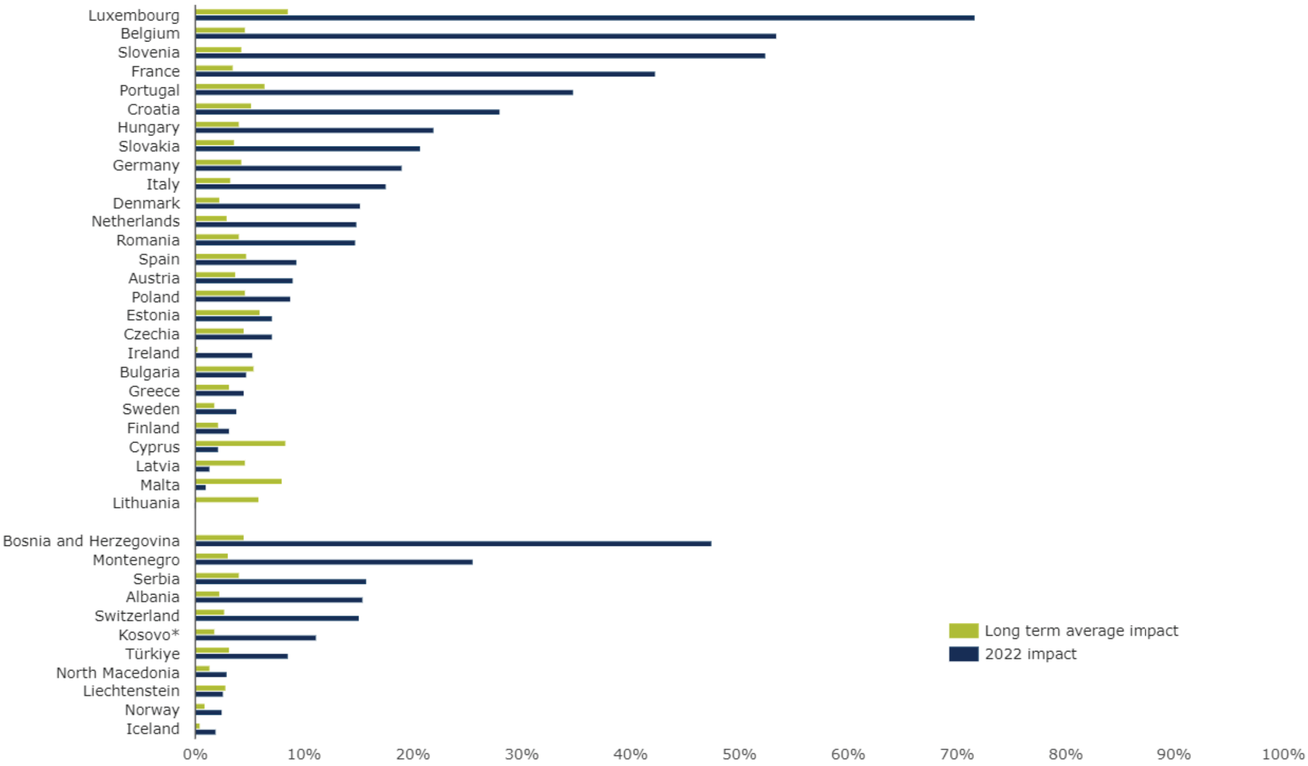


Fig. 1. Drought impact area during 2022 in comparison to the 2000–2020 average drought impact, in % of the country territory [10].

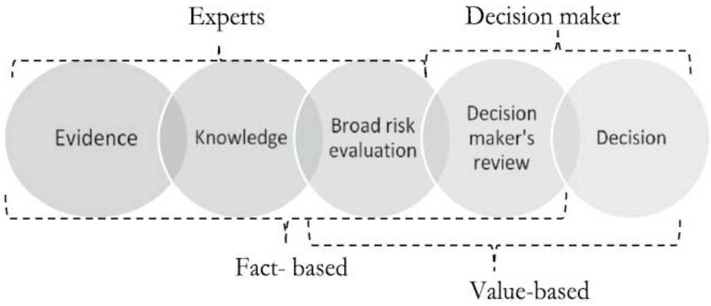


Fig. 2. Risk management model linking the various stages in risk analysis informs three key questions in decision-making [43].

substantial pressure on water resources and increase competition for them, involving both agriculture and entities supplying water to the population [16].

Climate change, which affects the availability of resources for providing the population with safe drinking water, underscores the necessity of implementing risk management procedures in the operation of water supply facilities, including the abstraction areas for water intake. For over 20 y, the World Health Organization has recommended an approach to water safety based on risk management across the entire water supply chain, from abstraction areas to the consumer's tap. This approach led to the revision of Directive 98/83/EC (Drinking Water Directive DWD) in 2015 and the adoption of a new directive on the quality of water intended for human consumption (DWD 2020/2184) by the European Parliament and the Council of Europe in January 2021 [17]. In Poland, this legislation is still in the process of implementation. The objective of the new drinking water directive is to safeguard the health of water consumers by implementing prevention actions based on risk management procedures in water supply systems. The literature review revealed that risk management encompasses various tools for identifying, assessing, controlling, and monitoring potential threats to the supply of safe water (Table 2).

The risk management process in WSS is highly complex, encompassing the entire water supply chain according to the new DWD. The primary objective in effectively managing the risk of supplying safe water to consumers is to implement preventive actions through a system of multi-barriers, identifying numerous threats based on expert knowledge and archival data (Fig. 2: Experts and Fact-based). This system enables the ongoing collection of key operational data and information on the dynamic variability of system operating conditions, continuous risk analysis, and the making of rational decisions (Fig. 2: Value-based and Decision maker). Therefore, integrating a risk analysis tool into everyday water supply practices as part of the Decision Support System (DSS) becomes a practical tool that supports management staff and WSS operators in making informed decisions.

One of the elements for enhancing the operational safety of water supply systems is the diversification of water supply sources, which is a fundamental protective barrier for the operation of WSS. The diversification of the water intake system to provide water to a settlement unit is becoming increasingly important in the face of existing and deepening climate changes. The result of climate change is the observed dynamic shifts in surface and groundwater resources, leading to significant limitations in the availability of resources intended for supplying water to the population. In assessing the rational level of water source diversification in the WSS, safety analyses utilize the dispersion index according to Pielou [64–66], enabling an analysis of the continuity of water supplies to consumers. Also known as the Pielou uniformity index [67], the Pielou dispersion index is a statistical measure of evenness (dispersion) used in ecology and various fields. This indicator measures how evenly different species are represented in a given community or ecosystem. Therefore, it has found wide application in various fields:

- Ecology: to assess the balance of species in a given ecosystem [67–69].
- Resource management in agriculture, forestry, and fishing: assessing the impact of various species on the total resource [70–72].
- Economics: for analyzing the uniformity of customers and products in a business context [73].
- Biology and medicine: in the analysis of genetic diversity or bacterial composition in biological samples [74–77].

The Pielou index is used in various fields to evaluate evenness or diversity in communities, providing a better understanding of the structure of a given system. However, it is not yet a widely used method in examining the stability of water supply and sewage systems. Only a few examples of the Pielou index's application in sanitary engineering research can be found in the literature [64–66,78–82]. The literature review revealed that, aside from Rak et al. [64–66], the Pielou index, a measure of uniformity, is not directly employed in the risk management of WSS. However, the concept of uniformity assessed by this indicator can be related to specific aspects of risk management in WSS as a tool in analyses of:

- Uniform exploitation of water supply sources to minimize risks associated with their unavailability or potential water shortages in specific areas.
- Uniform distribution of the water supply network to minimize the risk of failures or damages in one area, ensuring the continuity of water supply.
- Uniform distribution of funds in risk management, interpreted as the equal allocation of resources and

Table 2
Hazard analysis instruments in risk management in water supply systems

Rist analysis methods	Level of application in WSS structure/Risk assessment stage	References
Hazard and operability study (HAZOP)	All levels/Hazard identification and risk assessment	Jüttner et al. [18]; Marhavilas et al. [19]; Mohammadfam et al. [20]; Sikandar et al. [21]; Kletz [22].
Coarse risk analysis (CRA)	All levels/Hazard identification and risk assessment	Jüttner et al. [18]; Hansson and Aven [23].
Fault tree analysis (FTA)	Mainly water treatment/Hazard identification and risk assessment	Hauptmanns et al. [24]; Tchórzewska-Cieślak et al. [25]; Boryczko et al. [26]; Lindhe et al. [27]; Abedzadeh et al. [28].
Even tree analysis (ETA)	All levels/Hazard identification and risk assessment	Beim and Hobbs [29]; Yang et al. [30]; Zimoch et al. [31]; Santos et al. [32]; Rosqvist et al. [33]; Ezell et al. [34]; Doménech et al. [35].
Failure mode and effect analysis (FMEA)	Mainly water treatment/Hazard identification and risk assessment	Gheibi et al. [36]; Hwang et al. [37].
Geographic information system (GIS)	Mainly catchment area/Hazard identification and risk assessment	Doyle and Grabinsky et al. [38]; Booth and Rogers et al. [39]; Zimoch and Paciej et al. [40]; Zimoch and Paciej et al. [41]; Zimoch [42].
Markov analysis	Water treatment	Mpindou et al. [43]; Fu et al. [44]; Chiam et al. [45]; Shi et al. [46]; Sempewo and Kyokaali et al. [47]; Li et al. [48]; Zhang et al. [49].
Monte Carlo simulation	All levels/Hazard identification and risk assessment	Goharian et al. [50]; Tabesh et al. [51]; Barbeau et al. [52].
Quantitative microbial risk assessment (QMRA)	Water quality/Hazard identification, risk assessment and assessment	Medema et al. [53]; Schijven et al. [54]; Kenza et al. [55]; Petterson [56].
Risk matrix	All levels/Hazard identification and risk assessment	Lane and Hrudey [57]; Nunes et al. [58]; Rak et al. [59]; Budiyono et al. [60]; Zimoch and Paciej [41]; Zimoch and Paciej et al. [61]; Zimoch and Paciej et al. [62]; Rucka and Suchanek et al. [63].

Fig. 3. Location of the city of Głubczyce, south-western Poland.

protective barriers within WSS risk management. This approach may help in effectively responding to various threats, such as failures, pollution, or changing climate conditions.

In practice, the direct application of the Pielou index to the risk management of water supply systems is limited. However, the concept of equity can be an element of a comprehensive approach to sustainable and effective risk management in water supply. Taking into account the above the aim of this article is to analyze the efficiency of the intakes that make up the power supply system for the municipal water supply system in the city of Głubczyce, located in the southwestern part of Poland. This analysis serves as the basis for assessing the degree of diversification of water supplies to consumers and ensuring the integrity of the WSS.

2. Research object

The city of Głubczyce is situated in the southern part of the Opole Province in south-western part of Poland (Fig. 3).

The city covers an area of 12.52 km^2 and is home to over 12,000 residents. The water supply system in Głubczyce comprises a Water Production Subsystem (including water intake and transport), a water storage subsystem, and a water distribution subsystem. The operation of the collective water supply system in the city of Głubczyce is based on four water intakes with variable daily capacity (Fig. 4) and three reserve and equalizing tanks, which together form the municipal water supply system (MWSS).

The Powstańców intake contributes the largest share to the water supply of the MWSS, meeting up to 70% of the total water demand, while the Basen intake has a smaller local share. In 2022, during the drought, there was a significant reduction in the efficiency of the Mickiewicza intake (54%) and the Basen intake (90%), which operated for only 287 and 86 d a year, respectively (Table 3). Additionally, urban intakes supply water to 23 rural towns included in the system (Table 4).

The municipal water supply system (Fig. 5) has two Water Production Subsystems, WPSs Kołłątaja and WPSs Powstańców (Table 4), which pump water into the water supply network, comprising the municipal water distribution subsystem (MDSs). The operation of the Water Production Subsystem in the city (Table 4) is based on the operation of 4 independent water intakes, from which the Kołłątaja intake takes deep water for the operational needs of the WPSs Kołłątaja. On the other hand, the intakes at Powstańców, Mickiewicza and "Basen" work in an integrated system forming WPSs Powstańców. Although the "Basen" intake uses deep water resources mainly for the needs of the municipal swimming pool, in the event of a crisis or emergency, it also supplies the municipal network. The water captured in WPSs Powstańców is directed to two storage tanks with a volume of 1,000 m^3 each other, from where it is pumped to the water supply network. In the event of an emergency, it is possible to turn off the water storage tanks and pump water directly to the municipal system.

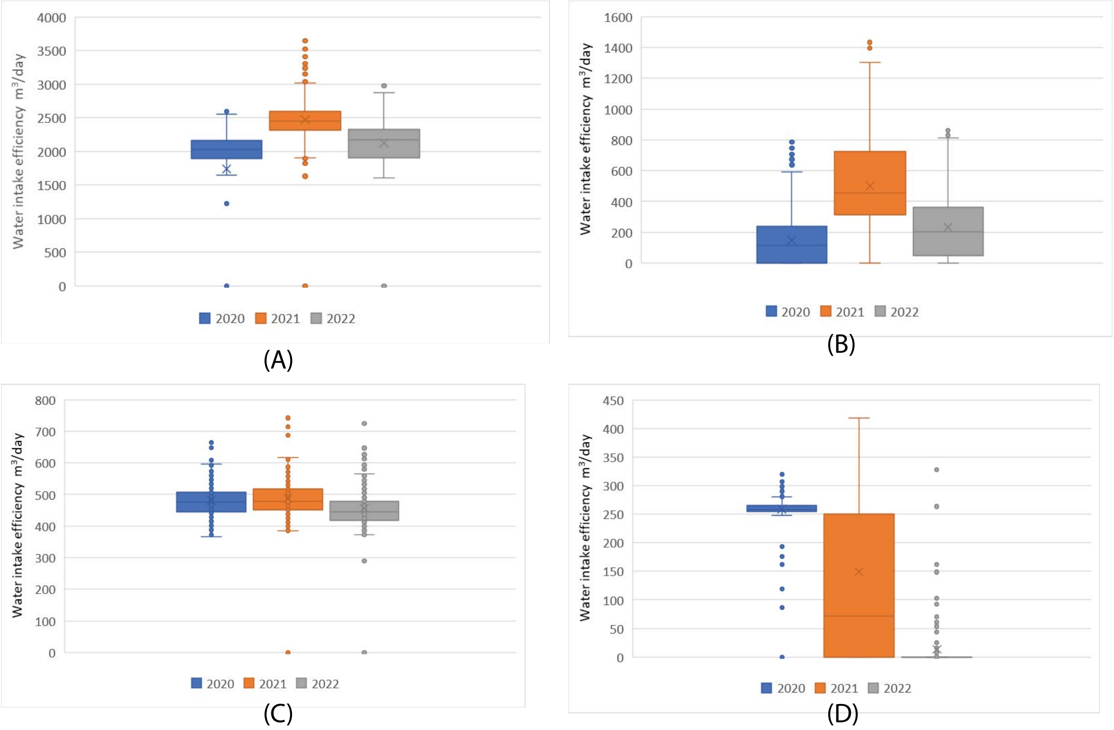
The technical infrastructure of WPSs Kołłątaja, on the other hand, includes a reserve equalizing tank with a capacity of 680 m^3, from which water is directed to the water pumping room and then to the municipal water distribution system. Storage tanks secure water supplies in the event of a crisis in the water supply network.

The total length of the water pipe network in the city of Głubczyce amounts to 52.5 km, with the dominant distribution network being 33.6 km, which constitutes 64% of the total length of the water pipes in the city. A full description of the water supply infrastructure in the city of Głubczyce, taking into account the type of network, length, percentage share in the total structure, as well as the number of water supply connections is presented in Table 5.

3. Research methods

The study analysed the emergency situations caused by the occurrence of failures in individual supply systems. In the research part, unit indicators of water demand were used for calculations, taking into account the average daily water consumption, according to the following criteria [84]:

- amount of water related to human physiology: q_{ph} = 2.5 L/Inh·d;
- minimum amount of water for a few days: q_{min} = 7.5 L/Inh·d;
- necessary amount of water for a period of several weeks: q_{nec} = 15 L/Inh·d;



(A) (B) (C) (D)

Fig. 4. Variability of intake capacity of the municipal water supply system in Głubczyce in 2020–2023. (A) Powstańców water intake, (B) Mickiewicza water intake, (C) Kołłątaja water intake, and (D) Basen water intake

Table 3
Efficiency characteristics of the municipal water supply system in Głubczyce city

	Period	Municipal water supply system – water intake			
		Powstańców	Mickiewicza	Kołłątaja	Basen
Number of towns supplied		23, including the town of Głubczyce			
Number of days of operation per year	2020	366	249	366	366
	2021	365	362	365	287
	2022	365	287	364	86
Average daily water production in 2020–2023 (m³/d)		2,118.00	295.00	476.00	155.00
Total annual water production (m³/y)	2020	637,059.00	54,695.00	175,992.00	94,630.00
	2021	903,500.00	183,368.00	177,904.00	54,601.00
	2022	778,500.00	84,636.00	167,149.00	20,825.00
Percentage share in the total production structure in years 2020–2023 (%)		70	10	15	5
Average daily water consumption in Głubczyce city (m³/d)	2020	1,745.00	150.00	482.00	259.00
	2021	2,475.00	502.00	487.00	150.00
	2022	2,133.00	232.00	458.00	57.00
Average annual water demand in rural communes (m³/y)	2020	254,958.00	–	–	–
	2021	361,591.00	–	–	–
	2022	311,565.00	–	–	–

Table 4
Characteristics of water intakes in the municipal water supply system

	Period	Water Production Subsystem	
		Powstańców	Kołłątaja
Water intakes		Mickiewicza, Powstańców, Basen	Kołłątaja
Maximum daily efficiency (m^3/d)	2020–2022	5,496.00	720.00
Average daily water production (m^3/d)	2020–2022	2,567.87	475.84
	2020	2,154.48	482.17
	2021	3,127.31	487.41
	2022	2,421.81	457.94
Production efficiency reserves (m^3/d)	2020–2022	2,928.13	244.16
	2020	3,341.52	237.83
	2021	2,368.69	232.59
	2022	3,074.19	262.06
Average daily water production for WPSs (m^3/d)	2020–2022	1,438.01	233.16
	2020	1,206.51	236.26
	2021	1,751.29	238.83
	2022	1,356.21	234.39
Volume of reserve and equalizing tanks (m^3)		V_1: 1,000 V_2: 1,000	V_3: 680
Water supply area (%)		Głubczyce city-56% of daily production	Głubczyce city-49% of daily production

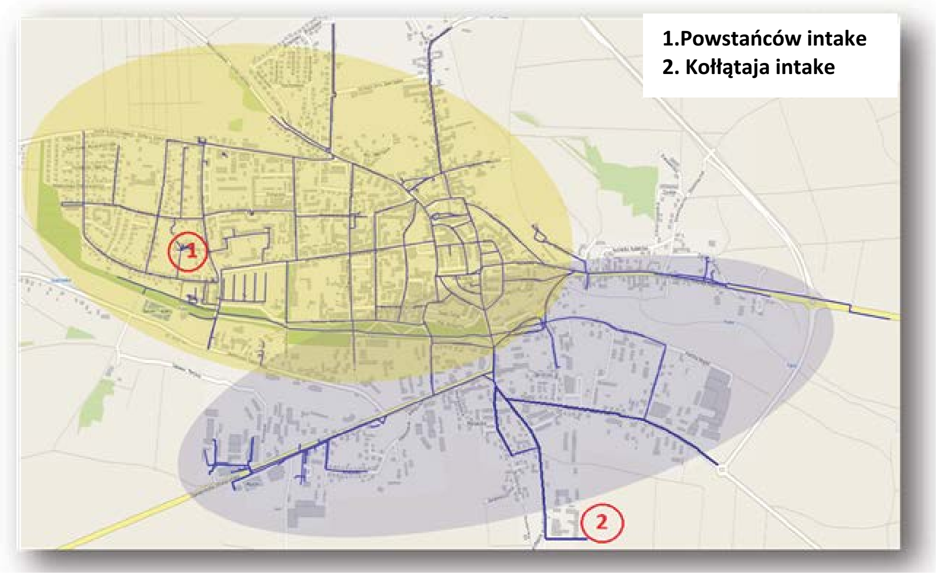


Fig. 5. Municipal water supply system of Głubczyce city.

Table 5
Characteristic of water pipe network in Głubczyce city

Type of water pipe network	Length (km)	Percentage in the total structure (%)	Number of water connections (pcs)
Main network	2.00	4%	
Distribution system	33.60	64%	1,476
Water supply connections	16.90	32%	
Sum	52.50		

- required amount of water in an emergency: $q_{\text{req}} = 30$ L/Inh·d.

The demand for water Q_{ph}, covering the physiological needs of water consumers was determined according to Eq. (1) [84]:

$$Q_{\text{ph}} = q_{\text{ph}} \cdot N_{\text{Inh}} \tag{1}$$

where q_{ph} - unit indicator of water demand for human physiological purposes [L/Inh·d], N_{Inh} - the number of inhabitants.

Evaluating the degree of diversification of water supply in the MWSS, a two-parameter assessment using an additive model was used, in which the two-parameter diversification index was determined from Eq. (2) [64–66,79–81]:

$$d_{\text{MWSS}}\left(\text{SW}\right) = d_{\text{SW}}\left(Q\right) + d_{\text{SW}}\left(V\right) \tag{2}$$

where d_{MWSS}(SW) - the two-parameter water supply diversification index in MWSS according to Shannon and Weaver, $d_{\text{SW}}(Q)$ - water intake diversification index, determined from Eq. (3), $d_{\text{sw}}(V)$ - index of diversification of the water volume accumulated in storage tanks, determined from Eq. (4).

The study adopted the following comparative scale for the d_{CWSS} index [64]:

- no diversification of d_{MWSS} £ 0.5
- low diversification $0.5 < d_{\text{MWSS}} \leq 1.0$
- average diversification $1.0 < d_{\text{MWSS}} \leq 1.7$
- sufficient diversification $1.7 < d_{\text{MWSS}} \leq 2.3$
- satisfactory diversification $d_{\text{MWSS}} > 2.3$.

While evaluating the diversification, the shares of water intakes in the MWSS in the two-parameter method, the value of the intake diversification index $d_{\text{SW}}(Q)$ and the water volume in storage tanks $d_{\text{SW}}(V)$ were determined based on the Shannon and Weaver diversification model from the following formulas [64,65,79]:

$$d_{\text{SW}}\left(Q\right) = -\sum_{j=1}^{m}\left(u_j\right)\cdot\left(\ln\left(u_j\right)\right) \tag{3}$$

$$d_{\text{SW}}\left(V\right) = -\sum_{k=1}^{s}\left(u_k\right)\cdot\left(\ln\left(u_k\right)\right) \tag{4}$$

where $d_{\text{SW}}(Q)$ and $d_{\text{SW}}(V)$ are defined in Eq. (2), u_j - share of the j-th WPSs capacity in the total water demand of the MWSS, m - number of WPSs, u_k - share of the k-th storage tank's volume in the total volume of network water storage tanks, s - number of network water storage tanks.

The research method also included a safety analysis regarding the continuity of water supply to the consumer, using the Pielou dispersion index. For the interpretation of the degree of diversification, the degree of dispersion of water supply to the consumer was taken into account, which was determined using Eq. (5) [64–66,79–81]:

$$d_p = \frac{-\sum_{i=1}^{n}\left(\ln\left(u_i\right)\right)}{\ln\left(n\right)} \tag{5}$$

where u_i - share of i-th elements in total the MWSS (0–1), n –number of elements in the MWSS.

In the research process, a two-parametric evaluation of the dispersion of water supply was carried out using the Pielou index, based on Eq. (6) [64,85]:

$$d_{\text{MWSS}}\left(P\right) = d_p\left(Q\right) + \alpha \cdot d_p\left(V\right) \tag{6}$$

where $d_{\text{MWSS}}(P)$ - two-parametric Pielou index of the dispersion of water supply in MWSS, $d_p(Q)$ - water resource dispersion index, according to Eq. (5), $d_p(V)$ - water volume dispersion index in storage tanks from Eq. (5), α - weight of the water volume allocation parameter in the MWSS.

The allocation parameter α is the ratio of the sum of the volumes of network water storage tanks to the sum of the production capacity of water intakes. The results were related to the categorisation and evaluation scale of water resources dispersion (Table 6).

4. Results and discussion

For the municipal system of collective water supply in the city of Głubczyce, a study of the degree of diversification of water supply to inhabitants was carried out using the Shannon–Weaver and Pielou two-parameter method. The individual shares were determined based on the daily production capacity of the water intakes and the volumes of the network storage water tanks.

4.1. Shannon–Weaver index for the city of Głubczyce

Using the shares of the four individual water intakes within the MWSS of Głubczyce (Table 7, from u_1 to u_4) in the total daily water production based on Eq. (3), the water intake diversification index was determined:

$$d_{\text{SW}}\left(Q\right) = -\begin{pmatrix} 0.69\ln\left(0.69\right) + 0.07\ln\left(0.07\right) \\ +0.15\ln\left(0.15\right) + 0.09\ln\left(0.09\right) \end{pmatrix} = 0.943 \tag{7}$$

Additionally, based on the shares of the volume of individual storage tanks within the MWSS (Table 7, from u_1 to u_3) and using Eq. (4), the indicator of water volume diversification in network storage tanks was determined:

$$d_{\text{SW}}\left(V\right) = -\begin{pmatrix} 0.38\ln\left(0.38\right) + 0.37\ln\left(0.37\right) \\ +0.25\ln\left(0.25\right) \end{pmatrix} = 1.082 \tag{8}$$

Table 6
Categorization and assessment scale of the degree of dispersion of water resources [85]

Dispersion category	Scale of the degree of dispersion
No dispersion	$d_{\text{MWSS}}(P) = 0$
Low dispersion	$0 < d_{\text{MWSS}}(P) \leq 1.5$
Average dispersion	$1.5 < d_{\text{MWSS}}(P) \leq 2.0$
Sufficient dispersion	$2.0 < d_{\text{MWSS}}(P) \leq 2.5$
Satisfactory dispersion	$2.5 < d_{\text{MWSS}}(P) \leq 3.0$

Table 7
Characteristics of the share of *i*-th elements in the total MWSS structure

Share parameter	Water intake of MWSS of Głubczyce			
	Powstańców	Mickiewicza	Kołłątaja	Basen
Q - shares in the total capacity u_i	$u_1 = 0.69$	$u_2 = 0.07$	$u_3 = 0.15$	$u_4 = 0.09$
V - shares in the total volume u_i	$u_1 = 0.38$ $u_2 = 0.37$	–	$u_3 = 0.25$	–

Table 8
Analysis of the possibility of water supply depending on the occurrence of a given scenario of a crisis situation

Scenario	Average daily water consumption (m³/d)	Capacity of intake (m³/d)				Balance (m³/d)	Result
		Powstańców	Kołłątaja	Mickiewicza	Basen		
Scenario I	1,617.01	0.00	720.00	220.00	258.00	–419.01	Need to use an alternative method of water supply
Scenario II		5,496.00	0.00	220.00	258.00	4,356.99	Water supply provided
Scenario III		5,496.00	720.00	0.00	258.00	4,856.99	Water supply provided
Scenario IV		5,496.00	720.00	220.0	0.00	4,818.99	Water supply provided

Consequently, the two-parameter water supply diversification Shannon and Weaver's index in the MWSS of Głubczyce city, as determined from Eq. (2), has achieved a value:

$$d_{\text{MWSS}}(\text{SW}) = 0.943 + 1.082 = 2.025 \tag{9}$$

Based on the adopted scale of the two-parameter diversification Shannon and Weaver's index in the municipal water supply system of Głubczyce city, the diversification level of water resources was found to be sufficient.

4.2. Dispersion Pielou index for the city of Głubczyce

Based on the efficiency shares of the four independent water intakes in MWSS Głubczyce and the shares of individual volumes of water in storage tanks (Table 7), the degree of dispersion of water supplies to the consumer, d_p, was determined using Eq. (5):

Q of water intakes:

$$d_p(Q) = \frac{-\begin{pmatrix} 0.69\ln(0.69) + 0.07\ln(0.07) \\ +0.15\ln(0.15) + 0.09\ln(0.09) \end{pmatrix}}{\ln 4} \tag{10}$$

V of stored water reserve and equalizing tanks:

$$d_p(V) = \frac{-\begin{pmatrix} 0.38\ln(0.38) + 0.37\ln(0.37) \\ +0.25\ln(0.25) \end{pmatrix}}{\ln 3} = 0.985 \tag{11}$$

The calculation assumed a parameter weight of $\alpha = 0.88$ and the two-parameter diversification Pielou index of water supply in the WSS was determined according to Eq. (6):

$$d_{\text{CWSS}}(P) = 0.680 + 0.88 \cdot 0.985 = 1.547 \tag{12}$$

The dispersion category according to Pielou for the city of Głubczyce was defined as average dispersion. The result obtained means that upgrades or extensions to the system should be carried out in order to maintain continuity of operations in the event of an emergency. So far, the lack of events that were considered impossible, and thus apparent safety, should not dull the vigilance of the operators of municipal water supply systems, who should strive for a justifiably high diversification of water resources.

During the study, 4 scenarios of the occurrence of a crisis situation causing drinking water supply interruption in the city of Głubczyce was analysed:

- Scenario I: failure on the Powstańców intake,
- Scenario II: failure on the Kołłątaja intake,
- Scenario III: failure on the Mickiewicza intake,
- Scenario IV: failure on the Basen intake.

The results of the emergency analyses based on failures of individual supply systems, taking into account unit indicators of water demand, together with the average daily water consumption, are presented in Table 8.

The results of the analyses showed that in the event of an emergency at the Kołłątaja intake (Scenario II), the Mickiewicza intake (Scenario III) and the Basen intake (Scenario IV), the continuity of water supply in MWSS of Głubczyce will be ensured by taking over the entire water production by the Powstańców intake.

In the event of a failure at the Powstańców water intake, due to the lack of possibility to fully cover the water supply by another active intakes, an additional analysis was carried out taking into account the required water demand, amounting to Q_{req} = 360 m³/d. This scenario does not allow for the supply of water to the all inhabitants of the city,

Table 9
Results of analysis taking into account the unit indicator of the required water demand for Scenario I

Scenario I	Required water demand Q_{req} (m^3/d)	Alternative water intakes	5 L bottles (pcs)	Water cisterns with a capacity of 5 m^3 (pcs)
	360	Mickiewicza intake (220 m^3/d)	4,000	4
	360	Basen intake (258 m^3/d)	0	4

therefore, it takes into account the amount of unit water demand at the level of the required daily water consumption in an emergency (q_{req} = 30 L/Inh·d). The analysis taking into account the unit indicator of the required water demand in the event of Scenario I is presented in Table 9.

The results of the conducted analysis indicate that in the event of a failure at the Powstańców water intake, it is necessary to use water bottles, in the case of using the alternative Mickiewicza intake, in the amount of 4,000 bottles/d and 4 water cisterns/d. However, if the alternative water intake "Basen" is used, it is necessary to use an additional 4 water cisterns/d. The analysis of the results showed that it is justified to purchase 4 cisterns for drinking water or sign a contract with a potential supplier of water cisterns for the duration of an emergency in the water intake.

5. Conclusion

- One of the elements of increasing the operational safety of the MWSS is the diversification of water supplies to the consumer. It ensures the continuity of water delivery to consumers in the event of emergencies on the water supply infrastructure. Diversification of the water intake system for supplying the population with water is becoming increasingly important in view of existing and worsening climate change. The effect of climate change is the observed dynamics of changes in surface and groundwater resources, which results in significant reductions in the available resources for supplying the population with water.
- The dimensionless values of the Pielou index, serving as an indicator of the degree of diversification, provide a universal measure for comparing and assessing all WSS, irrespective of their structure, size, or the number of inhabitants supplied. This method holds particular significance for small WSSs with a limited number of intakes, as it facilitates the determination of the level of alternative water supplies using cisterns or packaged water.
- The outcomes of the analysis of diversification levels, employing the Pielou index, can serve as a compelling argument for water supply system managers to prioritize the imperative for ongoing diversification of water sources. Furthermore, emphasis is placed on the inclusion of the allocation parameter α in evaluating the capacity of water in network reservoirs, advocating for the incorporation of emergency water reservoir volumes. Consequently, the conducted research underscores the significance of maintaining a balanced proportion of abstracted water from different sources relative to the overall water demand.
- The conducted analysis of the continuity of water supply to the inhabitants of Głubczyce city showed that only in the event of a failure at the Powstańców water intake, alternative supplies of drinking water should be provided by means of water cisterns and drinking water bottles.
- The analysis of the results showed that it is justified to purchase 4 drinking water cisterns or sign a contract with a potential supplier of cisterns for the duration of an emergency in the water intake.
- The results of the analysis carried out according to the Pielou index ($d_{MWSS}(P)$ = 1.547) showed that it is necessary to modernize or expand the collective water supply system in order to maintain operation continuity in the event of an emergency.

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