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Microbiological safety of water in the risk management of operating water supply systems – a case study of Silesia, Poland

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ABSTRACT

According to Directive 2020/2184, each water supplier is required to develop a water supply risk management system, such as the World Health Organization's recommended Water Safety Plan, implement it and apply it to daily water supply practices. An important element of risk management in water supply systems (WSS) is to ensure the supply of water that is healthy and clean, that is, free of all microorganisms and parasites and any substances in quantities or concentrations that pose a potential danger to human health. Ensuring the microbiological safety of water, while minimizing the risks associated with disinfection by-products, is particularly important in extensive WSS, where water can take days to transport, and where hydraulic parameters and sediments deposited in water supply networks favor the growth of microorganisms. This paper proposes an analytical method to support the determination of areas sensitive to the loss of microbiological safety of water, while using the model to optimize the dose of disinfectant at water treatment plants and water chlorination points in the distribution subsystem. The developed methodology is part of a review of operating procedures, especially with regard to minimizing the risk of secondary microbiological contamination of water. The research model took into account the chemical as well as microbiological variability of water quality, its age, and the operational data of the WSS operation collected by the Geographic Information System (location of water quality monitoring points, spatial location of water supply infrastructure facilities), as well as the size of the population potentially exposed to water of uncertain microbiological quality. The result of the analyses is a spatial interpretation of the loss of microbiological safety of water presented in the form of risk maps.

Keywords: Water Safety Plans; Risk; Microbiological risk; Water supply system; Geographic Information System; Risk maps

1. Introduction

On May 10, 2012, the Right2Water initiative was registered, whose full name reads "Access to water and sanitation is a human right! Water is a public good, not a commodity!". The initiative called on the European Commission to submit draft legislation implementing the UN-recognized human right to water and sanitation infrastructure that promotes water supply and sanitation services as an accessible basic public service for all and the World Health Organization-promoted risk management approach to water safety. More than 1.6 million EU citizens have supported this initiative [1]. The end result of all the activities resulting from this initiative was the passing of Directive 2020/2184 on the quality of water intended for human consumption by the European Parliament and Council (EU) on December 16, 2020. The provisions contained therein change the approach to management, including the conduct of operation of water supply systems and the rules for conducting supervision in the field of health safety of consumers

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of water intended for human consumption [2]. The implementation of this directive in daily water supply practices necessitates a change in the approach to operating collective supply systems. An obligation to manage water supplies with risk assessment throughout the water supply chain from intake to tap at the consumer has been introduced. The World Health Organization has developed a strategy for a comprehensive approach to water safety management with guidelines to enable its implementation called the Water Safety Plan [3,4]. The literature on water supply risk management is extensive. It includes both descriptions of methods and proposed examples of a systematic approach to risk analysis and assessment [5–21].

Both the European Union in its Directive 2020/2184 on the quality of drinking water [2] and the World Health Organization (WHO) in its documents on drinking water safety [3,21] define the overarching goal of providing consumers with safe and clean water. The directive focuses on this aspect while completely overlooking issues related to the organization of water supply and provision of water services, as well as the aspect of public health management itself, such as prevention or the development of outbreaks and management of epidemics, in the context of water-related environmental health risks. Knowledge of waterborne diseases and how to prevent them is steadily increasing due to improved analytical capabilities and systematic data collection and analysis. The U.S. Center for Disease Control and Prevention (CDC), which has been collecting and analyzing the data on water-related diseases since 1971, has played a special role in analyzing them. The CDC is constantly expanding the scope of analysis to include not only new risks but also socioeconomic aspects (medical costs, absenteeism, etc.). Previously, it produced reports every few years; since 2015, the data has been entered into the National Outbreak Reporting System [22]. The system analyzes all cases and outbreaks of epidemic diseases transmitted by various routes (through food, water, animals, between individuals, from the environment and by unspecified means). Analysis of these data (Table 1) shows, for example, that a total of 1,000 outbreaks (17,125 cases) of waterborne disease were reported to the system between 2011 and 2021, accounting for only 1.67% of all reported outbreaks (0.83% of reported cases). 2,109 cases of water-related diseases required hospitalization, accounted for as much as 4.90% of all hospitalizations (43,023). There were 217 deaths from water-related diseases, accounting for as much as 9.43% of all deaths reported to the disease system.

Data presented on the CDC website [22] also shows that the top 5 causes of drinking water-related epidemics in the US from 1971 to 2020 are: Legionella, Giardia, Norovirus, Shigella, Campylobakter. None of these microorganisms are monitored in accordance with current regulations. Detecting these diseases and determining whether they have been transmitted through water is only possible through efficient epidemiological surveillance. This surveillance should take into account not only reported cases but also reports from pharmacies indicating an increase in anti-diarrheal drug sales in a specific area.

Table 1
List of characteristics of waterborne epidemics for 2011–2021 [22]

Years 2011–2021	Reported water-related diseases - (A)	All reported diseases - (B)	% A in B
Outbreaks	1,000	59,736	1.67
Disease cases	17,125	2,068,586	0.83
Hospitalizations	2,109	43,023	4.90
Deaths	217	2,300	9.43

The approach to waterborne disease analysis represented by the US CDC, is in line with the 2011 WHO recommendations for conducting waterborne disease surveillance: policy guidance on water-related disease surveillance and technical guidance on water-related disease surveillance, prepared by the Regional Office for Europe of the WHO. Unfortunately, there is a lack of studies on water-related diseases in Poland, which does not facilitate a consistent assessment of how water supplies are implemented and the adequacy of measures taken by the National Sanitary Inspectorate authorities to minimize health risks in drinking water.

One of the serious operational problems of water supply system (WSS) is ensuring the microbiological safety of the water. The applied disinfection of water injected into the network at treatment stations should effectively ensure the microbiological safety of the water not only at the point of supply to the water network, but throughout the distribution subsystem. Ensuring the microbiological stability of water is a particularly difficult operational task in extensive water supply systems, where water is transported over considerable distances over long periods of time, accompanied by potential secondary water contamination events [23–27]. One effective protective barrier in managing the risk of loss of microbiological water quality are spatial risk analyses. These analyses allow the designation of critical areas where water chlorination points should be implemented, along with the intensification of measures to control the microbiological quality of tap water and at the consumer.

Performing an analysis and spatial assessment of water supply risk, especially in WSS with high daily water demand and extensive distribution subsystems, requires access to and aggregation of large amounts of data, including, among others: technical parameters of WSS infrastructure, water quality studies, data on consumer interventions on water quality, WSS failure rate (loss of integrity), results of measurements of hydraulic as well as quality parameters made in real-time mode (online monitoring), etc. To collect this data and analyze it, and to use the results in the daily operation of water supply infrastructure, modern IT tools are essential. One such tool is Geographic Information Systems (GIS), which can be a component of integrating various data sources. In addition, they allow to analyze spatial locations and develop information layers for visualization through maps. Thus, analyses using GIS tools provide deeper insights into the data, allow one to create patterns, explore relationships and assess the state of operation of the WSS for different operating conditions. Through complex, multi-criteria analysis and visualization of the spatial distribution of a given piece of information, GIS tools are part of the Decision Support System (DSS) that supports the WSS operator in making informed rational decisions [28–30]. GIS systems have proven their usefulness in analyzing environmental pollution issues and water quality impacts [11,30,31]. There are also studies on waterborne diseases in the water supply system [32,33]. It is therefore reasonable to implement and interconnect the capabilities of GIS systems with methods for analyzing and assessing the risk of water supply to consumers throughout the water supply chain. The risk maps should be used to verify the operational parameters of the operation of the WSS and should be part of the DSS system in managing the safety of water supply to the consumer.

The purpose of this article is to present an innovative method for delineating areas susceptible to loss of microbiological safety of water with their spatial presentation in the form of risk maps. The developed tool for spatial risk analysis to ensure microbiological stability takes into account both the model of optimization of disinfectant doses at water treatment stations as well as at water chlorination points in the distribution subsystem. The developed tool has been implemented in assessing the risk of losing the microbiological safety of water supplied to residents of the Silesian agglomeration in southern Poland.

2. Study area

The water supply of the agglomerations of the Upper Silesian Industrial District and the Rybnik Coal District is carried out by the largest wholesale water supplier in Poland and Europe (Fig. 1), that is, Upper Silesian Waterworks Company (USWC), located in Katowice City. This company, in cooperation with local water supply companies, supplies water to nearly 3.5 million residents of Silesia (66 municipalities) and Lesser Poland (3 municipalities) [34]. The beginnings of the construction of the current water supply system for the residents of the Silesian agglomeration date back to the end of the 19th century, and the strategy of its development was strongly determined by industrialization of the region, including mining and metallurgical activities. Today, the water supply system is made up of 6 surface water intake subsystems, 4 groundwater intake subsystems, accounting for 10 water treatment subsystems, and a ring water distribution subsystem as well as 7 water storage tanks and 2 pumping stations (Fig. 1).

Surface water resources account for a significant share of total production (79%). The current average daily water

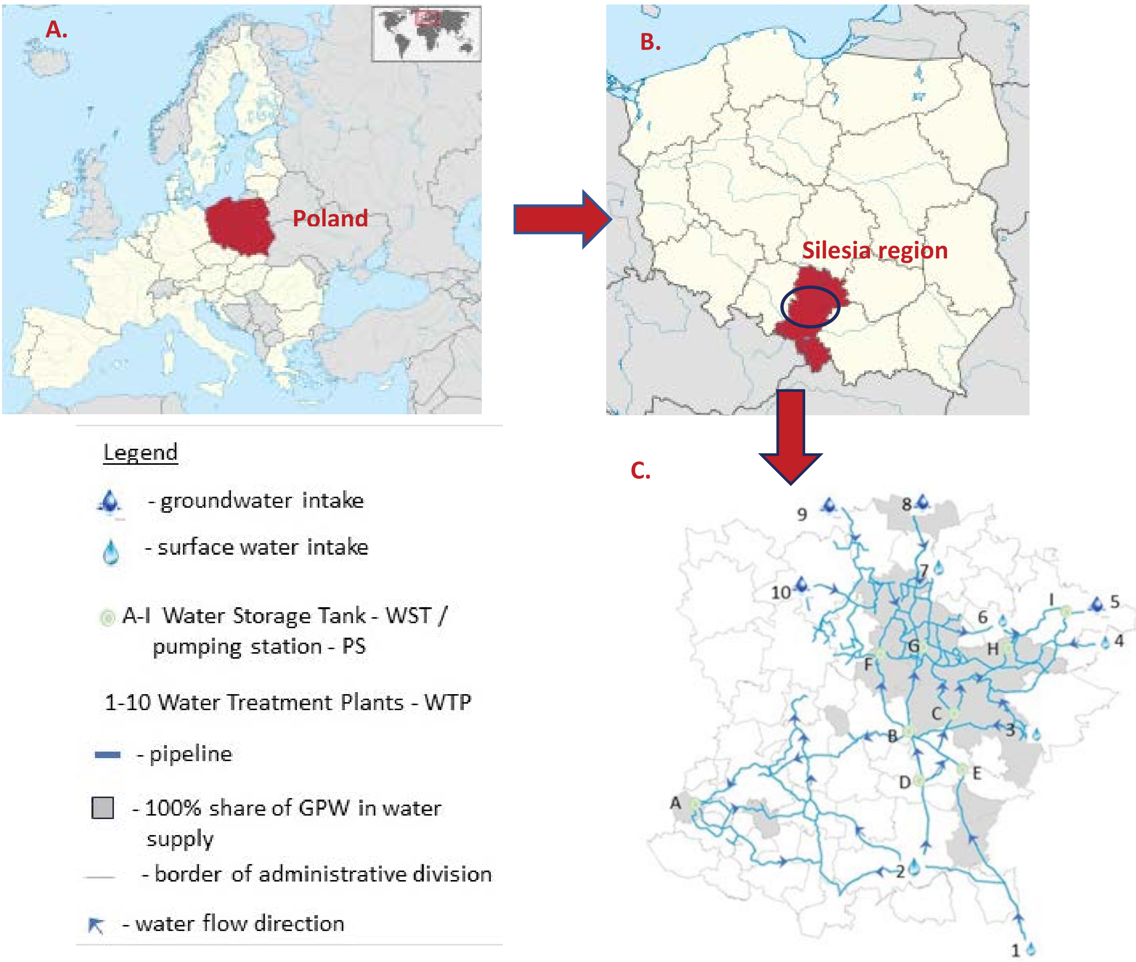

Fig. 1. Spatial structure of the water supply system for the inhabitants of Silesia, southern Poland; Surface water intakes: 1-Czaniec, 2-Goczałkowice, 3-Dziećkowice, 4-Maczki, 6-Będzin, 7-Kozłowa Góra; Groundwater intakes: 5-Łazy, 8-Bibiela, 9-Miedary, 10-Zawada; WST: A-Pszów, B-Mikołów, C-Murcki, F-Czarny Las, G-Góra Wyzwolenia, H-Zagórze, I-Łosień, PS: D-Paprocany, E-Urbanowice.

production is about 300 thousand m^3. The water production subsystem operates high efficient process lines, including coagulation, filtration on anthracite-sand rapid filters and activated carbon beds. These technologies ensure a high level of water treatment efficiency, guaranteeing both chemical and microbiological stability. The water utility supplies water to municipalities where there are no other water sources (gray regions on Fig. 1C.) At the same time, there are cities in Silesia that only partially cover the demand for water from USWC intakes. It can be assumed that in USWC's operational area, up to 85% of the population relies on water supplied by this water utility. A total of 864.2 km of trunk mains are used for transporting drinking water. This water supply infrastructure consists mainly of large-diameter pipes ranging from 1,800 to 500 mm, characterized by significant material diversity (Table 2).

The ring water distribution subsystem enables the company, in cooperation with local water supply companies, to ensure the safety of the region's water supply. No local water utility is able to supply drinking water to remote areas of Upper Silesia in the event of an emergency or natural disaster. In addition to pipelines, the water distribution subsystem comprises 7 water storage tanks, with a total capacity of 276.000 m^3, and pumping stations (Table 3).

The quality of distributed water for human consumption is supervised by a total of 15 units of local official water quality control authorities, namely State District Sanitary Inspectors and 2 units of the organization at the provincial level in the area of two provinces, Silesia and Małopolska. In 2022, Upper Silesian Waterworks Company carried out internal control of the quality of water intended for human consumption in accordance with the requirements of the Regulation of the Minister of Health [35] in a total of more than 150 measurement points covering points located in the water distribution subsystem (mains, storage tanks), at water treatment plants at the point of injection into the network. Annually, about 2.500 samples for Group A parameters and more than 150 samples for Group B parameters are performed as part of internal control [35]. In addition, raw water quality tests are conducted in the catchment area, at points of intake from the environment and at control points on process lines. As part of operational monitoring, about 2.500 samples are taken annually at water treatment plants and within the distribution subsystem. This, in combination with sanitary monitoring, amounts to approximately 230.000 tests. Additionally, real-time monitoring stations measure turbidity and the concentration of residual chlorine in the water at selected points within storage tanks. The monitoring system built in this way makes it possible to constantly control the quality of produced and distributed water and, after the results of the water quality tests are transmitted, to issue a sanitary assessment of water quality. During the analyzed period of 2021–2022, the State Sanitary Inspection authorities issued assessments confirming the water's suitability for drinking supplied by the company. The water supplied by USWC is safe water for Silesian inhabitants.

Table 2
Material structure of the water supply network in 2022 [34]

Material	Share (%)
Steel	62.4
Grey cast iron	3.5
Ductile iron	10.2
Reinforced concrete	4.3
GFK	0.1
PE	19.5

3. IT system at Upper Silesian Waterworks Company

The IT system implemented at USWC consists of three integrally related levels of system structure. Due to the nature of its operations, USWC collects and aggregates a wide range of information and data on the operation of the water supply system. This includes data related to both operational states (normal operating states and incidents) and hydraulic and water quality parameters. Within the framework of information management, the company has (Fig. 2) data collection systems, which constitute a comprehensive structure for acquiring and archiving 1st level IT system data. These data encompass internal information, such as the billing system CIS (Customer Information

Table 3
Water storage tanks and pumping stations in the Silesian water supply systems [34]

Item	Water storage tank and pumping stations	Maximum capacity (thousand m^3)	Water outflow
1	F	38	Gravitational
2	G	20	Pumping
3	I	5	Gravitational
4	B	96	Gravitational – direction to the central part of Silesia, Pumping – direction to southwest direction of Silesia
5	C	27	Gravitational
6	D	25	Pumping
7	A	27	Gravitational
8	E	18	Gravitational
9	H	20	Gravitational

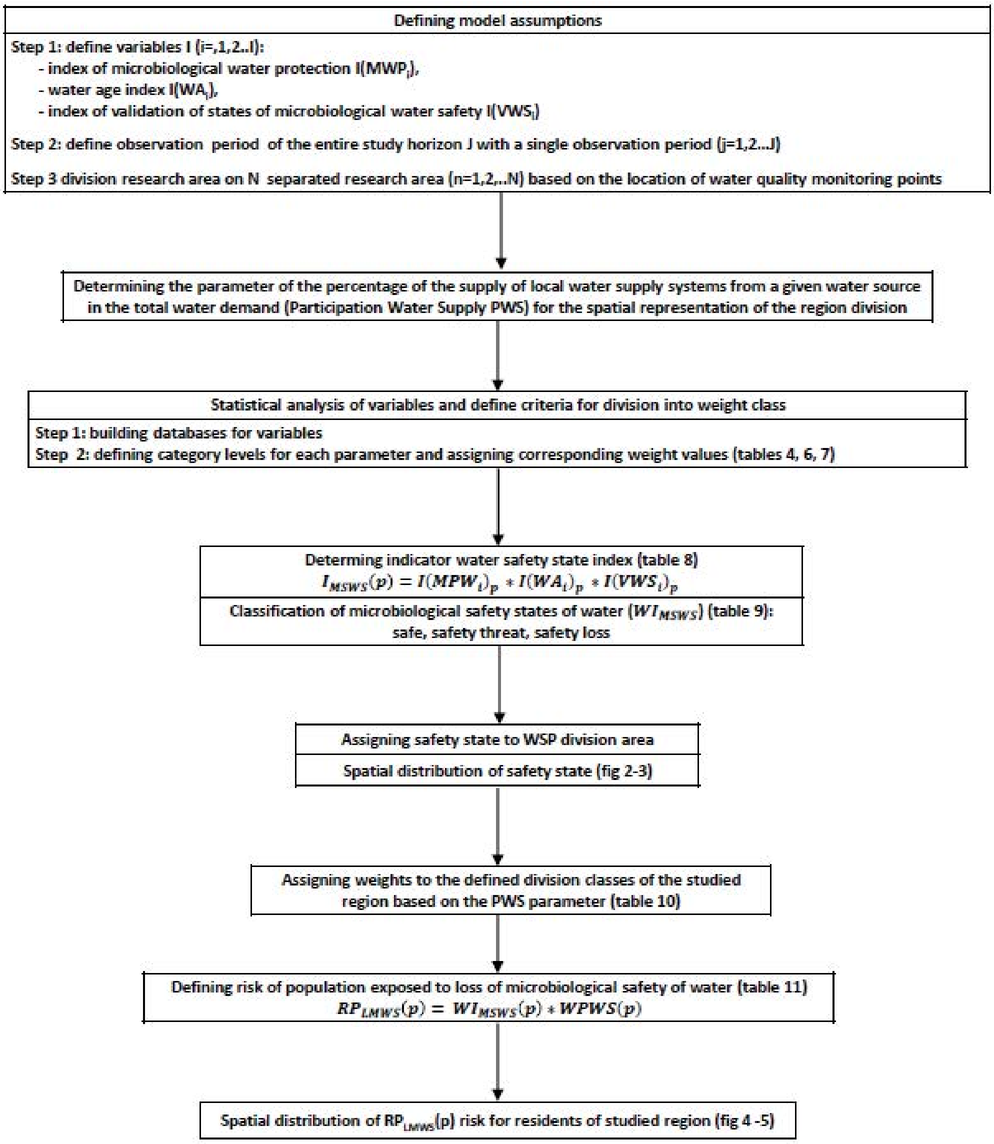

Fig. 2. Flowchart of spatial analysis for assessing the risk of population exposure to water with deteriorated microbiological quality - $RP_{LMWS}(p)$.

System), telemetry system SCADA (Supervisory Control and Data Acquisition), which covers measurements of flow, pressure, residual chlorine concentrations, and turbidity, as well as GIS for inventorying spatial data used for the identification of WSS infrastructure. This infrastructure includes technical characteristics of pipes, tanks, and pumping stations, as well as the location of water meters and measurement wells complete with their identifiers. In addition, the water treatment plants have individual local SCADA subsystems. The company also uses the LIMS (Laboratory Information Management System) to support laboratory operations. In addition, industry data is collected, such as a list of exceedances of parametric values of drinking water, a record of failures, and a record of the amount of water treatment chemicals dosed. Level I of the IT system structure used by the company for collection also collects transmissions from water meters and metering equipment built on the network, which are collected in a database system. The CIS consumer information system includes 739 water meters that record flow rates and pressure heights at specific intervals. The main SCADA system consists of 533 devices that record flows, pressures, reservoir water levels, residual chlorine concentration and water turbidity. The company also uses external data, for example, the TERYT address database, data sources EGiB (Land and Building Register), PRG (State Border Register), web services: WMS (Web Map Service, for example, orthophotomap) or WFS (Web Features Service).

Level II of the IT system, including the Integrated Information System, is utilized for managing spatial data and integrating both internal company data and externally acquired data. This IT level serves as the primary source of information for Level III, encompassing analytical modules: the hydraulic model, quality model, loss analysis model, and spatial analysis model. On the other hand, the implemented hydraulic model, which is a Level III component within IT system, undergoes continuous verification based on current data. This verification includes factors such as network repairs or alterations in the zoning of the water distribution subsystem.

Level III IT is used to perform simulations of the system's behavior under various operating states using a hydraulic model, a quality model and a water loss analysis model. It also allows for water quality analysis, including parameters like water age and residual chlorine concentration. The obtained analysis results form the basis for optimizing individual operational processes, such as the dosage amount of disinfectant and water flows with zoning. The optimization module performs tasks based on two multi-criteria optimization algorithms: evolutionary and genetic. The results of the analyses can be presented in tabular form as well as in the form of spatial visualizations (water age, chlorine distribution, flows, and pressures). These visualizations can be created using methods like kriging. The IT system used, along with the optimization module, is a part of the DSS for the technical divisions.

4. Research methodology

The aim of the research is to develop an algorithm for the spatial distribution of the risk to the population exposed to the loss of microbiological safety of water (RP_{LMSW}) during its transportation to consumers in extensive water supply systems (Fig. 2). The results of these analyses are presented in the form of maps indicating the risk of microbiological stability loss in the water supply network. Spatial risk interpretation enables the identification of critical areas (unacceptable risk) for water chlorination points and facilitates the implementation of rational actions aimed at targeted water quality control, as well as the optimization of the water chlorination process throughout the entire WSS. The proposed research methodology adopts three parameters of the model, which are defined in the *i*-th classes, namely:

- index of microbiological water protection $I(\mathrm{MWP}_i)$ determined by the level of free chlorine concentration in defined 3 states of residual chlorine content in transported drinking water;
- water age index $I(\mathrm{WA}_i)$;
- index of validation of states of microbiological water safety $I(\mathrm{VWS}_i)$ determined as the presence or absence of coliform bacteria in water samples at defined three states of residual chlorine content.

An additional element of the spatial distribution model of the risk of the population exposed to the loss of microbiological safety of water during its transport to consumers is the PWS (participation water supply) parameter, which takes into account the level of exposure, defined as the percentage of supply to local water supply systems by USWC in the total water demand of a region. In the research model, analyses are based on the results of water samples taken as part of water quality monitoring, specifically, internal water quality inspections reported to the State Sanitary Inspection authorities. The incorporation of key variables ($I(\mathrm{MWP}_i)$, $I(\mathrm{WA}_i)$, $I(\mathrm{VWS}_i)$) into the model, determining the state of microbiological stability of water based on various division criteria, establishes a multi-parameter model for spatial analysis of population exposure to the risk of microbiological water safety loss. The model also considers the percentage of water supplies from a specific source in the total water demand of a given region, which is important for assessing health risks for consumers of tap water.

The first stage of the proposed research model is the spatial division of the WSS operating area. It should be emphasized that the location of the monitoring points represents point spatial geometry, and therefore the locations of the points do not represent the coverage of the continuous study area. Therefore, it is necessary to determine unit areas with a geostatistical algorithm that aims to change the description of space from a discontinuous point geometry to a geometry of polygons tangent to each other, which constitute a continuous coverage of the area. In the first step, for each *j*-th observation period of the entire study horizon ($j = 1, 2, \ldots, J$), it is required to build in the GIS system a vector layer containing the location of monitoring points. Thiessen's polygon geostatistical algorithm was used to divide the study area, which is described by Eq. (1) [36]:

$$V(p) = \{x \in E \mid q \in S, d(x,p) \le d(x,q)\} \tag{1}$$

where p, x, q – spatial analysis points, representing the location of water quality control sites, $V(p)$ – the area of analysis representing Thiessen's polygon area, E – Euclidean space, corresponding to the study area, S – a finite set of N points belonging to the Euclidean space E, including designated water quality control sites in the WSS, d – Euclidean distance between selected control points.

All points representing the space located inside the p-th polygon are located at a smaller distance to the p-th monitoring point than to any other point in this polygon.

The proposed research model adopts the calendar year as a single observation period. Generated, according to the above algorithm, vector layer of the division of the area of operation of the WSS for each *j*-th study period is built from tangent polygons, which represent the interpretation of the water quality control point to a given unit area.

In the second stage of the research model for the adopted three variables, parameters are analyzed to determine the risk of the population exposed to the loss of microbiological safety of water.

In order to determine the microbiological water protection index $I(\mathrm{MWP}_i)$ for the three defined *i*-th classes ($i = 1, 2, 3$), the concentrations of active chlorine in the water distribution subsystem were analyzed. For this purpose, three states were defined to protect water from secondary microbiological contamination during transportation. In order to determine the parameter, it was necessary to define a category for the distribution of residual chlorine concentration values. The limit thresholds for the partitioning of residual chlorine concentrations were determined on the basis of literature data, according to which a residual chlorine concentration of 0.05 mg/L provides sufficient microbiological protection of water for the duration of its transport. The second threshold was determined based on own studies of the distribution of residual chlorine concentration in the transported water. Based on the threshold limits thus adopted, three classes of chlorine concentrations in transported water were defined (Table 4).

The above classification includes unit measurements of residual chlorine concentration in distributed water. In order to determine the microbiological water protection index, the model also takes into account the minimum frequency of water quality testing, defined by the quantification of the probability of occurrence of the i-th category K_i of residual chlorine concentration (i = 1, 2, 3), as specified in national legislation. The probability of occurrence is determined by Eq. (2):

$$P_p\left(K_i\right)=\frac{L_p\left(K_i\right)}{\sum_{i=1}^{3}L_p\left(K_i\right)} \tag{2}$$

where $P_p(K_i)$ - probability of occurrence of the i-th category of chlorine Cl_2 concentration (mg/L) at the p-th monitoring point, $L_p(K_i)$ - number of studies classified into the i-th category of chlorine Cl_2 concentration (mg/L), at the p-th monitoring point, I - number of all chlorine concentration tests at a given p-th monitoring point, $I=\sum_{i=1}^{3}L_p\left(K_i\right)$.

On this basis, three states of MWP_i were defined (i = I, II, III) during its transport, identified by the magnitude of the concentration of residual chlorine in the water, which were assigned appropriate weights (Table 5)

In the research methodology, all water quality control points that are sites of permanent water chlorination, that is, at points of injection into the water supply network and at permanent chlorination points at water distribution subsystem were assigned a weight value of $I(MWP_i)_p$ of 1. The weight values assigned to each monitoring point are the basis for defining in the GIS system the value of the $I(MWP_i)_p$ index for the separated p-th polygon of the division of the WSS functioning area. Determining the doses of disinfectant used at water treatment plants and in permanent water chlorination points is made by the WSS operator.

Another variable taken into account in estimating the risk of loss of microbiological safety of water during its transport to consumers is the water age index at each p-th polygon $I(WA_i)_p$. This indicator is determined based on numerical hydraulic simulations reflecting variable WSS operating conditions. The water age at the n-th node of the hydraulic model (A_n), integrated with points in the telemetry system, is established using a set of random variables representing the water age. These variables result from mathematical simulations that consider the minimum, average, and maximum water consumption recorded during the analyzed period. Each of these nodes is assigned a weight value $W(A_n)$ as a function of water age according to the categorization shown in Table 6.

In the next step of the analysis procedure, a vector (point) layer of water meters is generated in the GIS system, to which a water age weight value is assigned. Subsequently, a spatial intersection operation is carried out between the vector layer of water meters described by the water age weighting index WA_n and the vector layer of study area division polygons obtained according to step one of the research methodology. This procedure allows spatial assignment of each water meter to the correct p-th polygon. Then, for each p-th polygon, the averaged value of water age – AA_p is determined as a weighted average of water age according to Eq. (3):

$$AA_p=\frac{\sum_{n=1}^{N}A_n\cdot WA_n}{\sum_{n=1}^{N}WA_n} \tag{3}$$

where AA_p – averaged age of water in p-th polygon, A_n – the age of water in the nth water meter in the area of the p-th polygon, WA_n – the weight of the age of water in

Table 4
Range of variation of residual chlorine concentrations in transported water

Residual chlorine concentration C_{Cl_2} (mg/L)	Concentration classes $C_{Cl_2} - K_i$
$C_{Cl_2} \geq 0.15$	1
$0.05 \leq C_{Cl_2} < 0.15$	2
$C_{Cl_2} < 0.05$	3

Table 6
Categorization of water age at measurement points

Water age criterion A_n (h)*	WA_n weight value
$A_n < 48$	1
$48 \leq A_n < 120$	5
$A_n \geq 120$	7

*Water age obtained based on hydraulic simulation including different water supply system operating conditions managed by the USWC Ltd.

Table 5
Classification conditions $I(MWP_i)_p$ with weight assignment at the p-th monitoring point

i-th state MWP_i	Weight $I(MWP_i)_p$	Classification condition for the i-th state $I(MWP_i)_p$
MWP_I	1	State defined by a probability of at least 0.9 of occurrence of category K_1 and at most 0.1 of category K_2 residual chlorine concentration in water
MWP_{II}	2	State defined by a probability of at least 0.75 of the occurrence of the combined K_1 and K_2 chlorine concentration states and at most 0.25 of the K_3 category
MWP_{III}	3	Other cases that do not meet the above requirements for MWP_I and MWP_{II} states

the n-th water meter, N – the number of all water meters in the p-th polygon.

Based on the determined weighted average water age AA_p in each p-th polygon, a global water age index weight $I(WA_i)_p$ is assigned, according to the adopted water age categorization shown in Table 7.

Another proposed parameter of the model is the validation index of water microbiological safety states, $I(VWS_i)$, which is determined by the presence of coliform bacteria in each state of residual chlorine content in drinking water. The inclusion of the relationship between the content of residual chlorine in drinking water and the defined states of microbiological water quality in the $I(VWS_i)$ index determines the integrity of the WSS. This integrity is interpreted by the probability that functions related to the security of water supplies to consumers are correctly performed by individual WSS components. For this purpose, two states of microbiological (Si) water quality were defined:

- S1 – no presence of coliform bacteria in the water sample tested,
- S2 – presence of coliform bacteria in the tested water sample.

Index $I(VWS_i)_p$ is determined for each water monitoring point (p-th) defining the boundaries of a given p-th polygon. This index is determined based on both the water quality state (Si) and the index of water protection against secondary micrological contamination $I(MWP_i)_p$. Based on the defined water safety validation states and the indexes of $I(MWP_i)_p$ in the p-th polygon, four classes of validation of water microbiological safety states (i = 1, 2, 3, 4) were defined. Table 8 provides a summary of $I(VWS_i)_p$ index weights for the distinct i-th states.

In the proposed research model for analyzing the spatial distribution of the microbiological water safety state index $I_{MSWS}(p)$ during its transportation to customers, each generated p-th polygon based on the location of the p-th point of planned internal water quality control is characterized by three variables, that is, $I(MWP_i)_p$, $I(WA_i)_p$ and $I(VWS_i)_p$. The value of the microbiological water safety state index $I_{MWS}(p)$ is determined according to Eq. (4):

Table 7
Classification of weights $I(WA_i)_p$

Variability of averaged water age value (h)	Weight $I(WA_i)_p$
$AA_p < 48$	1
$48 \le AA_p < 120$	2
$AA_p \ge 120$	3

Table 8
Classification $I(VWS_i)_p$ with assigned weight value

Validation state	MWP_i state	Si_p state	$I(VWS_i)_p$ weights
1	MWP_I	S1	1
2	MWP_I	S2	3
3	MWP_{II}	S2	5
4	MWP_{III}	S2	7

$$I_{MSWS}(p) = I(MWP_i)_p \cdot I(WA_i)_p \cdot I(VWS_i)_p \tag{4}$$

where $I_{MSWS}(p)$ – index of microbiological state of water safety for the p-th polygon, $I(MWP_i)_p$ – i-th value of the weight of the microbiological index of water protection MWP_i in the p-th polygon, $I(WA_i)_p$ – i-th value of the water age index weight in the p-th polygon, $I(VWS_i)_p$ – the i-th value of index weight of validation of states of microbiological water safety in the p-th polygon.

Table 9 presents the three-parameter matrix for calculating the microbiological safety state index values of water I_{MSWS} determined based on Eq. (4).

Based on the variability of the I_{MSWS} index, a three-level classification of state of microbiological water safety (MWS) was developed (Table 10).

The determined safety states are assigned for the p-th polygon of the vector layer, with the aim of generating a map of the spatial distribution of risk to the population exposed to a loss of microbiological water safety (RP_{LMWS}).

The proposed research model also considered the population's exposure level to the risk of microbiological water safety loss, which is determined by the percentage of the total water demand in a given region supplied by the wholesale water supplier (in our study, USWC Ltd.). This quantity is defined as PWS. To establish the threshold values

Table 9
Variability of I_{MSWS} index of microbiological state of water safety

$I(VWS_i)_p = 1$			
$I(MWP_i)_p$ \ $I(WA_i)_p$	1	2	3
1	1	2	3
2	2	4	6
3	3	6	9
$I(VWS_i)_p = 3$			
$I(MWP_i)$ \ $I(WA_i)_p$	1	2	3
1	3	6	9
2	6	12	18
3	9	18	27
$I(VWS_i)_p = 5$			
$I(MWP_i)_p$ \ $I(WA_i)_p$	1	2	3
1	5	10	15
2	10	20	30
3	15	30	45
$I(VWS_i)_p = 7$			
$I(MWP_i)_p$ \ $I(WA_i)_p$	1	2	3
1	7	14	21
2	14	28	42
3	21	42	63

for three levels of PWS, representing the distribution of the wholesale water supplier's percentage share (in our study, USWC Ltd.) in the total water demand of a given region, the Kolmogorov–Smirnov test was used to verify the null hypothesis (H_0) regarding the normal distribution of the feature under consideration. In practice, the normal distribution of a random variable can serve as a warning system for detecting unusual behavior. However, if the distribution deviates from the normal distribution, the use of quartiles is justified. They serve as a complementary method to statistical approaches involving the median, allowing the examination sample to be divided into more equally-sized subsets or isolating groups with an extreme intensity of the measured variable. Therefore, if the analyzed distribution of water supply shares is found to be consistent with a normal distribution, the mean (μ) and the sum of the mean and standard deviation (μ+δ) are proposed to determine the threshold values. However, in the case of a non-normal distribution, these thresholds are defined by the median (M_e) and the third quartile (Q_3) (Table 11).

In the last step, the risk of exposure of the population to access to water of deteriorated microbiological quality – $\text{RP}_{\text{LMWS}}(p)$ (risk to the population exposed to a loss of microbiological water safety) should be determined for each p-th polygon. It is determined according to Eq. (5)

$$\text{RP}_{\text{LMWS}}(p) = \text{WI}_{\text{MSWS}}(p) \cdot \text{WPWS}(p) \quad (5)$$

where $\text{WI}_{\text{MSWS}}(p)$ – the weight of the I_{MSWS} microbiological water safety state index determined for the p-th polygon (Table 10); WPWS(p) – weight of the supplier's share of the water supply to the PWS customer in the p-th polygon (Table 9)

Following the European standard 'Security of Drinking Water Supply – Guidelines for Risk and Crisis Management' [37], a three-level risk categorization has been adopted. The assignment to a specific risk category defined as acceptable risk, controlled risk, and unacceptable risk considers both the variability of water microbiological safety (I_{MWS}) and the size of the population exposed to water supply with deteriorated quality, as expressed by PWS, which represents the share of a specific water supplier in the total water supply of a given area. In order to vary the determination of the risk value of the RP_{LMWS} population based on formula 5, a two-parametric matrix was constructed (Table 12).

Based on the determined risk values of the PR_{LMWS} population, it was divided into three risk classes:

- tolerable risk – RP_{LMWS} value of 1–2 (green in Table 12),
- controlled risk – RP_{LWS} value of 3–4 (yellow in Table 12),
- unacceptable risk – RP_{LMWS} value of 6–9 (red in Table 12).

5. Discussion of results

The analysis of the spatial distribution of the population's risk of exposure to water of deteriorated microbiological quality – P_{LMWS} was performed for the part of the Silesian agglomeration to which water is supplied by the wholesale water producer and supplier – Upper Silesian Waterworks Company, based in Katowice. The spatial division of the area of operation of the WSS was made based on the locations of 109 points located on the trunk mains of the planned internal control of drinking water quality. At these points, water quality tests in 2021–2022 were performed at least 12 times per year within the range defined in the Regulation of the Minister of Health [35]. According to formula 4, for each p-th of the 109 polygons, the value of the microbiological state index of water supply safety $I_{\text{MSWS}}(p)$ was determined. Based on the $I_{\text{MSWS}}(p)$ values according to the three-level classification (Table 10), each polygon was assigned a class of microbiological safety state of the water along with the WSI_{MWS} weight assignment. The final stage of this part of the analysis is the spatial visualization of the distribution of the microbiological safety state of the water for the following study years, that is, 2021 (Fig. 2) and 2022 (Fig. 3).

Analyzing the spatial distribution of the microbiological safety state of MWS water for the separated study periods of 2021–2022, three areas characterized by the loss of microbiological safety state of water were determined (dark blue areas Figs. 2 and 3). In areas located in the southwestern part of the exploited Silesian WSS, the occurrence of a state of loss of microbiological safety of water is influenced by the fact that these regions are the most distant from the source of supply and are characterized by a small amount of transported water, low flow velocities, resulting in stagnant water and trace concentrations

Table 10
Three-level classification of microbiological safety states of water MWS

MWS states	Value	Weight WI_{MSWS}
Safe state	1–6	1
Safety threat state	7–18	2
Safety loss state	20–63	3

Table 11
Classification of the percentage of supply of local water supply systems by USWC in the total water demand of a region (participation water supply) with the assignment of weighting

PWS parameter		Weight value WPWS
Acceptance of hypothesis H_0	Acceptance of hypothesis H_0	
PWS ≤ μ	PWS ≤ M_e	1
μ < PWS ≤ μ + δ	M_e < PWS ≤ Q_3	2
PWS > μ + δ	PWS > Q_3	3

Table 12
Two-parameter RP_{LMWS} matrix

WI_{MWS} \ WPWS	1	2	3
1	1	2	3
2	2	4	6
3	3	6	9

Fig. 2. Spatial distribution of microbiological state of water safety $I_{MSWS}(p)$ for the water supply system of USWC in 2021.

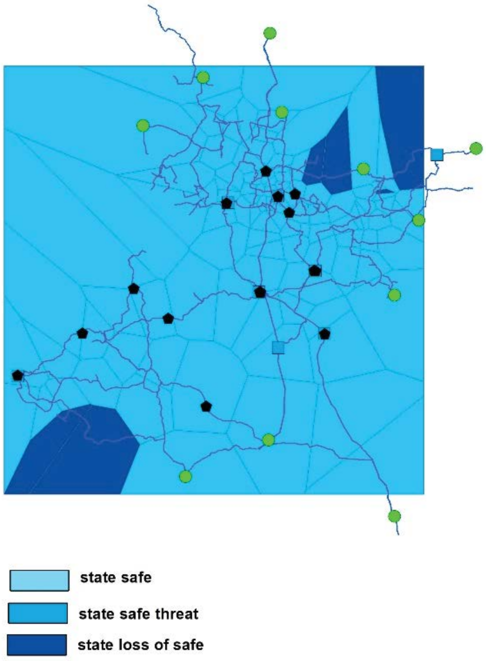

Fig. 3. Spatial distribution of microbiological state of water safety $I_{MSWS}(p)$ for the water supply system of USWC in 2022.

of residual chlorine. The state of loss of microbiological safety of water in the northeastern part of Silesia was found for the zones of variable supply of the WTP Będzin water treatment plant (Fig. 1C), which, due to the pressure system in the WSS, injects water into it only from 6 am to 10 pm. WTP Będzin captures surface water that contains a large load of contaminants (turbidity, manganese, microbiological indexes, total organic carbon), which is removed in unit water treatment processes. At WTP Będzin, the water undergoes pre-oxidation with chlorine dioxide or sodium hypochlorite, followed by successive processes of coagulation and flocculation (using aluminum polychloride), filtration on rapid sand and gravel filters, and disinfection with chlorine dioxide or sodium hypochlorite. In addition, significant daily changes in flow directions, pressure fluctuations were recorded in the area, resulting in sediment and biofilm breakup, among other things. It should also be noted here that the residents of this region are supplied with water from the west through the Murcki Network Storage Tanks in Katowice from the Goczałkowice Water Treatment Plant and the Dziećkowice Water Treatment Plant (Fig. 1C). In this area, the age of the water is more than 100 h.

In 2021, moreover, a state of impaired microbiological water safety was found in the southeastern area and the central part of the Silesian WSS. The southeastern area is supplied with water from WTP Czaniec (Fig. 1C), which treats surface water from the Soła River cascade. The station carries out coagulation on contact filters and disinfection of water with sodium hypochlorite. The water taken from the environment is characterized by a high load of organic matter and significant fluctuations in turbidity (5–150 NTU). This results in a rapid decrease in the concentration of residual active chlorine in the trunk pipeline, especially during summer periods with high water temperatures and after heavy rainfall. If coliform bacteria are found in water samples, the company uses mobile installations for spot additional dosing of disinfectant.

The classification of water supply areas to safety risk in central Silesia in 2021 (Fig. 2, dark blue areas) was due to incidental findings of single units of coliform bacteria. This may have been influenced by low water flow rates in water meter wells, or variable hydraulic operating conditions of the WSS operated by local water utilities.

As part of its operational activities related to ensuring the microbiological safety of water supplies, USWC carries out dosing of disinfectant in strategic facilities to secure water for the duration of its transport, that is, at water treatment stations, pumping stations, network storage tanks, points of permanent water chlorination on the trunk network and intervention water chlorination points on the trunk network put into operation only in the spring and autumn seasons. In addition, the company has mobile sodium hypochlorite dosing plants, which are used when even single units of coliform bacteria are found.

In the next step of the analysis, the risk of exposure of the population to access to water of deteriorated microbiological quality – $RP_{LMWS}(p)$ – was determined for each p-th polygon, based on USWC's share of the local water utility's water supply PWS(p) and the identified microbiological safety state of the water interpreted by its I_{MSWS} index. An analysis of the verification of the null hypothesis H_0 with the K-S test showed that PWS does not have the character of a normal distribution. On this basis, PWS distribution thresholds for each class were determined based on the median M_e and the third quartile Q_3 (Table 13).

Table 13
PWS classification for the water supply structure of the Silesian agglomeration

PWS_{USWC}	$WPWS_{USWC}$ weights
$PWS_{USWC} \le M_e$	1
$M_e < PWS_{UWSC} \le Q_3$	2
$PWS_{UWSC} > Q_3$	3

Table 14
List of Silesian agglomeration where the risk of exposure of the population to access to water of deteriorated microbiological quality supplied by USWC has been identified

Item	Settlement unit	PWS_{USWC}	PR_{LMWS}
1	Katowice	100	Unacceptable
2	Mysłowice	100	Unacceptable
3	Siemianowice Śląskie	100	Unacceptable
4	Będzin	53	Controlled
5	Zabrze	44	Controlled
6	Dąbrowa Górnicza	38	Controlled
7	Gliwice	11	Controlled
8	Wojkowice	7	Controlled
9	Wodzisław Śląski	98	Controlled

Table 14 summarizes the settlement units for areas for which the state of microbiological water safety was found to be impaired. At the same time, the $PR_{LMWS}(p)$ risk classification is presented for these areas, along with its spatial interpretation in the form of risk maps (Figs. 4 and 5).

The local water supply companies listed in Table 14 on positions 1–3 are supplied with water exclusively by Upper Silesian Waterworks Company and have no other way to carry out the task of collective water supply. The company applies the highest standards of operation and keeps customers and official water quality control authorities informed about the state of water quality, including incidental events of deterioration. The above risk analysis confirms the need to realize a safe water supply for the residents of a water region with the full cooperation of all water supply stakeholders. It is also essential to cooperate, in the development of crisis management procedures, with entities providing collective water supply, as well as municipal, district and provincial authorities and water supply authorities at both local and provincial levels.

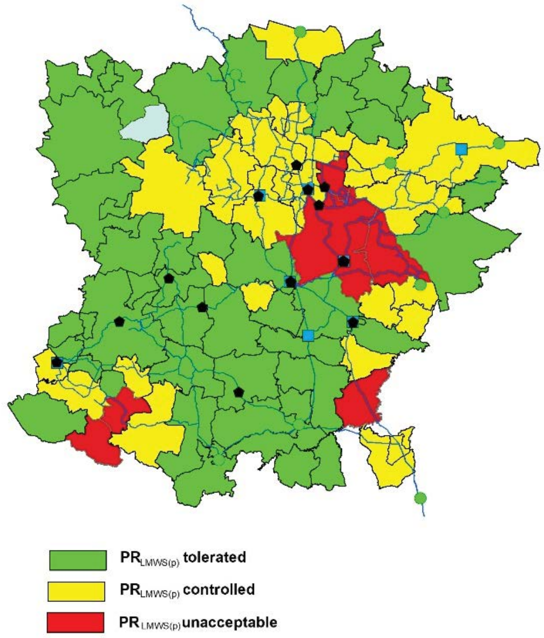

Fig. 4. Spatial distribution of $RP_{LMWS}(p)$ risk for Silesian residents in 2021.

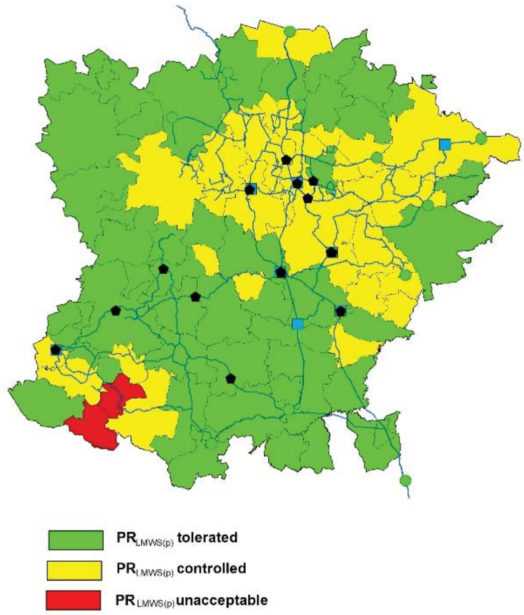

Fig. 5. Spatial distribution of $RP_{LMWS}(p)$ risk for Silesian residents in 2022.

6. Summary

Directive 2020/2184 introduces mandatory exploitation of WSS based on risk management throughout the entire water supply chain, from intake to the consumer's tap. In risk management, one of the basic principles is the use of control measures and multiple protective barriers enabling the verification of the operational parameters of the WSS. The proposed model, on one hand, serves as a control measure and, on the other hand, allows for supervision over separate protective barriers functioning in a given water system (e.g., the effectiveness of water chlorination during its transport). Moreover, it enables the development of a strategy involving the provision of alternative sources of water supply, that is, a strategy for the diversification of water supplies.

The proposed research model allows the spatial presentation of the microbiological safety status of water, enabling the assessment of the risk to populations exposed to potential microbiological safety loss. This information serves as a valuable tool for WSS operators in managing water disinfection processes at water treatment plants. Additionally, the use of risk maps, which identify areas at high risk of microbiological contamination, empowers WSS operators to adjust disinfectant dosages not only at water treatment plants but also at specific chlorination points within the distribution network. This targeted approach minimizes disinfectant usage while ensuring microbiological stability during water transport, thereby reducing the formation of disinfection by-products.

The proposed spatial risk analysis method can be applied to any large WSS with multiple independent sources of water intended for human consumption. When using this model in accordance with the population exposure risk assessment flowchart for water with deteriorated microbiological quality, the analyst will only need to verify the limit values of the model variables based on the specific operating conditions of a given WSS.

The proposed model of spatial risk analysis provides additional insights, including guidance on the optimal placement of new water chlorination points, particularly during high-temperature seasons. Risk maps from the study reveal that in large water supply systems in the Silesian region, the risk of microbiological water quality deterioration (refer to Fig. 4 and 5, highlighted in red) is inevitable during water transport. The conducted research showed that corrective actions, such as improving the efficiency of water chlorination in the water supply network, eliminated the risk of unacceptable loss of microbiological safety of water in the central part of the Silesian agglomeration (cities: Mysłowice, Sosnowiec, the eastern part of Katowice, Siemianowice Śląskie, and Będzin) and in the south-eastern part (Wilamowice town) in 2022. However, remedial actions taken in the southwestern part of Silesia (the city of Wodzisław Śląski), increasing the intensity of water chlorination in the water supply network, did not lead to risk minimization in the next year of analysis (2022). This justifies undertaking investment activities in this region aimed at increasing the number of water chlorination points in distribution subsystem. Therefore, the results of the analysis confirm that the supplied water is safe and the areas at risk of loss of microbiological safety are mainly at the ends of the water supply network (the city of Wodzisław Śląski). The main factor including this classification is the age of the water, resulting from the oversizing of the water supply network and, thus, the low velocities of water flow maintained at 0.01 m/s. Another factor contributing to microbiological water deterioration is the changing nature of the operation of WSS operated by the company's customers. This results in changes in the direction of water flow, pressure fluctuations, hydraulic surges, and sediment breakage.

The spatial analysis model for microbiological water supply security is a crucial component in Decision Support Systems implemented for water supply risk management systems. The model identifies areas vulnerable to disinfectant deficiencies in water distribution networks and incorporates validation elements for control measures, such as testing for the presence of coliform bacteria - an important indicator for maintaining WSS integrity. The integrity is determined by the probability that the functions related to the security of water supplies to consumers are correctly performed by individual WSS components, including the water disinfection process. Simultaneously, the model highlights areas where the microbiological safety of water is compromised due to incidental events, enabling an estimation of the population exposed to water of uncertain quality.

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