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Localization method for water quality monitoring points using chlorine concentration measurements in real water network

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ABSTRACT

The paper presents a proposal for a method of water quality monitoring locations with the use of water quality model (WaterGems Software – Bentley), which simulates free chlorine concentration changes in a water supply network in conjunction with the heuristic method, based on elements of fractal geometry describing a water supply network. Basing on the iterative structure of fractal sets, the authors proposed to divide the network into sub-areas. The selection of sub-areas and the measurement points location is made possible by applying validity rankings. The rankings were determined by *W* and *W*1 indexes calculated by four coefficients describing the daily water demand, the required certainty of the water supply of demanded quality, the effects of water quality deterioration and the concentration of disinfectant in the water supply network. The *W* index referring to the sub-area ranking determines the order of location of water quality monitoring points, whereas the *W*1 index, describing the ranking of the nodes, indicates the specific location of that point. Thanks to the ranking method, it is possible to plan the sequence of installing measurement sensors. The elaborated method was tested in the existing water supply network.

Keywords: Monitoring; Water quality; Water supply network

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1. Introduction

Deterioration of water quality in a distribution system may occur during its storage and transportation [1,2]. There are numerous factors that contribute to secondary water pollution in water supply systems. They may result from different reasons, for example, lack of chemical and biological water stability, low disinfectant concentration, water residence time, pipes material, and they may occur individually or jointly, aggravating their negative impact [3–11]. Since water supply systems are critical infrastructure, it is necessary to maintain the safety of drinking water and protect the system against contamination and terrorist attacks [12]. The monitoring of water quality should be treated as a tool that improves the security of water supply systems. The need for monitoring the quality of water in water supply companies stems directly from the legal regulations that determine their activity and water supply standards. Initially, the monitoring was carried out only for water intakes. Then, it was expanded to the supply system, and currently it encompasses networks and the entire water supply chain. The crucial and the most difficult stage in the design of monitoring is to determine the location of measurement points. This issue was not clearly established both in the current Polish Legal Regulations [13] and in international standards such as Council Directive 98/83/EC [14] and World Health Organization Guidelines for Drinking Water Quality (2011) [15]. Hence, numerous methods for

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determining the location of measurement points were devised; they can be divided into two main groups: heuristic methods, which require an analysis of the existing hydraulic conditions of a water supply network and predict water pollution occurrence for determining the location of the measurement points [16–21] and the optimizing methods, which employ algorithms for finding the appropriate location for water quality sensors [22–30]. The first heuristic methods were devised in the 1970s, including the method created by Church and RaVelle [16], which involved a number of measurement devices that would cover the maximum number of people, as well as the method of Lee and Deininger [17], who proposed to locate water quality sensors in order to maximize the water supply range. Ghimire and Barkdoll presented two heuristic methods of selecting the sensor location [18,19]. In the first, sensors are placed at junctions characterized by the highest water demand. In the other method, sensors are placed at the junctions with the greatest mass of flowing water (mass-based approach). A heuristic method based on the elements of fractal geometry theory was put forward by Kowalski [20]. In that approach, elements of risk theory were assumed as the basis for evaluating the correctness of the indicated measurement point location. In that methodology, significant risk parameters were distinguished, which include: volume of water in the non-monitored network, maximum detection time of a pollutant from the moment of its appearance, and detection time relative to the volume of water in the monitored network. Tinelli [21] proposed a method based on practical consideration of topology and water supply work. The localization of measuring points was based on minimizing the number of sensors and the amount of contaminated water.

The optimizing methods, based on the application of algorithms, were devised by numerous scientists [22–30]. Harmant et al. [22] devised an algorithm aiming at the maximization of three parameters: water consumption, pipe diameter and water retention time. This algorithm was formulated as a multi-criteria weighed sum problem. Al-Zahrani and Moied [23,24] applied an optimization method based on genetic algorithms to solve the issue of water quality sensor location by taking into account the flow size. Eliades and Polycarpou [25,26] employed an iterative algorithm for deepening Pareto solutions to determine suitable locations for water quality sensors. In other works, these authors proposed a multi-objective optimization, which is adequate for more than one function of the objective; it is studied and solved with a multi-objective evolutionary algorithm. Wu and Walski [27] employed an optimizing multiple criteria task, which was solved by using a genetic algorithm with the pollution scenarios generated from the Monte Carlo method. Cheifetz et al. [28] proposed an approach based on a greedy incremental algorithm to near-optimally solve the sensor placement problem dealing with large-scale water systems. Piller [29] presented an optimization, which resolved conflicting criteria such as minimizing time and maximizing the probability of contamination detection, as well as minimizing the number of the exposed population. Zhao et al. [30] presented a sensor placement algorithm based on greedy heuristic and convex relaxation. They used this algorithm to repeatedly sample random subsets of events.

The monitoring activities are also enhanced with the use of computer models which make it possible to determine the so-called water age and to calculate the concentration of a disinfecting agent [31,32]. Simulations of changes in the concentration of free chlorine in a water supply system facilitate the identification of locations where an insufficient or too high concentration of this element may arise increasing the risk of microbiological water pollution and formatting the disinfection by-products [33–36].

The chlorination in the water station causes the disinfectant to spread through the entire water network. Due to requirements of water quality which must be free from pathogenic microorganisms, it is essential to maintain permanently minimum residual chlorine at any point of the network. However, due to chlorine decay in transported water, it is necessary to increase the initial level of chlorine in the tank outlet to prevent insufficiency of chlorine concentration in remote parts or dead ends of the water network. Another solution may be to implement the booster chlorination stations in various points of the network. In this case the optimization of the number and the choice of location of these stations are needed [37,38]. Thanks to rechlorination stations, not only the total chlorine dosage but also the amount of residual chlorine can be minimized. Another solution applicable in low-income settings can be the cheap automated in-line chlorine dozers that can disinfect drinking water without electricity. Such chlorinators can be placed nearby home water connections [39].

This study presents a methodology for the selection of water quality monitoring locations basing on the water quality model created in WaterGems Software (Bentley), which shows changes of free chlorine concentration in a water supply network, in conjunction with the heuristic method [20] based on the elements of fractal geometry. The authors proposed a method for evaluating the representativeness of measurement points using a self-defined ranking of importance, which takes into account the daily water demand, reliability of supplying water of required quality, effects of water quality deterioration and the concentration of chlorine in particular areas and junctions of a water supply network. The method of locating water quality monitoring points was applied to a real water supply network and was preceded by field measurements and model studies.

2. Description of the object, research methodology

In the study an existing water supply network was investigated. The network supplies water to approximately 86,000 residents. The total length of water pipes is 233.57 km, while the length of connections amounts to 122.96 km. The water pipes operate in a mixed looped-branched arrangement. The pipes are made of grey cast iron or ductile iron, galvanized steel, PVC, PEHD and asbestos cement. There are two water stations in the network, that is, “DZ” and “ZDZ”. In the “DZ” station, there are two tanks with a total active capacity of 7,720 m^3. From the tanks, the water is directed to the second pumping station. In 2017, the “DZ” pumping station operated with the mean daily efficiency of 9,570 m^3/d, under the pressure of p = 0.52–0.55 MPa. The “ZDZ” station comprises four tanks with a total capacity of 20,000 m^3. In 2017, the “ZDZ” pumping station operated under the pressure of

p = 0.21–0.24 MPa, with the mean daily efficiency amounting to approximately 6,093 m^3/d. The water in the water supply network undergoes constant disinfection with gaseous chlorine. The concentration of chlorine at the outlet from both stations ranges from 0.15 to 0.25 g/m^3. Additionally, the water in the "DZ" station is disinfected with UV radiation. Fig. 1 presents the scheme of the water supply network with marked locations of the stations and locations where the concentration of free chlorine was measured.

The changes in the concentration of free chlorine were assumed as the basis for the selection of water quality monitoring locations. These changes were determined with the use of the water quality model created in WaterGems (Bentley) Software. The indications of the measurement point locations were based on a heuristic method involving a two-stage ranking of importance. The ranking, devised by the authors, was based on the formula defining the usefulness parameter.

3. Calibration of the hydraulic model

The water quality model that constituted the basis for the method of selecting the location of measurement points required designing and calibrating of a hydraulic model. The hydraulic model, which was made available by the local water supply company, was designed in EPANET 2.0 software; it comprised 1,092 junctions and 1,332 connections. The model prepared in that way was converted to WaterGEMS V8i Software by Bentley and provided with the missing data. In order to calibrate the hydraulic model, the measurements of the water flow in the water supply network were carried out in eleven locations. The measurements were performed with PORTAFLOW 300 portable ultrasonic flowmeter by Micronics, with the maximum measurement error of ±2%. In order to determine the values of replacement roughness, seven sections of the water supply network were selected. The measurements were performed with CellBox hydrant pressure gauges by Biatel (two for fitting on underground hydrants and two for installing on surface hydrants), with the readout accuracy of ±0.5%, which use pressure converters and record values under the fire flow conditions every 10 s and with PORTAFLOW 300 portable ultrasonic flow meter manufactured by Micronic, with the maximum measurement error of ±2%. In the majority of cases, the sections of pipes considered were found in a branched water supply network; thus, the unidirectional flow was maintained. In turn, in the sections of pipes found in the looped network, some valves were closed to ensure the right flow direction.

3.1. Design and calibration of a water quality model

A water quality model was devised in WaterGems Software based on a calibrated hydraulic model. Free chlorine was assumed in the model as an indicator of water quality. Simulation of changes in its concentration in time required assuming a mathematical model of chlorine decay and designating the coefficients of the kinetic model. The primary model, in which the coefficient of chlorine decay in water mass k_b and pipe wall k_w had to be determined, was assumed as the basis for calculations. The k_b coefficient, determined in the laboratory reached 0.002 h^{-1} (coefficient of correlation R = 0.916, and the coefficient of determination R^2 = 0.8403). The values of k_w coefficient were determined during the water quality model calibration, by trial and error. The model calibration required conducting the measurements of free chlorine concentration in selected pipes of the water supply network considered (Fig. 1). Since the chlorine concentration measurements in the existing water supply station are performed only at the outlet, a mobile set-up for measuring the pH and free chlorine concentration was designed and constructed. It comprised a PUP mobile measuring set-up with Liquiline CM442 digital transmitter (Endress+Hauser), Chloromax CCS1442 measurement electrode (Endress+Hauser) with a digital sensor for amperometric measurement of free chlorine concentration, with ranges from 0.01 to 5 mg/dm^3 of free active chlorine (HOCl), with the maximum measurement error of 1%, CPS11D (Endress+Hauser) pH measurement electrode with a built-in temperature sensor, ranging pH from 0 to 14, CCA250 (Endress+Hauser) flow assembly for the installation of chlorine and pH sensors with flow regulation. The location of the points for measuring free chlorine concentration is presented in Fig. 1.

3.2. Method for selecting the water quality monitoring locations

The determined values of free chlorine concentration cannot constitute the only criterion for indicating the location of water quality monitoring locations; therefore a new method, based on the heuristic method described by Kowalski [20], employing fractal geometry elements, was devised. The proposed method is based on the importance

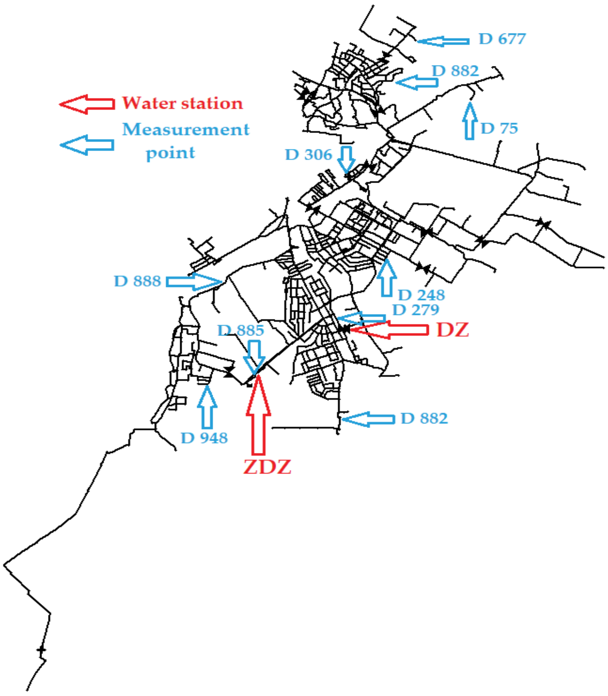

Fig. 1. Scheme of the water supply network. Arrows indicate the locations of stations and free chlorine measurement points.

ranking of particular junctions. The usefulness indicator, upon which the ranking is based, is dependent on the daily water demand, on required water supply reliability, on results pertaining to the lack of supply with water of adequate quality and on the concentration of the disinfectant (free chlorine) in the analyzed locations of the water supply network. Particular actions taken in order to determine the location of measurement points are presented in Fig. 2.

Due to a large number of junctions, the selection process was recurrent. By using the fractal nature of the set corresponding to the geometric structure of the water supply network [20] and by applying the self-similarity principle, in the first stage the network was divided into the same subareas – squares with the edge length equal to the distance traveled by water with the average flow rate in the network over 6 h.

For each subarea, the usefulness indicator was determined, on the basis of which the importance ranking was prepared for the purpose of selecting the location of measurement points. At the second stage, particular junctions were subjected to a detailed analysis. A ranking of junctions was prepared, separately for each subarea occupying the top place in the ranking from the first stage. Ultimately, the junction with the highest-ranking position in each subarea with the highest-ranking position from the first stage was assumed as the indication for the sensor location.

The importance rankings of subareas and particular junctions were based on the usefulness indicator W described in Eq. (1)

$$W = Q \cdot a \cdot b \cdot c \quad (1)$$

where Q–coefficient defining the daily water demand, a–coefficient defining the reliability of water supply with the required quality, b–coefficient defining the effects of water quality deterioration, c–coefficient defining the average disinfectant concentration (free chlorine).

In the first stage, that is, the analysis of subareas, the values of the above-mentioned coefficients were determined as a total for the entire subarea (Q) and dominant (a, b, and c). In the second stage, involving the analysis of junctions in selected subareas, these values were determined individually for particular junctions.

The values of the considered coefficients were determined on a five-degree scale. Table 1 presents the values of Q coefficients, dependent on the daily water demand. Percentage values of the total daily water demand for all junctions were proposed.

The a coefficient describing the reliability of water supply with the required quality was dependent on the type of water residents (Table 2), while the b coefficient defining the effects of water quality deterioration–on the type of facilities (Table 3).

The value of c coefficient, corresponding to the average concentration of the disinfectant (free chlorine), was determined in a slightly different way. The upper concentration limit was assumed as 0.3 mg/dm^3 (according to Polish Regulation) [13]. Then, five ranges of concentrations were determined (Table 4).

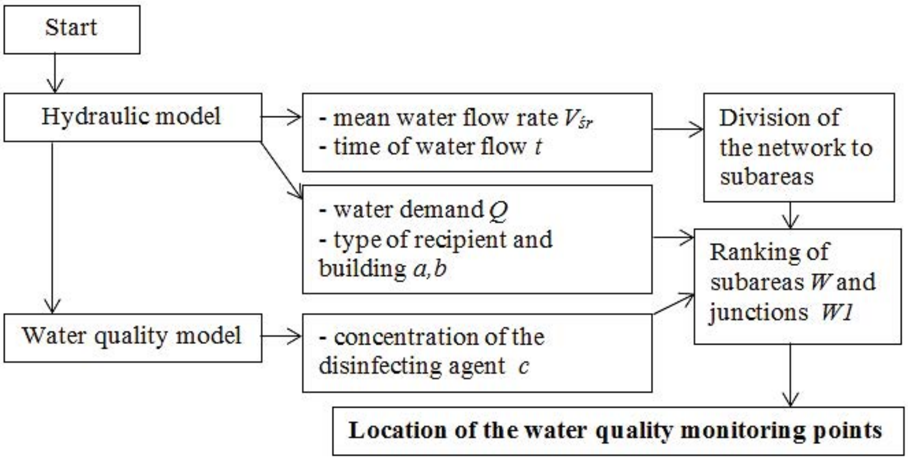

Fig. 2. Stages of selecting the water quality monitoring locations.

Table 1
Values of the Q coefficient defining the daily water demand for a subarea (maximum daily water demand for subarea is 4,906.10 m^3/d)

Daily water demand	Q coefficient
0%–20% of maximum daily water demand for a subarea	1
21%–40% of maximum daily water demand for a subarea	2
41%–60% of maximum daily water demand for a subarea	3
61%–80% of maximum daily water demand for a subarea	4
81%–100% of maximum daily water demand for a subarea	5

Table 2
Values of the *a* coefficient defining the reliability of supplying water of adequate quality

Type of dominant residents	*a* coefficient
Residential buildings	1
Schools, offices, administration	2
Shopping centers, shops	3
Industry, catering, clinics	4
Water-intensive industry, hospitals, fire service	5

Table 3
Values of the *b* coefficient defining the results of water quality deterioration

Type of dominant facilities	*b* coefficient
Storage and industrial areas	1
Shopping centers, shops	2
Residential buildings, schools, offices, administration	3
Catering	4
Water-intensive industry, hospitals	5

Table 4
Values of the *c* coefficient describing the mean concentration of free chlorine in a subarea

Concentration of free chlorine in the water supply network (mg/dm^3)	*c* coefficient
0.21–0.30	1
0.16–0.20	2
0.11–0.15	3
0.06–0.10	4
0.00–0.05	5

4. Results

Following the calibration process, the hydraulic model met the requirements established by AWWA [40]. The calibration of the water quality model was performed with a trial and error method, by changing the values of the k_w coefficient for the concentration of chlorine simulated in the computer software to correspond to its real concentration in selected measurement points. The calibration was performed for a time span of 120 h with a 10 min time step. The quality of fit was assessed by Statistica 13 Software package for 2,267 pairs of results. The best results were obtained for k_w coefficient equal to 0.12 h^{-1}. The coefficient of correlation *R* reached the value of 0.9396, while the coefficient of determination R^2 amounted to 0.8828. Fig. 3 shows the concentrations of free chlorine at the hour of maximum water demand.

The water supply network was divided into 14 subareas, marked with letters from *A* to *N*, following the methodology presented in point 2. A ranking of importance was prepared for the subareas, by calculating the *W* indicator in line with Eq. (1). The *J* and *K* subareas were excluded from the ranking since this is where the stations, in which the water is subjected to quality control prior to entering the network, are located. Table 5 shows the results of the ranking along with the coefficients (determined in accordance with Tables 1–4) used for calculating the *W* indicator.

Table 5
Ranking of subareas

Subarea	Ranking of subareas					Position in the ranking
	Q	*a*	*b*	*c*	*W*	
D	2	5	5	3	150	1
G	5	1	3	5	75	2
H	4	3	2	3	72	3
C	3	1	3	4	36	4
A	3	1	3	4	36	5
F	1	1	3	5	15	6
M	1	1	3	5	15	7
L	1	1	3	5	15	8
B	1	1	3	5	15	9
N	1	1	3	5	15	10
E	1	1	3	4	12	11
I	1	1	1	5	5	12
J	"ZDZ" subarea					*x*
K	"DZ" subarea					*x*

The *D* subarea reached the top position in the ranking. Assuming that only a single water quality monitoring point is to be selected, it will be located in this subarea. If more measurement points need to be selected, the second sensor would be located in *G* subarea, while the third – in *H*, which corresponds to their respective positions in the ranking.

Then, the ranking pertaining to the importance of junctions in particular subareas was determined. This enabled the authors to select the places in which the water quality monitoring locations should be established (Fig. 4). Numbers 1–10 correspond to the respective positions in the ranking and the sequence of sensor installation. A red dot marks the junction selected for water quality monitoring locations. Letters *A*–*N* denote the subareas.

All selected water quality monitoring locations are placed at a significant distance from each other, except for locations 7 and 8. Since these points are placed at the end of the water supply network, these subareas can be combined and a single common location can be established.

5. Conclusions

The main purpose of the study was to create a method of locating water quality monitoring points in a water supply network, basing on chlorine concentration measurements in the network. The development of the new method resulted from the lack of guidelines for measuring sensors placement and from the lack of a universal, easy-to-implement method for solving the problem of water quality monitoring point location in various types of water supply networks.

The proposed method takes into account the values of water demand, reliability of supply and effects of water quality deterioration, as well as the concentration of chlorine in

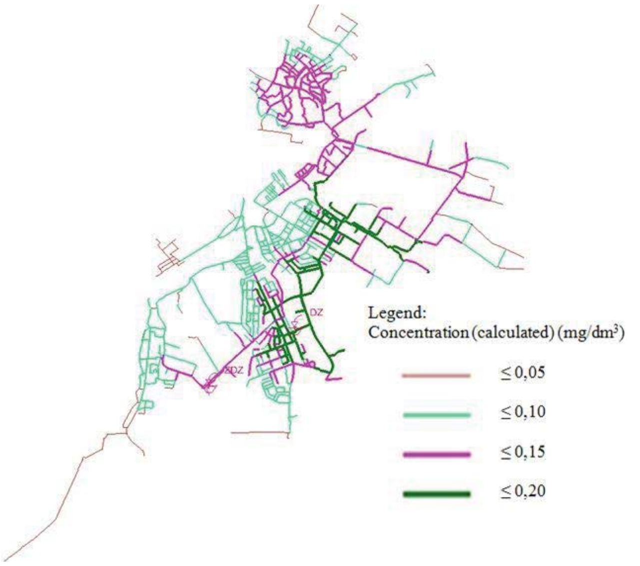

Fig. 3. Values of free chlorine concentration at the hour of maximum water demand.

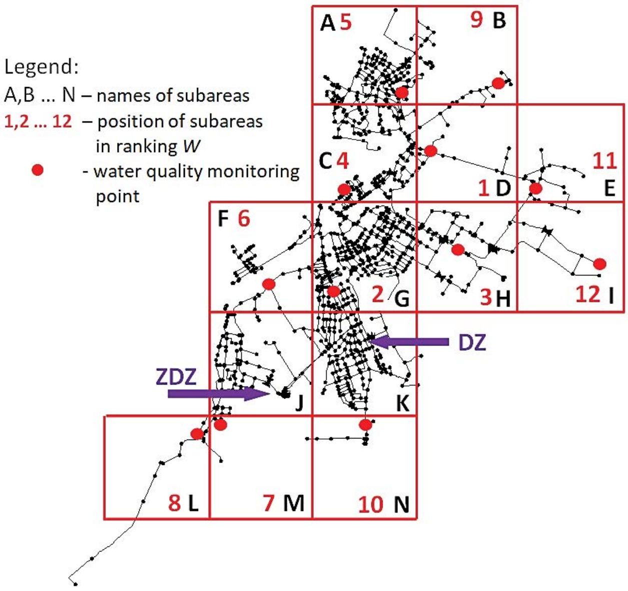

Fig. 4. Scheme of the water supply network with proposed locations of junctions, selected for installation of water quality sensors.

particular areas and junctions of a water supply network. That is why, the indicated locations for the monitoring of water quality seem to be more accurate, in comparison to other heuristic methods.

Basing on the iterative structure of fractal sets, the authors proposed to divide the network into sub-areas. This division significantly accelerated the selection process and caused the sensors not to be located close to each other. The labor-intensive analysis of all junctions was reduced only to those found in the subareas selected beforehand.

Thanks to the ranking method, it is possible to plan the sequence of installing measurement sensors. The first sensor should be installed at the location corresponding to the highest position in the ranking, whereas the additional sensors at the locations occupying the subsequent positions in the ranking. To determine the usefulness indicator *W*, using the data from the numerical model and the maps, turned out to be relatively easy, and can be implemented by technical personnel in water supply companies.

Considering the results obtained, the authors conclude that the proposed method can be successfully employed for determining the locations of water quality monitoring points in existing water supply networks. However, the method still needs to be further verified and applied to other existing water networks.

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