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GEOSTATISTICAL METHODS IN WATER DISTRIBUTION NETWORK DESIGN - A CASE STUDY

METODY GEOSTATYSTYCZNE W PROJEKTOWANIU PRZEBIEGU SIECI WODOCIĄGOWEJ - STUDIUM PRZYPADKU

Abstract: Modeling of the loads of water supply networks and their subsequent forecasting is an element necessary for making optimum decisions in the process of planning the development and operation of the water supply networks. The results of this modeling are decisive for the selection of the diameters of the pipelines and their arrangement on the water demand area. This study presents the results of estimation of average values of loads for the selected investment variants. The aim of the article is to present the possibility of simulations and analyses of the geostatistical interpolation methods. Data input in the model regarded the fragment of the real water supply network administered by the Municipal Water and Sewerage Company in Warszawa. Results of the computer analyses for the presented investment variants were related to the operating data of the water supply network and the data on water demand for the years 2014-2017 and 2018-2025. The aim of this paper is to present the advantages of GIS for the water supply systems and to prove that using the appropriate IT system, with provision of proper data processing, may lead to decisions which are optimum in view of the established, often very complex criteria.

Keywords: ordinary kriging, water network modeling, water demand

Introduction

The 21st century marks the first time in history that half of the global human population resides in urban areas [1]. Predicting and managing urban water demand is complicated by the tightly coupled relationship that exists between human and natural systems in urban areas [2]. In 2010, about 85 % of the global population had access to piped water supply through house connections. Water supply networks are part of the master planning of communities, counties, and municipalities [3]. Water utilities worldwide face increasing challenges to preserve the hydraulic and water quality integrity of their water distribution networks. These challenges stem from burgeoning populations and migration to urban cities that continue to increase the load on aging, inefficient, and already strained infrastructures [4]. The optimal design of water distribution networks is a real optimization problem that consists of finding the best way to convey water from the sources to the users, satisfying their requirements [5].

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Distributed structure of the water supply network, variability of the operation parameters with the simultaneous need to make numerous decisions at the same time cause that management of the network infrastructure is a complex process [6]. This difficult decision making process may be supported by the available geographic information systems that are being developed taking into account the water distribution system administrators. Results of the analyses performed on the hydraulic models may be helpful in making decisions related to modernization and extension of the water supply systems. They also allow for minimization of the effects of random events and thus for reduction of the risk and costs incurred by water supply companies.

Hydraulic model of the water supply system is one of the basic research tools used to analyze the properties and operation of the water supply system of the city. Quality of the tests and results of simulations performed with the use of a hydraulic model of the system is closely connected with the precision of mapping of all water supply system facilities, their hydraulic parameters as well as water supply and intake conditions. The following elements decide on the quality of the hydraulic model of the water supply network [7]:

- mapping of the water supply system structure,
- identification of the water supply system elements,
- models of water intake and parameters of the water supply network.

Water demand is generated through dynamic and continually evolving processes on the basis of multiscale interactions between human agents and the natural world. This recognition has led to a recent increase in the development and implementation of dynamic models. Most demand functions are constructed as static; however, research has shown that current water use is strongly influenced by past water use [2].

Geographic information systems (GIS) are the basic tool for collection and processing of spatial information related to the Earth surface. The GIS is commonly understood as a system for collection, storage, analysis and visualization of this type of data. GIS programs are the tools aimed at implementation of operations on attributes of elements of space, i.e. they mainly relate to digital maps which may by processed and shared in any manner. One of the most important elements of the urban/metropolitan areas includes water supply and sewerage networks that, through their spatial dimension, constitute anthropogenic component of the environment and are subject to principles of collection and analysis of data typical for geographic information systems. GIS and spatial quantitative analysis techniques have become increasingly important and pervasive components of water demand analysis [8, 9]. This results from the fact that each network element may be described by the assumed data model with geographic coordinates in the form of localization data and the attributes important in view of design and operation activities in the form of non-spatial data.

Distributed structure of the water supply network, variability of the operation parameters with the simultaneous need to make numerous decisions at the same time cause that management of the network infrastructure is a complex process. Results of the analyses performed on the hydraulic models may be helpful in making decisions related to modernization and extension of the water supply systems. The aim of the article is to present the possibility of simulations and analyses of the geostatistical interpolation methods which are the most accurate, since they are based on the random function theory. Due to the extensive character of the subject, only the ordinary kriging method was described herein. Results of the computer analyses for the presented investment variants were related to the operating data of the water supply network and the data on water demand for the years 2014-2017 and 2018-2025 prepared on the basis of the report "Forecast of the development of housing resources in Warszawa" prepared by the Development Department of the Company. The comparisons between various variants was performed using Bentley's WaterGEMS and ArcGIS program. In the studies, the materials relating to pressure measurements for Bialoleka district were used, obtained in cooperation with the Municipal Water and Sewerage Company in Warszawa.

Methods of the analysis

At the first stage of the tests, the variogram function was used for evaluation of the degree and character of the spatial variability of water supply pressure value. Databases were developed that included data related to information on the subsequent measurement numbers and values of X and Y coordinates, specifying the locations of pressure measurements and values of the water supply pressure. The semivariogram function is given by the following formula (1) [10, 11]:

$$\gamma^*(h) = \frac{1}{2n_h}\sum_{i=0}^{n_h}\left[z\left(x_i+h\right)-z\left(x_i\right)\right]^2 \tag{1}$$

in which values $z(x_i+h)$, $z(x_i)$ correspond to the values of water supply pressure in points x_i and x_i+h separated from each other by the distance h; n_h number of pairs (x_i, x_i+h) values of water supply pressure in points separated by the distance h, used in calculation of the semivariogram $\gamma^*(h)$ function.

Equation (2) and the zero load condition (3) create together the equation system referred to as the ordinary kriging [11-13]

$$\sum_{j=1}^{n} w_j\tilde{C}_{ij} + \mu = \tilde{C}_{i0} \qquad \forall i = 1,\dots,n \tag{2}$$

The sums of weights equal to one are the condition for zero load of kriging measurement [14, 15]:

$$\sum_{i=1}^{N} w_i = 1 \tag{3}$$

Minimization of error variance of model $\tilde{\sigma}_R^2$ is performed by finding its formula and comparing the relevant partial derivatives to this formula (4). The total error variance of the model has the following form [15]:

$$\tilde{\sigma}_R^2 = \tilde{\sigma}^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} w_i w_j \tilde{C}_{ij} - 2\sum_{i=1}^{n} w_i\tilde{C}_{i0} \tag{4}$$

The above equation is a relationship in which the variance of model $\tilde{\sigma}_R^2$ and co-variance $\tilde{C}_{ij}$ may be treated as parameters, whereas the weights may be treated as unknowns. In the case of designation of error variance, at first the parameters for the selected model of random variable functions should be determined and then the weight set found for which the error variance will have the minimum value. The method of Lagrange multipliers is one of the simplest methods of minimization of many functions with constraints:

$$\tilde{\sigma}_R^2 = \tilde{\sigma}^2 + \sum_{i=1}^{n}\sum_{j=1}^{n} w_i w_j \tilde{C}_{ij} - 2\sum_{i=1}^{n} w_i \tilde{C}_{i0} + 2\mu\left(\sum_{i=1}^{n} w_i - 1\right) \tag{5}$$

This method allows for changing the problem of minimization with constraints into a problem of minimization without constraints. The function subject to minimization is replaced by the so called Lagrange function with additional unknown μ, by which the constraint is multiplied. In consequence, the Lagrange function is obtained which will be minimized [16, 17].

In order to evaluate and compare spatial distributions, the paper uses several types of prediction error:

Mean prediction error (*ME*), which is a measure of estimator bias, a mean value of differences between the measured and predicted values [18]. The value of this error should be as low as possible and should be expressed in the same units as the predicted values:

$$ME = \overline{r} = \frac{1}{n}\sum_{i=1}^{n} r_i \tag{6}$$

Mean standardized prediction error (*SEM*) is the standard deviation of the sample-mean's estimate of a population mean. The error value should be as close to zero as possible and expressed as a dimensionless quantity:

$$SEM = \frac{s}{\sqrt{n}} \tag{7}$$

The mean squared prediction error (*MSE*) is the sum of squared values of differences between the actual and predicted values [19]:

$$MSE = \frac{1}{n}\sum_{i=1}^{n} r_i^2 \tag{8}$$

Root mean square prediction error (*RMSE*) is a frequently used measure of the difference between values predicted by a model and the values actually observed from the environment that is being modelled (9). These individual differences are also called residuals, and the *RMSE* serves to aggregate them into a single measure of predictive power [20-22].

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} r_i^2} \tag{9}$$

Prediction quality statistics which take into consideration both the dispersion and bias of error distribution are, among others, *MSE* and *RMSE*.

Analyzed network profile

Water supply network is a multi-node and multi-mesh system (thousands of nodes) described with nonlinear algebraic equations. The network model consists of: water sources, water supply pumps, pumping stations, water supply network with specified topology and specified pipeline sections and water consumers that specify the time-varying water demand. Most of the parameters characterizing the water supply network are strictly defined. On the other hand, water demand in the water supply network is subject to daily, weekly and seasonal stochastic fluctuations [23]. The control system allows for maintenance of fixed pressure in the supply point, independently of the current water intake. The pipeline network with a specified topology and parameters of the particular sections of the pipeline connects the water treatment stations with the customers. Distributed water supply network users generate the network load depending on the time of the day, week or season [24]. Water demand is subject to stochastic changes and the aim of the water supply network control system is to ensure supply of water with specified parameters of water pressure and quality for each user [25].

Population prediction is one of the necessary factors for designing water supply systems. Therefore, population should be estimated precisely to continuously supply increasing water demand for the community [26]. Modeling of the loads of water supply networks and their subsequent forecasting is an element necessary for making optimum decisions in the process of planning the development and operation of the water supply networks [27]. The results of this modeling are decisive for the selection of the diameters of the pipelines and their arrangement on the water demand area. The International Standard gives the definition of DN (nominal size) when applied to components of a pipework system, as specified in those standards which use the DN designation system. The term Diameter Nominal refers to the internal diameter of a pipe, in which sizes are measured in millimeters. On the other hand, the accuracy in the estimation of the average loads influences the efficiency, operation and reliability of the water supply system functioning. This study presents the results of estimation of average values of loads for the selected investment variants.

Bialoleka is one of 18 districts of Warszawa, located in the northern part of the city. In 1951 Bialoleka became a part of Warszawa administrative territory. According to the Central Statistical Office data, the district's area has 73.04 square kilometers and 112 845 citizens. It is one of the fastest developing parts of the city. The development of some housing estates is quite chaotic. It is characterized by the construction of housing estates on elongated agricultural plots, typical for rural areas instead of building urban estates with a regular grid of streets, which is perceived in negative terms by city planners. The west side of the analyzed area reaches the banks of the Vistula River. The area is subdivided into following parts:

- industrial, where many industries are located in central, southern and southern-western parts,
- housing estates with high density housing located in the central-western part,
- housing estates with prevalent detached housing-northern and central-northern parts,
- housing estates in village areas and arable lands.

The paper uses prognoses of population growth in individual urban information system (UIS) areas. A detailed division is presented in Figure 1.

The analysis assumes a demand for water of 130 dm^3/inhabitant per day and a growth of population in entire Warszawa occurring in accordance with the index calculated for each UIS area.

The conducted research confirms that an increase of settlement in housing estates shall occur in all specified UIS areas. In both analyzed periods, the largest increase in population will occur near the north-west and south-east limits of the district i.e. by about 8000 inhabitants in the years 2014-2017 and by about 16000 in the years 2018-2025.

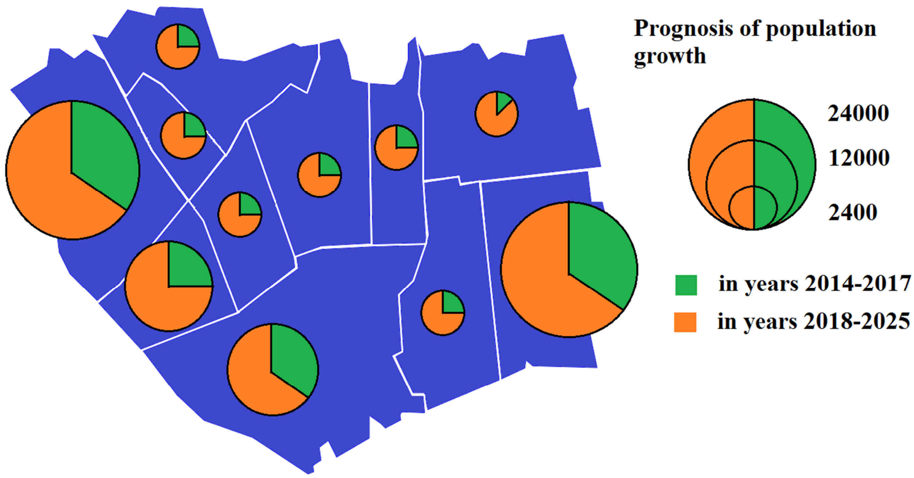

Fig. 1 Prognosis of rate of settlement in new housing buildings, with division into UIS units in the years 2014-2017 and 2018-2025

The demand for water for the entire metropolitan area will increase by 5.23% in the years 2014-2017 and by 17.26% in the years 2018-2025.

Water network infrastructure variants

In the further part of the paper, the possibilities of application of geostatistical methods in the analysis of water supply infrastructure occurrences are presented. The obtained results are shown on the vector layer covering the district area. The spatial scope and intensity of the areas of various values of the analyzed variable are presented on the map.

As a result of spatial developmental of the city and growing number of district inhabitants, construction of the following investments was proposed:

- DN 400 mm water supply pipeline (length ca 1800 m) in Daniszewska, Szlachecka, Pawla Wlodkowica, Bialolecka and Wielkiego Debu streets, DN 400 mm water supply pipeline (length ca 650 m) in Echa Lesne street (stage 1),
- DN 300 mm water supply pipeline (length ca 900 m) in Sliwkowa and Kamykowa streets (stage 2),
- DN 300 mm water supply pipeline (length ca 900 m) at the section Echa Lesne - Ostrodzka (stage 3),
- DN 200 mm water supply pipeline (length ca 1174 m) in Warzelnicza and Hemara streets (stage 4),
- DN 500 mm water supply pipeline (length ca 2150 m) in Borecka and Szklarniowa streets (stage 5),
- DN 250 mm water supply pipeline (length ca 700 m) along Armii Krajowej Street at the section Glebocka - Ostrodzka, DN 200 mm water supply pipeline (length ca 1040 m) at the section Glebocka - Geodezyjna (stage 6),
- DN 100 mm water supply pipeline (length ca 60 m) at the section Jasiniec - Geodezyjna (stage 7).

As a result of the performed simulation for the considered data on additional water demand, based on the estimated future number of inhabitants, pressure tests were carried out for the analyzed area (Fig. 2a). The figure presents "Variant 0" for the existing water supply infrastructure. Areas with high pressure of 28.36-47.41 mH_2O are marked blue. Areas with medium pressure of 23.3-28.36 mH_2O, are marked green, whereas areas with very low pressure of 0-7.18 mH_2O are marked red. Once the water demand calculated based on the data on the number of inhabitants is included, the minimum pressure in the east part rapidly drops, complete lack of water is also probable.

a) b)

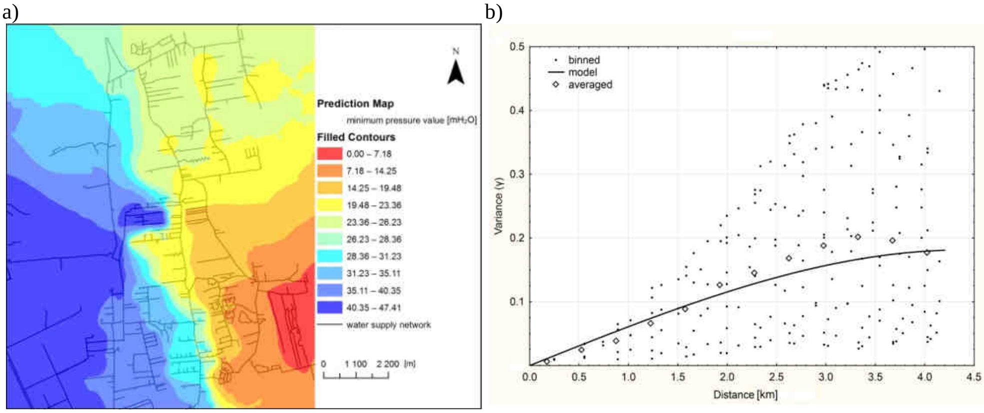

Fig. 2. Probable distribution of pressure with additional water demand for a) Variant 0, empirical semivariogram of the pressure value with the adjusted theoretical model for b) Variant 0

At the 2nd stage, the test of the spatial data structure is performed with the use of the variogram function. It consists in calculation and analysis of empirical variogram showing spatial data correlation. The variogram should be interpreted as a function showing diversification of values in two points in relation to their distance and azimuth of the straight line crossing these points. With increasing distance, the values of the variogram function increase, which results from the decreasing probability of the random variable value. Above a certain distance referred to as the range, the observations seem to be independent - variance does not increase and reaches the value referred to as the sill. As variogram is the function calculated for the given direction, it may indicate anisotropy in the spatial diversification of data. If variograms calculated in the same point for two different directions will be different in terms of the nature of the approximation function, range or sill, the directional diversification of the analyzed data may be concluded.

For the analyzed area, empirical (experimental) variogram was drawn, which presents dependencies between the variance and distance between the sampling points [28]. The obtained experimental variogram is characterized by quite a regular shape, which probably results from the number of the analyzed measuring points. On its basis, a theoretical variogram was determined. However, prior to choosing this variogram, it was analyzed which of the models was suitable for description of empirical semivariance [29]. In the analyzed example, linear behavior of the variogram near the origin of the system is observed, which suggests the use of spherical model. The selection of a particular model type depended on the moment in which the tangent drawn (in the origin of the coordinate system) for the diagram reached the sill value. Due to the fact that the intersection occurred at the distance equal to 2/3 of the impact range, the spherical model was selected. Having reached the sill, the variogram saturates [30].

The next step covered modeling of the variogram, which consisted in adjustment of the theoretical mathematical variogram to the previously created experimental variogram. The variograms were adjusted "manually". In order to verify adequacy of the previously selected theoretical models of variograms (taking into account the independent test of sampling points), cross-validation was performed for the given estimation method [30, 31]. The known methods of this type include, i.a.: triangulation, Thiessen polygon method, minimum curvature method, inverse distance method, polynomial regression or Lagrange method, etc. In consequence, the ordinary kriging method was selected, which is connected with estimation of values of the given parameter for the particular point, taking into account the value of the neighboring points. Kriging is often referred to as B.L.U.E. (best linear unbiased estimator), since it minimizes error variance as compared to the remaining estimation methods which do not minimize this variance [32, 33].

In order to provide spatial distribution of the water supply pressure value, it was necessary to test the spatial variance and create the variogram model for Variant 0 (Fig. 2b). At the first stage, the spatial correlations were tested based on the analyzed 1571 readings of the water supply pressure. The variogram was modeled using the spherical model. The system of the measuring points, resulting from the sensor system, influenced determination of the experimental variogram.

Appearance of the semivariogram is very characteristic, i.e. values of semivariogram $\gamma(h)$ increase along the increasing distance h, reaching the sill value. The distance h, at which the semivariogram diagram begins to stabilize, reaches the sill equal to 2.86 km, is referred to as the range or zone of impact. For the distances h greater than the range equal to 2.86 km, spatial autocorrelation does not occur or is negligible. The value of the nugget effect equal to zero and sill which amounted to 0.181. Despite the untypical system of measuring points, it is clearly visible that the range of correlation of the pressure value variogram amounts to 2.86 km, which means that the measurements indicate to spatial dependence at such a long distance.

The primary task was the mapping of the hydraulic layout of the water supply network in its existing condition, to serve as a basis for further studies and measurements. The changes of individual parameters in the system were compared to the stable condition (condition without noticeable changes in the network). Additionally, the probable water pressure in selected branching points was visualized using geostatic methods. Addition of new sections improving the effectiveness of the model by expanding the water supply network was suggested in the proposed investment variants.

In further variants, attempts were made to improve the network parameters and provide the required water pressure. This was done using computer modeling of an increasing demand for water and expanding the network with additional connections. The newly designed sections are located in the central and southern part of the water supply network.

Processing data on the functioning of the network required developing own methods of processing the collected information on actual water consumption. Modern digital maps were used to recreate the pipe system with exact diameters, lengths and elevations. Computer simulations were performed using computer software whose reliability has been confirmed in scientific and practical applications. The obtained data allowed for calibrating the designed models. The experimental part covers several variants simulating the existing distribution systems and the solutions aiming towards controlling water pressure and flow. The paper presents six most representative solutions.

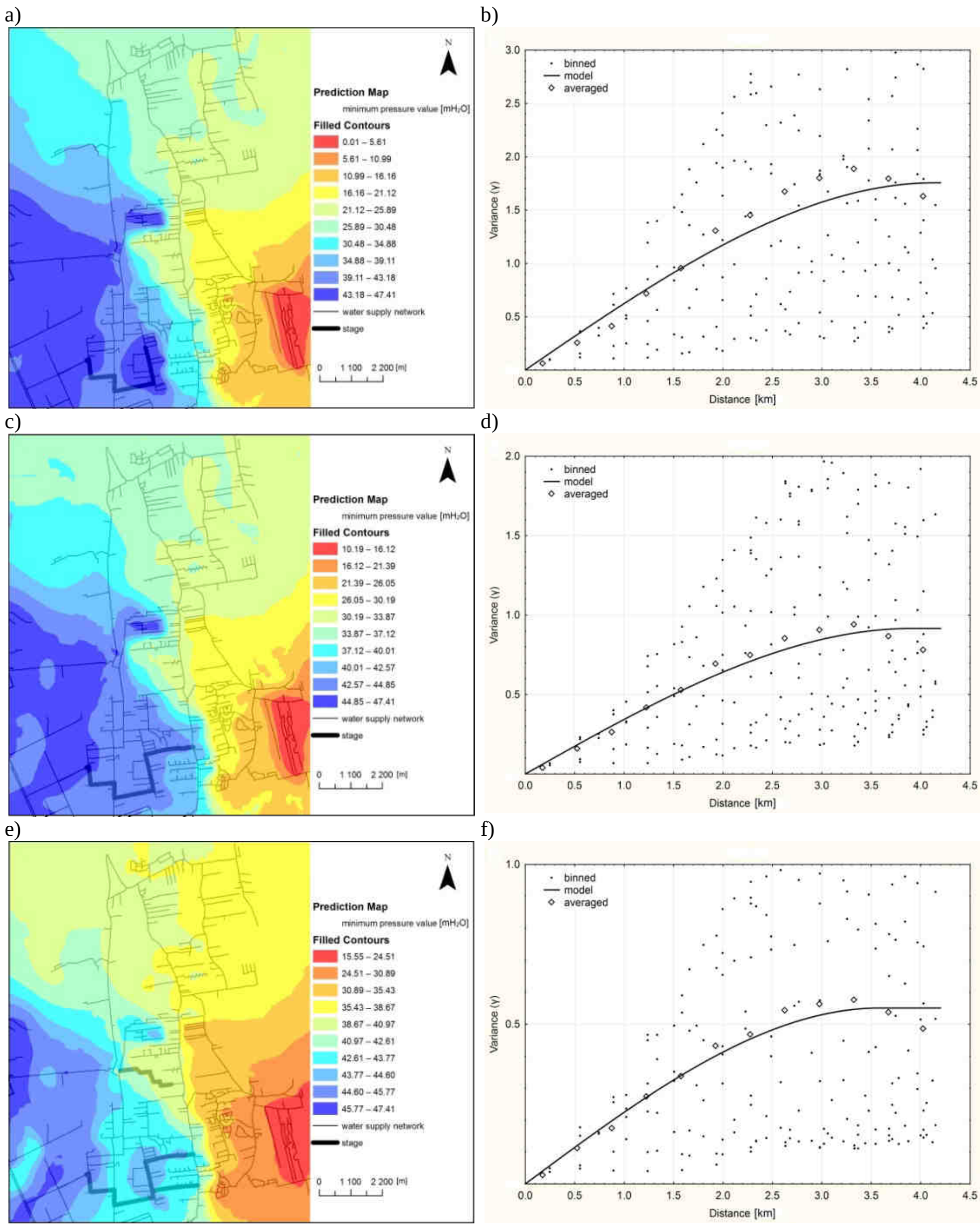

Fig. 3. Probable distribution of pressure with additional water demand for: a) Variant 1, c) Variant 2, e) Variant 3, empirical semivariogram of the pressure value with the adjusted theoretical model for: b) Variant 1, d) Variant 2, f) Variant 3

Probable pressure distribution with additional water demand for Variant 1 (Fig. 3a) based on the number of inhabitants estimated by the Development Department and based on the report "Forecast of the development of housing resources in Warszawa". As part of this variant, the following investments will be implemented:

- DN 400 mm water supply pipeline (length ca 1800 m) in Daniszewska, Szlachecka, Pawla Wlodkowica, Bialolecka and Wielkiego Debu streets, DN 400 mm water supply pipeline (length ca 650 m) in Echa Lesne street (stage 1).

As a result of the performed estimation, the following results were obtained. Areas with high pressure of 30.48-47.41 mH_2O are marked blue. Areas with medium pressure of 21.12-30.48 mH_2O, are marked green, whereas areas with low pressure of 0.01-5.61 mH_2O are marked red. In case of the proposed investment project, the water pressure will probably decrease in the most exposed area from a maximum of 7.18 mH_2O to a maximum of 5.61 mH_2O. In the northern part of the water pipeline, the maximum pressure will increase from 31.23 to 34.88 mH_2O, as compared to the current condition. Additionally, in the area near the newly-built section, the minimum pressure increased to 39.11 mH_2O.

The probable distribution of pressures at additional water demand in Variant 2 is presented in Figure 3c. As part of the investment project in Variant 1 (stage 1), it has been additionally proposed to build the following section of the water supply network:

- DN 300 mm water supply pipeline (length ca 900 m) in Sliwkowa and Kamykowa streets (stage 2).

As a result of the performed estimation, the following results were obtained. Areas with high pressure of 37.12-47.41 mH_2O are marked blue. Areas with medium pressure of 30.19-33.87 mH_2O, are marked green, whereas areas with low pressure of 10.19-16.12 mH_2O are marked red. In case of the proposed additional investment project, the water pressure increased considerably to 10.19 mH_2O in the most exposed area. In the northern part of the water supply network, the minimum pressure increased from 21.12 to 30.19 mH_2O and in the vicinity of the designed sections it increased from 39.11 to 42.57 mH_2O.

The probable distribution of pressures with an additional water demand in Variant 3 is presented in Figure 3e. As part of the investment project in Variant 2 (stage 1, stage 2), it has been additionally proposed to build the following sections of the water supply network:

- DN 300 mm water supply pipeline (length ca 900 m) at the section Echa Lesne - Ostrodzka (stage 3),
- DN 200 mm water supply pipeline (length ca 1174 m) in Warzelnicza and Hemara streets (stage 4).

Results of the prediction show an increase in minimum water pressure in the exposed area from 10.19 to 15.55 mH_2O. In case of the proposed investment project variant, the water pressure in the water supply network in the entire analyzed area has equalized. The proposed construction of the water pipeline in the central part of the water supply network caused the increase of minimum water pressure in the northern part of the pipeline from 30.19 to 35.43 mH_2O, while an additional section located in the south caused a slight increase of minimum pressure in this area from 40.01 to 42.61 mH_2O.

Areas with high pressure of 42.61-47.41 mH_2O are marked blue. Areas with medium pressure of 38.67-42.61 mH_2O, are marked green, whereas areas with low pressure of 15.55-24.51 mH_2O are marked red.

The probable distribution of pressures with an additional water demand in Variant 4 is presented in Figure 4a. As part of the investment project in Variant 3 (stage 1, stage 2, stage

3, stage 4), it has been additionally proposed to build the following section of the water supply network:

- DN 500 mm water supply pipeline (length ca 2150 m) in Borecka and Szklarniowa streets (stage 5).

The proposed construction of an additional main in the central part of the water supply network will probably cause an increase in minimum water pressure in the entire district. The water pressure will increase from 43.77 to 44.61 mH_2O in the vicinity of the newly-built section, from 35.42 to 37.49 mH_2O in the northern part of the network and from 15.55 to 16.82 mH_2O in the easternmost part of the area. Areas with high pressure of 43.72-47.41 mH_2O are marked blue. Areas with medium pressure of 40.43-43.72 mH_2O, are marked green, whereas areas with low pressure of 16.82-26.57 mH_2O are marked red.

The probable distribution of pressures in the water supply network in Variant 5 is presented in Figure 4c. In case of the investment project in Variant 4 (stage 1, stage 2, stage 3, stage 4, stage 5), the construction of the designed section (stage 2) has been excluded, while the following investment project has been proposed additionally:

- DN 250 mm water supply pipeline (length ca 700 m) along Armii Krajowej street at the section Glebocka - Ostrodzka, DN 200 mm water supply pipeline (length ca 1040 m) at the section Glebocka - Geodezyjna (stage 6).

Results of the prediction show an increase in minimum water pressure from 16.82 to 23.08 mH_2O. Excluding section 2 (2nd stage) had an impact on pressure in the water supply network in the western part of the district, where the area with maximum water pressure has grown in size considerably. On the other hand, the proposed investment project in the form of a new section (6th stage) would result in increasing the minimum pressure in the entire eastern part of the analyzed area from 26.57-40.43 mH_2O to 31.45-41.48 mH_2O. Areas with high pressure of 42.61-47.41 mH_2O are marked blue. Areas with medium pressure of 41.48-43.30 mH_2O, are marked green, whereas areas with low pressure of 23.08-31.45 mH_2O are marked red.

The probable distribution of pressures with an additional water demand in Variant 6 is presented in Figure 4e. As part of the investment project in Variant 5 (stage 1, stage 2, stage 4, stage 5, stage 6), it has been additionally proposed to build the following section of the water supply network:

- DN 100 mm water supply pipeline (length ca 60 m) at the section Jasiniec - Geodezyjna (stage 7).

The optimum pressure values required for correct operation of the water supply network have been obtained in Variant 6 (Fig. 4e). Owing to the new sections, the efficiency of the entire water supply network will increase. In a simulation of an increased demand, the new water pipelines will provide the pressure allowing for normal use of the network in times of maximum water demand. In the exposed area, the probable pressure in water pipelines increased considerably and reached a minimum of 31.88 mH_2O. In the analyzed case, water pressures similar to values currently found in the network have been obtained despite a considerable expansion of the water supply infrastructure. In case of the proposed investment project variant, the water pressure in the water supply network in the entire analyzed area has equalized. Areas with high pressure of 42.09-47.41 mH_2O are marked blue. Areas with medium pressure of 41.38-42.09 mH_2O are marked green, whereas areas with low pressure of 31.88-36.51 mH_2O are marked red.

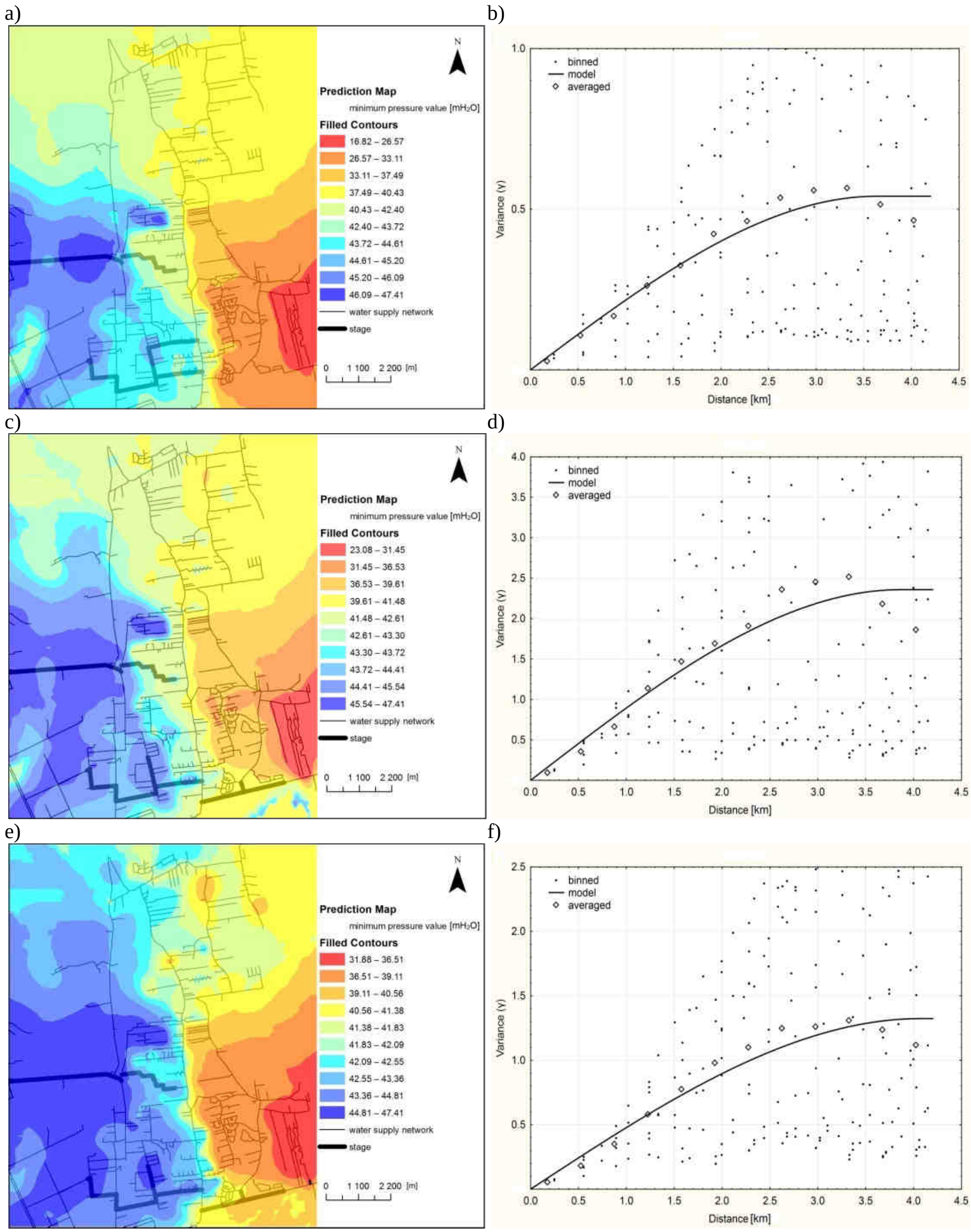

Fig. 4. Probable distribution of pressure with additional water demand for: a) Variant 4, c) Variant 5, e) Variant 6, empirical semivariogram of the pressure value with the adjusted theoretical model for: b) Variant 4, d) Variant 5, f) Variant 6

Additionally, the spatial variance for the investments were tested. The variogram models were characterized by the nugget effect equal to zero. Saturation of the variograms amounted to 1.75 in Variant 1 (Fig. 3b), 0.90 in Variant 2 (Fig. 3d), 0.54 in Variant 3 (Fig. 3f), 0.53 in Variant 4 (Fig. 4b), 2.35 in Variant 5 (Fig. 4d) and 1.32 in Variant 6 (Fig. 4f). Small ratio of the nugget effect to the saturation value of the variogram indicates that these errors do not influence the obtained spatial arrangement.

The system of measuring points, resulting from the network system influenced, to some extent, determination of the experimental variogram. Despite the untypical system of measuring points, it is clearly visible that the range of correlation of the variogram amounts to approximately from 2.20 to 2.86 km, which means that the pressure value measurements indicate spatial dependence at such a long distance.

Prediction errors for individual spatial distributions performed using ordinary kriging are found in Table 1. A particular decrease of the average prediction error value was found in case of spatial distributions of minimum pressure in Variant 6, while in case of an increased water demand in the years 2018-2025, the error value more than doubled.

Table 1

Prediction errors of Ordinary Kriging for minimum water pressure [mH_2O]

Investment project variant	**Prediction error value**			
	ME	***SEM***	***MSE***	***RMSE***
Variant 1	0.0029	0.0069	0.7898	0.8887
Variant 2	0.0059	0.0060	0.5520	0.7430
Variant 3	0.0027	0.0046	0.2754	0.5248
Variant 4	0.0025	0.0046	0.2697	0.5193
Variant 5	0.0043	0.0102	0.3216	0.5671
Variant 6	0.0053	0.0118	0.1642	0.4052
Variant 6 (in years 2018-2025)	0.0194	0.0122	1.0630	1.0310

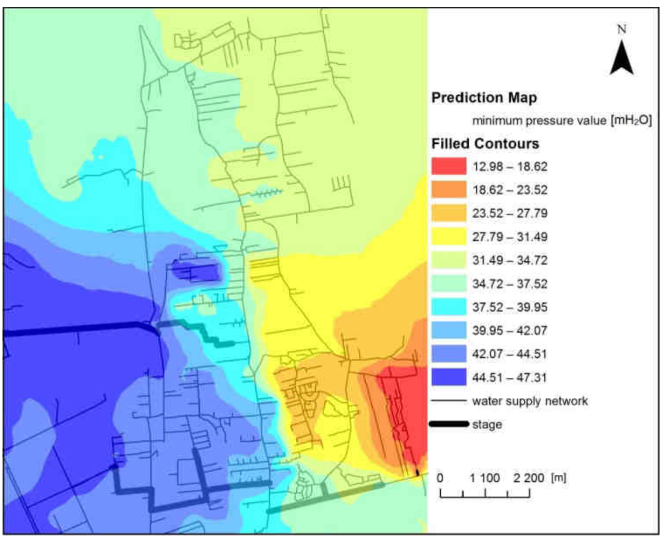

Fig. 5. Probable distribution of pressure with additional water demand for Variant 6 including water demand for the years in 2018-2025

A prediction of a pressure test has been performed for probable distribution of pressure in the selected Variant 6, using an estimated future number of inhabitants and an increased demand for water in the years 2018-2025 (Fig. 5).

The predicted minimum pressure will decrease from 31.88 to 12.98 mH_2O in the critical, easternmost area. In the northern part of the water supply network, the minimum water pressure will decrease and stabilize at 31.49-37.52 mH_2O. However, taking into consideration the results of predictions performed for the current water supply infrastructure (Variant 0), it should be noted that despite the proposed expansion of the water supply infrastructure and increasing its effectiveness resulting in a probable increase of minimum pressure in the entire district, the problem of insufficient pressure in its easternmost areas will not be eliminated.

a) b)

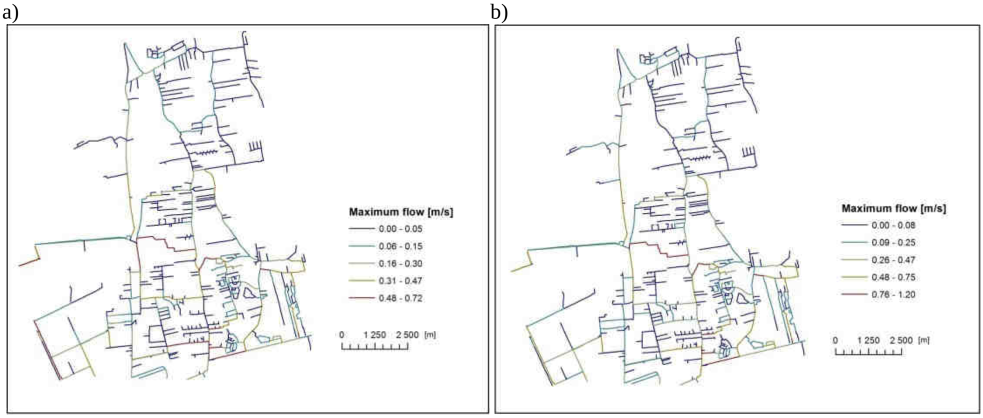

Fig. 6. Spatial distribution of water flow in horizontal pipes for Variant 6 including water demand for: a) the years 2014-2017, b) the years 2018-2025

Calculations were performed for the selected variant of the created model. The largest observed flow velocity at the demand predicted for the years 2014-2017 was found in section no. 4 (stage 4), mid-way along the length of section no. 6 (stage 6) and mid-way along the length of section no. 3 (stage 3), reaching values between 0.48 and 0.72 m/s (Fig. 6a). In the case of water demand predicted for the years 2018-2025, the flow velocity in section no. 4 (stage 4) and no. 6 (stage 6) increased and reached a maximum value of 1.20 m/s (Fig. 6b). Analysis of the results obtained for the studied variants shows that water flow velocity in the network is optimum in the selected variant. In all newly-proposed water pipeline sections, the water flow velocity far exceeds 0.1 m/s i.e. is above the water stagnation velocity.

Results and discussion

Based on the available data and on the water demand calculated on the basis of the estimations of the number of inhabitants, it may be stated that probably the Company will not be able to provide water supply with the guaranteed pressure compliant with the "Rules of water supply and wastewater discharge on the area of the city of Warszawa" amounting to 25 mH_2O on the entire area of Bialoleka district. In Variants 1-5, the east part of district area is that where the probability of pressure drop below 25 mH_2O is the greatest.

The predictions performed indicate that the optimum pressure and flow values required for correct functioning of the modeled water supply network were obtained in Variant 6. In the discussed case, a pressure close to those found in the network currently was obtained despite the increased number of inhabitants in the studied area.

In order to provide the required pressure in the water supply network in the studied area, predictions were performed for a digital model of the water supply system in conditions of water demand increasing over time. As a result of this analysis, modernization of the water supply infrastructure has been proposed, including the following investment projects:

- DN 400 mm water supply pipeline (length ca 1800 m) in Daniszewska, Szlachecka, Pawla Wlodkowica, Bialolecka and Wielkiego Debu streets, DN 400 mm water supply pipeline (length ca 650 m) in Echa Lesne street (stage 1),
- DN 300 mm water supply pipeline (length ca 900 m) at the section Echa Lesne - Ostrodzka (stage 3)
- DN 200 mm water supply pipeline (length ca 1174 m) in Warzelnicza and Hemara streets (stage 4),
- DN 500 mm water supply pipeline (length ca 2150 m) in Borecka and Szklarniowa streets (stage 5),
- DN 250 mm water supply pipeline (length ca 700 m) along Armii Krajowej Street at the section Glebocka - Ostrodzka, DN 200 mm water supply pipeline (length ca 1040 m) at the section Glebocka - Geodezyjna (stage 6).

Additionally, it would also be beneficial to build the proposed DN 100 mm section with a length of 60 m connecting water pipelines in Geodezyjna and Jasiniec streets (stage 7), which would increase the pressure in the critical area of Lewandow housing estates to about 31 mH_2O.

The analysis performed proves that selecting the designed DN 300 mm water supply pipeline section (length ca. 900 m) between Echa Lesne and Ostrodzka streets (stage 3) for implementation in conjunction with other investment projects is more beneficial than constructing the DN 300 mm water supply pipeline section (length ca. 900 m) between Sliwkowa and Kamykowa streets (stage 2).

However, because of the predicted construction projects and the following increase in the number of inhabitants in the analyzed area in the years 2018-2025, the planned water pipelines will probably not guarantee obtaining a pressure of 25 mH_2O in Lewandow housing estates. In this scenario, the minimum pressure will not exceed 13 mH_2O. Therefore, it is required to take further action to enable obtaining the required pressure in eastern Bialoleka area in the future.

Analyses of scenarios predicting a considerable increase in water consumption in the analyzed area confirm that it is possible to connect further municipal users to the network and also that additional water uptake by industrial plants is permissible. This conforms to the tasks specified in the Development Strategy for the Capital City of Warszawa, providing for a considerable expansion of this part of the city.

The maximum water flow velocity in the newly-designed water pipelines in the selected variant is 0.72 m/s and increases with further increase of water demand to 1.2 m/s. The analysis of water flow velocity distribution performed using models of the studied water supply networks shows that in the majority of the water pipelines this value is considerably larger than the recommended value of 0.5 m/s. The water flow velocity is important for self-cleaning of the pipes and biological purity of water. If the water flow velocity is too low, sediments collect at the bottoms of pipelines. The flow capacity of the water pipeline decreases over time, which causes increased pressure and water flow velocity in the given section. When the flow velocity increases, the sediments collected in the pipes are picked up by the flow and polluted water is delivered to the end user. In case of long sections and low flow velocity, the water may stand in the pipes, which may cause the risk of secondary growth of bacteria.

The values of *ME* and *SEM* being close to zero, indicates that the predicted values are unbiased. *SEM* values are lower than *RMSE* shows that chosen model slightly under-estimates the variability of minimum water pressure in nodes. *RMSE* was used to check whether the prediction is close to the measured values. It is a measure of the error that occurs when predicting data from point observations and provides the means for deriving confidence intervals for the predictions. The smaller the *RMSE* value, the closer the prediction is to the measured value. A particularly low *RMSE* value was recorded in Variant 6, however in case of the same investment project variant taking into account the increased demand for water in the period 2018-2025, the error value increased considerably. Additionally, the modeled variograms are characterized by lack of short-distance variability and minimized measurement errors, confirming correct calibration of the measurement network model.

The developed hydraulic model requires ongoing updates using actual data. These data should be obtained from the monitoring system. Only this level of data exchange allows for performing the calibration process, which is the basis for correct operation of the model, taking into account the actual conditions in the network. Due to the prototypical nature of the study, supplementing them in the future with new information from the monitoring system developed by the company is indispensable for obtaining a correctly calibrated model.

The final decision on selecting the system functioning variant need not be identical to the decision being the result of the modeling. Its purpose is to support the decision making process, which should take into consideration numerous other factors e.g. economical ones. The applied modeling system has been used in practice. Finding a best solution for water supply network problems requires continuation of the conducted study. Further research will include more investment projects indispensable in the water distribution system owing to the increased water demand in the specified area.

Conclusions

As a result of the performed tests and analyses with the use of computer modeling, simulation results were obtained for each of the investment variants. Application of an appropriately developed and calibrated model enables testing various solutions and comparing results of each of them, which contributes to elimination of improper investments and generates cost benefits.

Kriging method is used for interpretation of data on continuous surfaces. Water supply network is a continuous linear facility and therefore, the created images visualize the areas of pressure value. This image will appropriately represent the pressure value, whereas reliability of the obtained results increases along with the increasing number of the control points. Kriging method also allows determination of areas on which the water pressure in the pipeline drops. This is also useful in establishing the reasons for water supply pressure drop as well as in extension and operation of the water supply systems. The necessity to limit operation costs of water and sewerage systems, to increase the efficiency of company management as well as the need of supporting the investment process proves that application of the proposed geostatistical method is justified.

The presented models may be widely used at the initial stage of designing the water supply network and their application may significantly facilitate the design process, thus contributing to limitation of hazards for normal operation and improvement of the system operation efficiency.

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