Rocznik Ochrona Środowiska

Volume 24	Year 2022	ISSN 2720-7501	pp. 493-504

https://doi.org/10.54740/ros.2022.035 open access

Received: 09 December 2022 Accepted: 27 December 2022 Published: 28 December 2022

The Concept of Calculating the Water Distribution System as a Repeatable Process with Elements of Diagnostics Using Neural Modeling

Jacek Dawidowicz
Bialystok University of Technology, Poland
https://orcid.org/0000-0003-1742-9463

corresponding author's e-mail: j.dawidowicz@pb.edu.pl

Abstract: Calculations of water distribution systems are most often performed many times because the correct solution from a technical point of view is rarely obtained after the first calculation run; hence, we can talk about a multistage calculation process. In connection with this, the calculation process of computer water distribution systems can be additionally supplemented with elements of process diagnostics. Diagnostic activities should be carried out using numerical algorithms, which can be a complement to classical hydraulic calculations of water distribution systems. The condition for reliable functioning of the diagnostic system formulated in this way is the efficient detection of computational irregularities. For this purpose, diagnostic problems were defined for the water pipes and the connection nodes in the water distribution system. The proposed diagnostic tests analyze the calculation results and indicate whether the solution is correct or, if irregularities are detected, suggest a way to solve the problem. Diagnostic tests are carried out using artificial neural networks.

Keywords: water distribution system, hydraulic calculations, process diagnostics, evaluation of calculation results, artificial neural networks

1. Introduction

The design of a water distribution system is inseparably connected with the performance of calculations, the main purpose of which is to determine the flow rate through individual lines, select diameters while maintaining appropriate flow rates, and calculate pressure losses and pressure levels in nodes. An important task also is to design the appropriate layout of pressure zones and the correct location of the zone pumping stations and reducing valves. The water distribution system should be designed in such a way as to ensure the supply of water to the places of its consumption, in an amount that covers the full demand for water of consumers, of appropriate quality and required pressure, in a continuous manner, under specific conditions of system operation and in a prospective period of operation (Knapik & Bajer 2010, Lansey & Mays 2000). It is extremely important to perform the calculations correctly at the design stage, but due to the considerable complexity of the water distribution system, the right solution is usually obtained after the repeated calculation procedure. Therefore, the calculation of the water distribution system can be considered as a kind of calculation process, while the issues of correction of the obtained results can be supplemented with elements of process diagnostics to automate calculations.

In water distribution system calculations, computer technology has been used for many years. The first computer programs appeared in the second half of the twentieth century (Ormsbee 2006). Since then, there has been visible progress in the technical capabilities and facilities of the latest programs for calculating water distribution systems (Rossman 2020), which increasingly use the capabilities of GIS (Kwietniewski 2013, Shamshi 2005) and CAD (Walski et al. 2003). The differences between them occur primarily in terms of calculations, the possibility of introducing modifications to the code, or the engineering advancement of graphics modules. However, this does not change the fact that the correct execution of calculations requires a good understanding of the theoretical issues that are the basis for algorithms used in calculation programs, a thorough assessment of the results obtained, and the correctness of the solutions used. Despite many years of development of programs for the calculation of water distribution systems, their capabilities in terms of intelligent evaluation of the obtained results are still quite modest. Attempts are being made to introduce elements of artificial intelligence mainly into computational procedures (Czapczuk et al. 2017, Czapczuk et al. 2015, Lingireddy & Brion 2005, Piasecki et al. 2018, Zhu et al. 2002), which is supposed to speed up calculations, especially in real-time control systems (Damas et al. 2000). In the case of design calculations, erroneous results can be obtained for calculation sections or nodes, although the individual input variables do not formally show irregularities. There may be too high pressure losses, too low, or too high average flow velocity in the pipe due to incorrect selection of the diameter of the water pipe; the pressure in the node may fall below the required value or exceed the permissible value. In the subject of assessing the correctness of the obtained calculation results, one can indicate publications that use artificial neural networks (Dawidowicz et al. 2018, Dawidowicz 2018a, Dawidowicz 2018b, Dawidowicz et al. 2021) or expert systems (Dawidowicz 2012). This article discusses the methodology for the calculation of the water distribution system understood as a repeatable process using elements of process diagnostics. The proposed diagnostic tests are carried out using artificial neural networks. Classification and a detailed discussion of individual methods of process diagnostics, including the use of computational intelligence methods, can also be found in the papers (Kościelny 2004a, Kościelny 2004b, Patan & Kościelny 2004, Palade et al., 2006).

2. Basic concepts of process diagnostics

Technical diagnostics is primarily associated with device failures. An extremely important and intensively developing field is also process diagnostics, which deals with the recognition of changes in the state of these processes, where processes are understood as a sequence of purposeful activities carried out at a fixed time by a specific set of machines, devices, or computer programs.

Diagnosing is understood as the process of detecting and distinguishing object damage (process irregularities) as a result of collecting, processing, analyzing, and evaluating diagnostic signals.

According to the terminology adopted by the SAFEPROCESS (Technical Committee on Fault Detection, Supervision and Safety of Technical Processes) of the international organization IFAC (International Federation of Automatic Control), three basic stages of diagnostic testing have been distinguished (Isermann & Ballé 1997):

- fault detection – detection of a fault in the facility and determination of the moment of detection,
- fault isolation – determination of the type, place, and time of fault occurrence; occurs after fault detection,
- fault identification – determination of the extent and nature of the fault variation over time; follows the location of the damage.

Depending on the specificity of the diagnosed process or its element, the above three stages of diagnosis may occur in different configurations. Combinations of diagnostic stages are the basis for constructing the so-called diagnostic tests. They consist in carrying out a set of tests, e.g. by computer software on the values of process variables or diagnostic signals, aimed at checking whether a given object (process) or its elements have the assumed properties within the set parameters.

3. Selected diagnostic problems in the calculation process of water distribution systems

Data for the calculations of the water distribution systems, as well as the results, consist of two basic sets that describe linear and point elements. The basic type of a linear element is the calculation sections of the water pipes, while the point elements are the connection nodes of the pipes. Therefore, diagnostic tests should evaluate the calculations for linear and point elements separately. To automate the diagnostics of the calculations of the water distribution system, problems have been identified that are analyzed by diagnostic tests.

3.1. Diagnostic problem in the calculation of water pipes of a water distribution system

In the case of water supply lines, the basic issue that should be checked is the diameter of the calculation section of the water line. Two basic reasons can be indicated that may affect the need to correct the calculations in relation to individual calculation sections of water pipes:

- incorrectly selected pipe diameter at the design stage,
- incorrect diameter of the existing conduit, which may be related to a change in flows in the operated water distribution system as a result of changing its structure or expanding the system.

The diagnostic test should check the diameter for current flow conditions and suggest the correct value if abnormal.

3.2. Problems with pressure head and pressure zoning in the water distribution system design and calculation

A much more complex problem is the assessment of the pressure in the nodes. In this case, there are several problems that the diagnostic test should recognize.

The pressure head (PH) is the height of a column of water necessary to develop a specific pressure at a given point. Proper values of a pressure head in an entire water distribution system should ensure the pressure head at individual nodes to be between the required pressure head H_r and the maximum pressure head H_{max} (Fig. 1). The sum of the pressure head and the elevation relative to a reference level is named the hydraulic head. A plot of hydraulic head along a pipeline forms a line called the hydraulic grade line (HGL):

$$\text{HGL} = \frac{p}{\gamma} + z \qquad (1)$$

where:
p – pressure,
z – the elevation above some reference, usually mean sea level,
γ – fluid density.

Determining whether the current pressure head in a network node is of a value within the recommended range is relatively simple. The algorithms used in the programs allow for calculating pressure losses in individual pipes and a pressure head in nodes, but do not analyze the pressure head in an entire water distribution system. An incorrect value of the pressure in the nodes can be caused by various reasons. It is important for a computer program to be able to point to an incorrect value during hydraulic calculations, diagnose a cause, and possibly suggest a solution that will solve the problem connected with the assessment of the pressure value in the nodes of the water distribution system. It is important that the computer system was able to indicate an incorrect value, diagnose the reasons, and possibly suggest a solution that will solve the problem during hydraulic calculations.

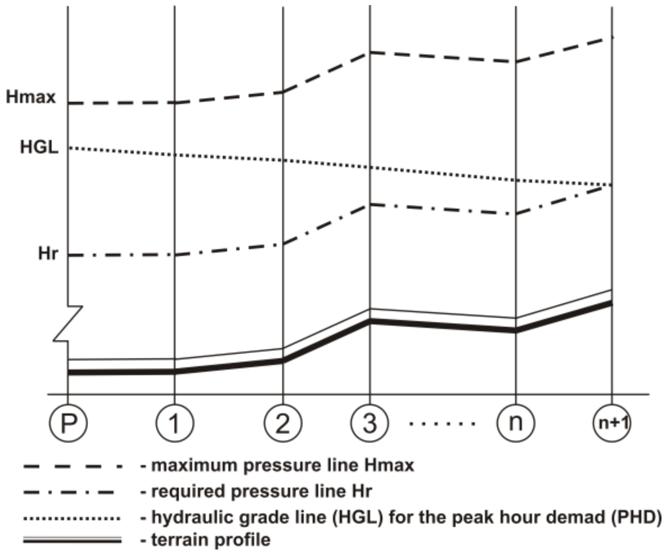

Fig. 1. Correct hydraulic grade line (HGL) for peak hour water demand (PHD)

The primary reason for incorrect pressure values is a wrong pressure in the water supply resulting from incorrect selection or operation of pumps or boosters. Another cause covers high pressure losses along one or several pipes resulting in the hydraulic grade line falling below the required value (Fig. 2). A frequent cause of this is the incorrect diameter of a pipe. Therefore, the correction of a pipe diameter should restore the proper course of the hydraulic grade line.

An important issue is to determine whether a system should comprise one pressure zone or should consist of more pressure zones. If a zoning of a system is necessary, it is important to properly locate zone pumping stations or reducing valves. A terrain with substantial level differences or long sections of conduits may involve a multi-zone water distribution system. Zoning can require rising of the pressure on a terrain rising above the water supply source (Fig. 3) or reducing it on an area much below the supply source (Fig. 4). One should determine the most advantageous location of the aforementioned network elements.

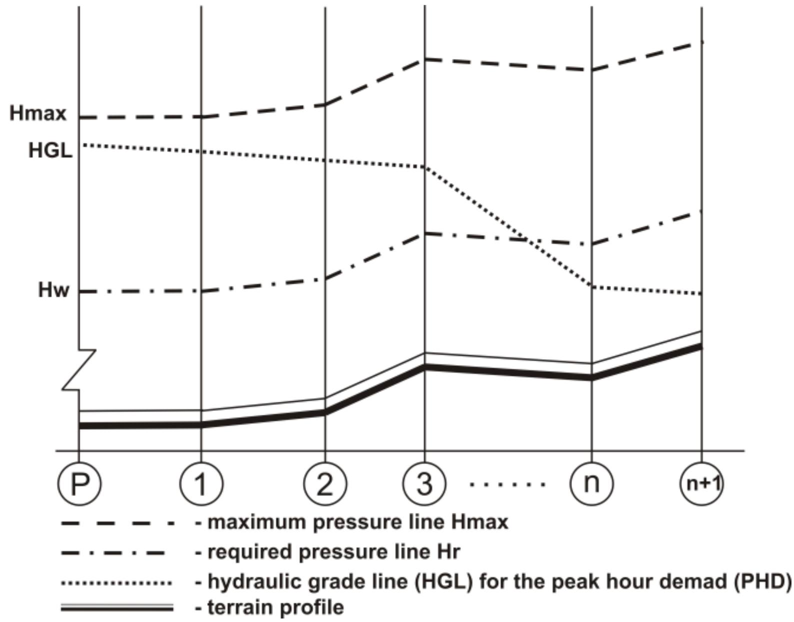

Fig. 2. Hydraulic grade line (HGL) in case of substantial pressure loss in one section of a pipeline

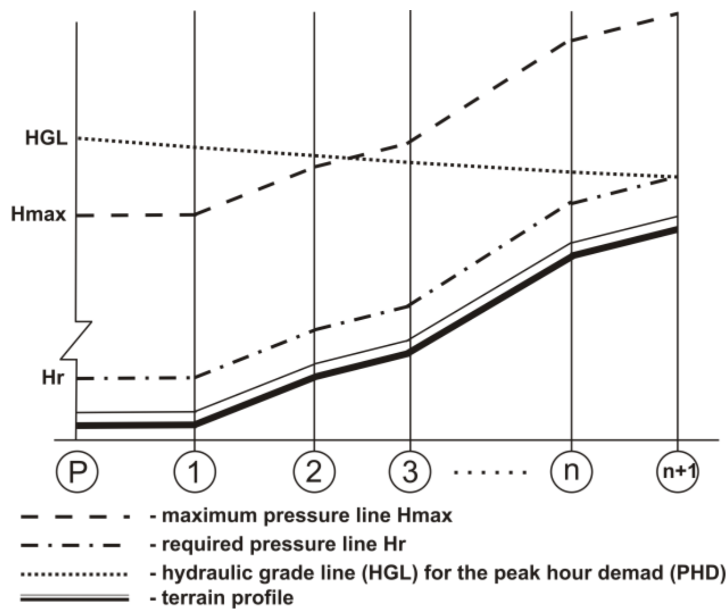

Fig. 3. Hydraulic grade line (HGL) for a raised terrain along the pipeline route

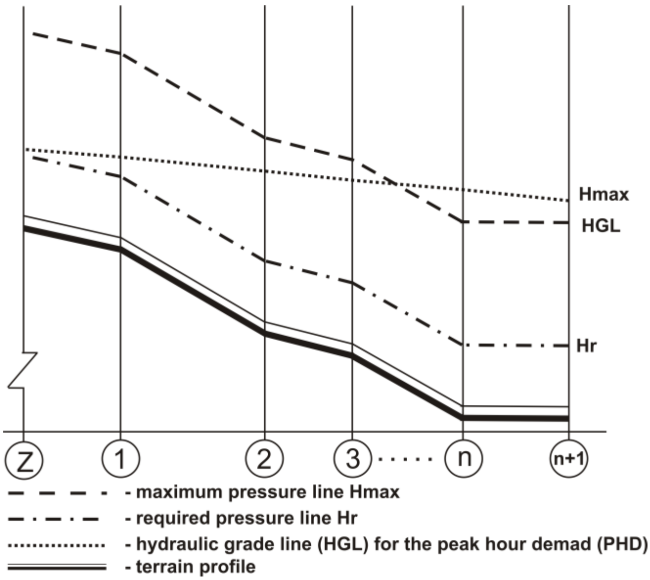

Fig. 4. Hydraulic grade line (HGL) for a descending terrain along the pipeline route

Another problem is also a significant length of a water distribution system on a flat land or on a land where the level differences are small because the pressure losses growing along the pipeline route can result in a high pressure head difference at end nodes of a network. A solution to this problem is a two- or multizone system. The location of a pumping station should be carefully analyzed.

4. Diagnostic methods of the water distribution system calculation process

Assuming that the object of diagnostic tests is the computational process of water distribution systems, the state of the process will be assessed after each computational run. This paper proposes two diagnostic methods for assessing the diameters of water pipes and the pressure in the nodes, together with checking whether additional pressure zones are needed.

4.1. Diagnostic method to select the diameters of water pipes

The proposed method for diagnosing the calculation results for water pipes consists in comparing the diameter adopted for calculations (selected or existing in the network) with the diameter obtained from the model of reference values, i.e., one that was prepared on the basis of a set of calculation results in which the diameters were corrected in the calculated and considered correct. This comparison of diameters can be understood as an assessment of deviations (residues) between the reference values obtained from the model and adopted for calculations.

In the proposed diagnostic method, the evaluation of the correctness of pipe diameter selection is based on the classification of diameters from the nominal variable SR = {DN90, DN110, DN160, DN225, DN250, DN300, DN350, DN400, DN450, DN500} using a neural network (Fig. 5). In this case, the neural network is a model of standard values, i.e. one that was prepared on the basis of a set of calculation results in which the diameters were corrected in the calculation process and considered correct. The nominal diameter DN_{ANN} obtained from the neural model is compared with the actual diameter DN. The actual diameter DN is understood as the designed diameter, taken from hydraulic calculations or existing in a functioning system. The comparison of DN_{SSN} diameters from the neural model and DN can be understood as the evaluation of the residuum in the diagnostic model. The diagnostic method proposes a diameter in the calculation section and evaluates the existing or accepted diameter for calculations. The method uses two aspects of the functioning of the artificial neural network, that is, the classification result and the activation value of the Softmax function in the output layer (Dawidowicz 2018b).

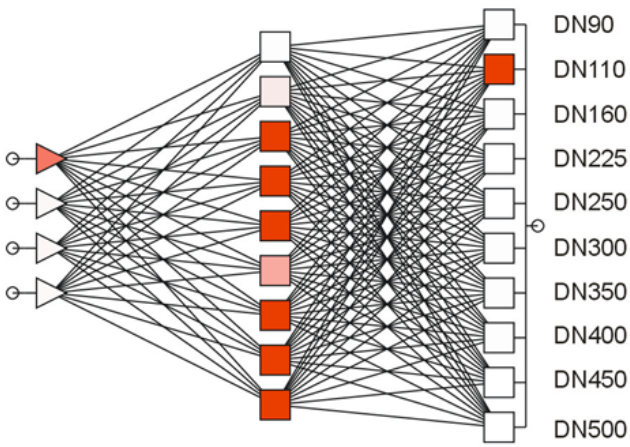

Fig. 5. Scheme of a neural network to assess the diameters of water pipes (Dawidowicz 2018b)

4.2. Diagnostic method for evaluating the pressure head and pressure zones of a water distribution system

Determining whether the pressure head is too low or high in a single node in relation to the allowable pressure range is not a major problem, while determining the cause of a particular condition and assessing the pressure distribution in the entire network is a much more complex task. The algorithms used in computer programs allow one to calculate the pressure in the nodes, but do not analyze the pressure distribution throughout the water supply network; hence the diagnostic method will introduce an additional element of evaluation of the obtained solution. If an incorrect pressure value occurs, there can be many different reasons for this condition. It is important that the computer system during hydraulic calculations is able to indicate an incorrect value, diagnose the cause, and possibly suggest a solution that will lead to solving the problem. In the proposed method, the diagnosis of computational parameters at the nodes will be carried out as a classification task using a properly constructed artificial neural network. Diagnostics of the calculations for the nodes will aimed at assessing the pressure in individual nodes and analyzing the division of the system into pressure zones. An assessment will be made of the need to correct the diameters of the pipes, use a network pumping station, or reduce the pressure in transporting water from the supply source to the analyzed network node.

The problem of assessing the pressure head and system layout was treated as a classification task. For this purpose, the nominal variable CWDS (Class of Water Distribution System) was defined, which includes five classes describing computational problems resulting from inappropriate pressure, the need to separate the pressure zone, and one class related to the correct course of the pressure line. The individual classes and their corresponding labels are as follows (Dawidowicz 2018):

- pressure head at a given water distribution node above the maximum value resulted from too high pressure head at the water supply node (label PHA – Pressure Head Above),
- pressure head at a given node below the required value resulted from too low pressure head water at the supply node (label PHB – Pressure Head Below),
- Recommended pipe diameter correction to reduce pressure losses between the water supply node and a given water distribution system node (label RDC – Recommended Diameter Correction),
- recommended installation of a network pumping station in a given node and separation behind a given node of a separated pressure zone (label NPS – Network Pumping Station),
- recommended installation of a pressure reducer at a given node and separation after a given node of a separated pressure zone (label PRD – Pressure ReDucer),
- proper pressure head and hydraulic grade line between the water supply node and a selected water distribution system node (label PHGL – Proper Hydraulic Grade Line).

To precisely describe the aforementioned parameters characterizing the class of the CWDS variable, the components of the input vector X for the artificial neural network learning were defined as follows:

- x1 − pressure head at the water supply node,
- x2 − length of the shortest distance in a network from the supply node to a selected water distribution system node,
- x3 − difference of land levels between the supply node and a selected node,
- x4 − largest difference in land levels along the shortest distance between the supply node and a selected node,
- x5 − sum of pressure losses along the shortest distance between the supply node and a selected water distribution system node,
- x6 − highest pressure head along the shortest distance between the supply node and a selected water distribution system node,
- x7 − weighted average of absolute roughness k of pipelines along the route between the supply node and a selected system node,
- x8 − pressure head at a selected node in the system.

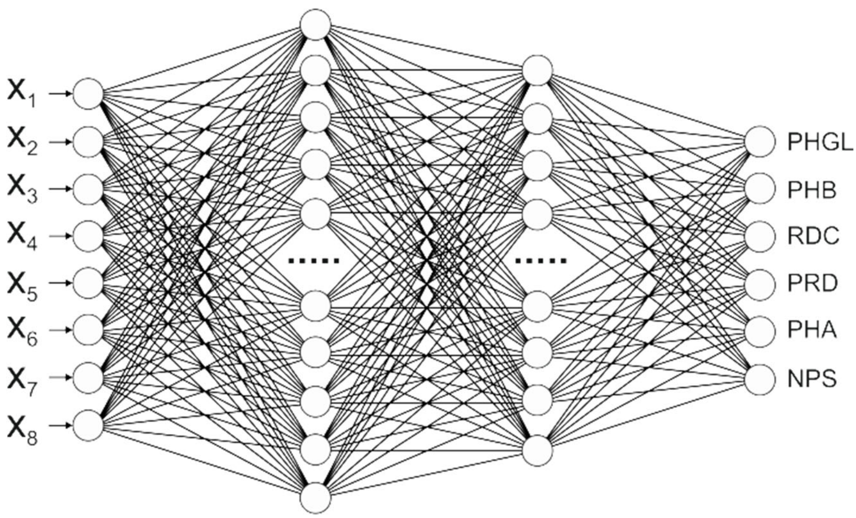

Fig. 6. Scheme of the neural network for the evaluation of a pressure head and pressure zones in water distribution systems (Dawidowicz 2018)

Summary

The article describes the assumptions of the water distribution system calculation method as a calculation process. The basic concepts of process diagnostics used in the discussed methodology were characterized. The problems that will be analyzed in the diagnostic process of calculations are described, and the artificial

neural networks that are the basis of diagnostic tests are described. The assumptions of diagnostic methods are discussed to verify the results of water distribution system calculations. Details of individual solutions with block diagrams and calculation examples are available in the cited literature.

References

Czapczuk, A., Dawidowicz, J., Piekarski, J. (2015). Artificial Intelligence Methods in the Design and Operation of Water Supply Systems. *Rocznik Ochrona Srodowiska*, *17*, 1527-1544 (in Polish).

Czapczuk, A., Dawidowicz, J., Piekarski, J. (2017). Application of Multilayer Perceptron for the Calculation of Pressure Losses in Water Supply Lines. *Rocznik Ochrona Srodowiska*, *19*, 200-210.

Damas, M, Salmeron, M., Ortega, J. (2000). ANNs and Gas for predictive controlling of water supply networks. In: *Proceedings of the IEEE-INNSENNS international joint conference on neural networks (IJCNN2000).* Como, Italy, 365-368.

Dawidowicz, J. (2012). Expert System for Evaluation of Water Distribution System Created with an Inductive Inference. *Rocznik Ochrona Srodowiska*, *14*, 650-659 (in Polish).

Dawidowicz, J. (2018a). Evaluation of a pressure head and pressure zones in water distribution systems by artificial neural networks. *Neural Computing & Applications*, *30*(8), 2531-2538. DOI: 10.1007/s00521-017-2844-8

Dawidowicz, J. (2018b). A Method for Estimating the Diameter of Water Pipes Using Artificial Neural Networks of the Multilayer Perceptron Type. In: *2nd International Conference on Artificial Intelligence: Technologies and Applications (ICAITA 2018)*, (50-53). Atlantis Press. DOI: 10.2991/icaita-18.2018.13

Dawidowicz, J., Czapczuk, A., Kruszynski, W. (2021). Kohonen Artificial Networks for the Verification of the Diameters of Water-pipes. *Rocznik Ochrona Srodowiska*, *23*, 835-844. DOI: 10.54740/ros.2021.057

Dawidowicz, J., Czapczuk, A., Piekarski, J. (2018a). The Application of Artificial Neural Networks in the Assessment of Pressure Losses in Water Pipes in the Design of Water Distribution Systems. *Rocznik Ochrona Srodowiska*, *20*, 292-308.

Dawidowicz, J., Kruszynski, W., Andraka, D., Czapczuk, A. (2018b). Assessing the Diameters of Water Pipes Using the k-Nearest Neighbours Method in the Calculations of Water Distribution Systems. *Rocznik Ochrona Srodowiska*, *20*, 528-537.

Isermann, R., Balle, P. (1997). Trends in the application of model-based fault detection and diagnosis of technical processes. *Control engineering practice*, *5*(5), 709-719.

Knapik, K., Bajer, J. (2010). *Waterworks: a textbook for students of higher technical schools.* Cracow: Publishing house of the Cracow University of Technology. (in Polish).

Kościelny, J.M. (2004a). Models in the Diagnostics of Processes. In: Korbicz, J., Kowalczuk, Z., Kościelny, J.M., Cholewa, W. (eds) *Fault Diagnosis* (29-58). Berlin: Springer. DOI: 10.1007/978-3-642-18615-8_2

Kościelny, J.M. (2004b). Process Diagnostics Methodology. In: Korbicz, J., Kowalczuk, Z., Kościelny, J.M., Cholewa, W. (eds) *Fault Diagnosis* (59-117). Berlin: Springer. DOI: 10.1007/978-3-642-18615-8_3

Kwietniewski, M. (2009). *GIS in water and sewage systems*. Warsaw: Scientific Publishing House PWN (in Polish).
Lansey, K, Mays, L.W. (2000). Hydraulics of water distribution systems. In: Mays L.W. (ed.) *Water distribution systems handbook*. New York: McGraw-Hill.
Ormsbee, L.E. (2006). The history of water distribution network analysis: the computer age. In: *Proceedings of the 8th annual water distribution systems analysis symposium*, (1-6). USA, Cincinnati: ASCE.
Palade, V., Bocaniala, C.D. (eds.). (2006). *Computational intelligence in fault diagnosis*. London: Springer Science & Business Media.
Patan, K., Korbicz, J. (2004). Artificial Neural Networks in Fault Diagnosis. In: Korbicz, J., Kowalczuk, Z., Kościelny, J.M., Cholewa, W. (eds.) *Fault Diagnosis* (333-379). Berlin: Springer. DOI: 10.1007/978-3-642-18615-8_9
Piasecki, A., Jurasz, J., Kaźmierczak, B. (2018). Forecasting daily water consumption : a case study in Torun, Poland. *Periodica Polytechnica Civil Engineering*, *62*(3), 818-824.
Rossman, L.A. (2000). *EPANET 2 users manual*. Cincinnati: U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory.
Shamsi, U.M. (2005). *GIS applications for water, wastewater, and stormwater systems*. New York: CRC Press Inc., Taylor & Francis Group.
Walski, M.T., Chase, D.V., Savic, D.A., Grayman, W.M., Beckwith, S., Koelle, E. (2003). *Advanced water distribution modeling and management*. Waterbury: Haestad Methods Solution Center, Haestad Press.
Zhu, D., Zhang, T., Mao, G. (2002). Back-propagation artificial neural networks for water supply pipe line model. *Tsinghua Sci. Technol.*, *7*(5), 527-531.