Nodal Demand Control Genetic Algorithm for Water Supply Systems

Sterowanie zapotrzebowaniem węzłowym w systemach zaopatrzenia w wodę z wykorzystaniem algorytmu genetycznego

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The management of water distribution networks is nowadays exposed to various hazards, and their operations need to meet a range of critical conditions, new to the industry, that need to be addressed and solved. This article describes an approach that could be applied in case of intermittent deficit of water supply, by controlling the nodal demand in a water supply network. The article provides a mathematical approach to meeting minimum required water demand in case of supply shortages. Based on a simple hydraulic model case study, a genetic algorithm is implemented to find optimal valve settings which provide a minimum supply of water under water deficit conditions. The results highlight limitations and advantages relating to the time taken to perform calculations. Moreover, some practical aspects are pinpointed in the discussion section.

Keywords: intermittent water supply, genetic algorithm optimization, nodal demand control, water distribution networks management.

Zarządzanie systemem zaopatrzenia w wodę obecnie narażone jest na różne zagrożenia, a funkcjonujące sieci wodociągowe muszą spełniać szereg nowych dla branży warunków krytycznych, które należy identyfikować i uwzględniać w procesach eksploatacji. W artykule opisano podejście, które można zastosować w przypadku okresowego deficytu zaopatrzenia w wodę, poprzez sterowanie poborem w węzłach sieci wodociągowej. W artykule przedstawiono model matematyczny sterowanie sieci w celu zaspokojenia minimalnego wymaganego zapotrzebowania na wodę w przypadku niedoborów zasobów. W oparciu o studium przypadku prostego modelu hydraulicznego, zaimplementowano algorytm genetyczny w celu znalezienia optymalnych ustawień zaworów, które zapewniają minimalne zaopatrzenie w wodę w warunkach deficytu. Wyniki wskazują na ograniczenia i zalety związane z czasem wykonywania obliczeń. Ponadto w części poświęconej dyskusji wskazano kilka praktycznych aspektów takiego podejścia.

Słowa kluczowe: przerywane dostawy wody, optymalizacja algorytmem genetycznym, kontrola zapotrzebowania węzłowego, zarządzanie sieciami wodociągowymi.

Introduction

The main aim of water supply is to provide water in the required amount and under the required pressure to all users. A well-designed system should provide such supply during normal operating conditions. In recent years, rapid urbanization and climate changes have led to problems with low levels of water at intakes (streams, lakes or aquifers). Many methods are presented in the literature with the purpose of tackling the challenge of water scarcity [1]. This research mainly concerns the development of methods for increasing water efficiency [2]–[7] and the implementation of integrated water resource management [6-12]. An important task of water resource management is to develop network operation algorithms that can be used when a water crisis occurs.

The management of a water distribution system (WDS) during abnormal conditions such as a water source deficit requires the development of new algorithms and operating procedures. One possible solution is a method to control water demand at nodes. The main thesis of this paper is that proper water demand management in real time makes it possible to minimize the effects of water shortages. This task should be formulated mathematically as an optimization problem. Finding a solution to such a problem in the optimization theory is possible with the use of a hydraulic model of the network with the use of an appropriate optimization method. The literature on the optimization of water supply systems is very wide and constantly developed, there are also attempts to systematize various methods [13].

The concept of nodal demand control was presented by Morosini et al.[14]. In that research the Max-Sum method was used to develop nodal demand control algorithms for a WDS. This paper presents a slightly different approach, based on the

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assumption that during a critical network situation a certain minimum level of service for all consumers should be maintained. A PDA (Pressure Driven Analysis) model of a water distribution system was used. After modification of the model, a genetic algorithm was tested to develop nodal control algorithms for a WDS.

Methodology

The first stage of the work was to derive a mathematical description of nodal demand control in a situation of water shortage. The presented approach is based on the EPANET PDD model[15]. The problem of nodal demand control is then described as an optimization task, by defining the objective function, limitations and optimization criteria. A genetic algorithm was tested for solving an optimization problem. The methodology is presented schematically in Figure 1.

Problem description

In order to supply users with the required amount of water, the hydraulic pressure at the receiving point (h_i) should be greater than or equal to the required design pressure at that point (h_{des}). A pressure excess ensures that the actual water supply (Q_i) is equal to the required demand (Q_{dem}). The situation in which the water supply network operates under normal conditions is shown in Figure 2.

When the supply capacity of the water source is reduced, the pumping station is not able to provide the required pressure at nodes of the network. This situation causes a pressure drop at each node ($h_{drop,i}$), as a result of which the amount of water supplied is reduced. If the reduced pressure is higher than the defined minimum pressure ($h_{min,i} < h_{drop,i} < h_{des,i}$), water is still supplied to the node, but in a quantity less than required ($0 < Q_{drop,i} < Q_{dem,i}$). If the pressure is below the minimum ($h_{drop,i} < h_{min,i}$), the water supply is interrupted ($Q_{drop,i} = 0$). The situation of a water supply system subject to a pressure drop is shown in Figure 3. In this case, the first customer still receives a water supply, but the supply of water to the second customer is not possible.

Nodal demand control makes it possible to change the water inflow to users. A pressure reduction for the first user (Δh) may cause an increase in pressure at other nodes (second user). In this situation both first and second users still receive a water supply. A water supply system with nodal demand control is shown in Figure 4; it is achieved by adding control valves at nodes.

A mathematical description of the problem is given in Table 1. The main aim of the described nodal demand control is to provide a minimum amount of water for every user.

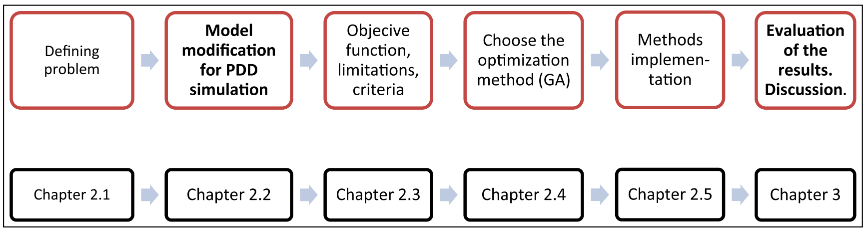


Fig. 1.
Research methodology
Rys. 1. Metodologia badań

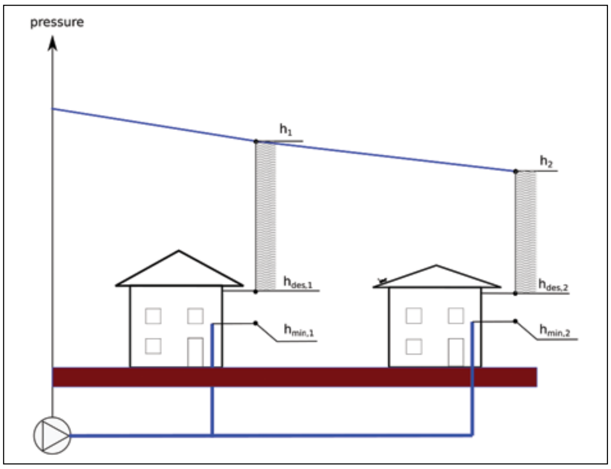


Fig. 2.
Pressure in the water supply network versus customer demand – the situation when customer demand is met
Rys. 2. Ciśnienie w sieci wodociągowej, a zapotrzebowanie użytkownika – sytuacja zaspokojenia zapotrzebowania klienta

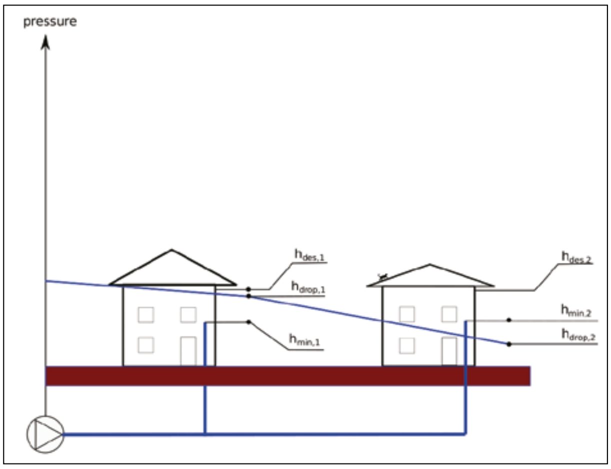


Fig. 3.
Pressure in the water supply network versus customer demand – the situation when water supply pressure does not cover customer demand
Rys. 3. Ciśnienie w sieci wodociągowej a zapotrzebowanie użytkownika – sytuacja, w której ciśnienie wody nie pokrywa zapotrzebowania klienta

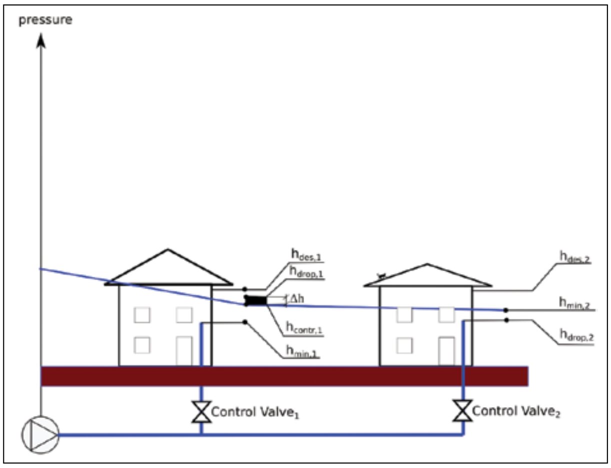


Fig. 4.
Pressure in the water supply network versus customer demand – a situation with demand control, reducing the supply to one user to ensure availability for others
Rys. 4. Ciśnienie w sieci wodociągowej a zapotrzebowanie odbiorców – sytuacja z kontrolą popytu, ograniczaniem podaży do jednego użytkownika w celu zapewnienia dostępności dla innych

Modification of the PDD model

WDS modeling in the EPANET program is performed using the Demand Driven Analysis (DDA) approach [16–18]. There are two assumptions behind the

Table 1. Relations of pressure and water supply in different network conditions
Tabela 1. Relacje ciśnienia i zaopatrzenia w wodę w różnych warunkach sieciowych

Normal condition	Pressure drop	Pressure drop with control
$h_1 > h_{des,1}$ $h_2 > h_{des,2}$	$h_{min,1} < h_{drop,1} < h_{des,1}$ $h_{drop,2} < h_{min,2} < h_{des,2}$	$h_{cont,1} < h_{drop,1}$ $h_{min,1} < h_{drop,1} < h_{des,1}$ $h_{cont,2} > h_{drop,2}$ $h_{min,2} < h_{drop,2} < h_{des,2}$
$Q_1 = Q_{dem,1}$ $Q_2 = Q_{dem,2}$	$0 < Q_{drop,1} < Q_{dem,1}$ $Q_{drop,1} = 0$	$0 < Q_{cont,1} < Q_{drop,1} < Q_{dem,1}$ $0 < Q_{drop,2} < Q_{cont,2} < Q_{dem2}$

algorithms run by the program's engine. First, the total water demand allocated to the nodes is fully met, irrespective of the network pressure conditions. Next, demand aggregation can be observed at the two nearest nodes, despite the fact that water distribution to consumers takes place along a single pipeline.

Calculation using the DDA method is justified and sufficient when designing a system and during its operation in normal conditions. However, in case of lower pressure due to an accident, power outage, isolation of a midsize area or any increased water outflow (leaks), the real outflow from the node, presented in Fig. 5 as *d* (m^3/s), depends on the network pressure *p* (psi).

Such a situation requires the Pressure Point Demand (PDD) approach to be used. This is primarily based on declaring the ratio of water outflow *q* from the node to the demand *d* at the node, given the actual pressure in the network. While calculations are being performed, demand will not change until the pressure falls below the predefined threshold of the required water pressure h_{des}.

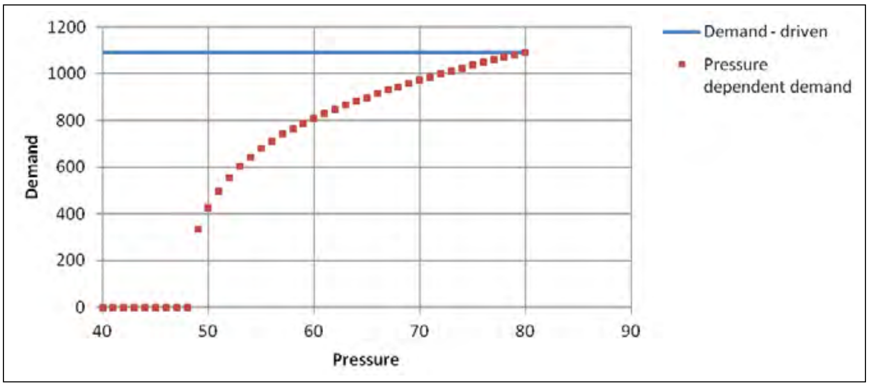
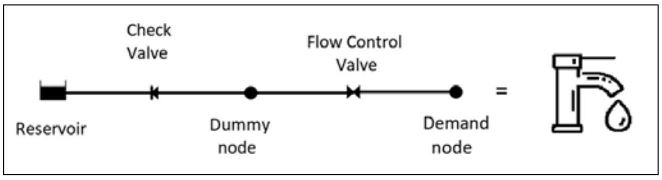


Fig. 5.
Relationship between pressure (p) and demand (d) using both demand-driven and pressure-dependent demand simulation [19]
Rys. 5. Zależność między ciśnieniem (p) a popytem (d) z wykorzystaniem symulacji przy stałym poborze i poborze zależnym od ciśnienia [19]

A review of PDA methods was presented by Paez, Suribabu and Filion in 2018 [20]. For the purpose of this work the method of Babu and Mohan [21] was used to perform calculations for a Pressure-Deficient Water Distribution Network. Water requirements assigned to so-called dummy nodes must be set at zero, since the reservoir collects water from the network (this enables calculation of the mass of water). The flow control valve (FCV) is designed to ensure that the supplied water flow does not exceed the requirement at that node, hence the setting of the FCV equals the water requirement at the node. The next valve is used only to connect the FCV and the reservoir. The model of a user node for PDD simulation in EPANET and the graphic symbol used in example network descriptions are shown in Figure 6.

Fig. 6.
User node definition used in PDD simulation
Rys. 6. Definicja węzła użytkownika używana w symulacji PDD



Use of these elements enables the modeling of real events occurring at a network's nodes. Since classic computation methods and WDN elements available in EPANET have been incorporated into the calculation, the results obtained provide better stability.

Formulation of the optimization problem

The main purpose of optimization is to find settings of valves installed at end users that will enable the supply of water to all consumers in given situations. An optimization problem requires definition of the objective (cost) function for which a global extreme value is sought. The value of this function strictly depends on, among others, the decision variables whose values are the solution to the optimization problem. For most practical problems, it is also important to identify the constraints that the solution must satisfy. Constraints may result from limitations on the physical functioning of the system, or may be additional requirements, imposed as quality criteria, for example. For the problem being analyzed, presented in Fig. 3, the cost function is defined with the equation *Eq.*, the decision variables *Eq.2* and the constraints *Eq.3, Eq.4.*

Cost function

$$\min \sum_{i=0}^{n} \left(Q_i(p,\Delta h) - Q_{i,req}\right)^2 \qquad Eq.\ 1$$

Variables

$$\Delta h = f(PBV\_set) \qquad Eq.\ 2$$

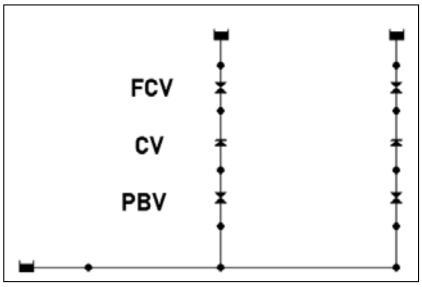


Fig. 7.
Water supply network diagram – Network A
Rys. 7. Schemat sieci wodociągowej – Sieć A

where:
PBV_set is the discrete setting of the control valve installed at the user node (Figure 4).

Constraints

$$0 \le PBV \le \Delta h_{max} \qquad Eq.\ 3$$

$$Q_i \ge Q_{min} \qquad Eq.\ 4$$

Genetic algorithm optimization

Preliminary analysis was performed using a simple water supply network model (Figure 7). PBV valves were introduced to calculate the value of the required pressure drop at the user. A detailed analysis was performed to assess how a change to the PBV settings impacts the water inflow to each user node.

Table 2. Comparison of results for example 1: brute force and genetic algorithms
Tabela 2. Porównanie wyników dla przykładu 1: algorytm brute force i genetyczny

	Brute force algorithm	Genetic algorithm
Value of goal function	94.137	94.137
TCV settings	0 3.05	0 3.03
Method settings	valve_setting_min = 0.0 valve_setting_max = 6.0 valve_setting_step: 0.01	valve_setting_min = 0.0 valve_setting_max = 6.0
Calculation time [s]	565.2	9.0

Water network analyses were performed using Matlab as the core of an environment in which several tools were integrated. The hydraulic model built in the EPANET program was loaded using the EPANET-Matlab-Toolkit library [22]. This package provides the methods to use the EPANET DLL directly in Matlab. The environment created made it possible to read the structure of EPANET models and then calculate the network hydraulic parameters for changed values of valve settings in accordance with the designed optimization algorithm.

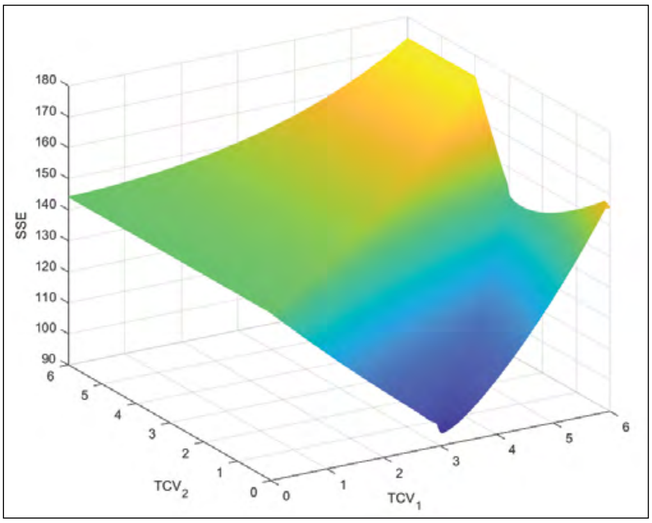


Fig. 8.
Graph with exhaustive search results for example A – TCV1 axis with valve 1 settings, TCV2 axis with valve 2 settings, and SSE axis with values of the objective function
Rys. 8. Wykres z wynikami metody pełnego wyszukiwania dla przykładu A – oś TCV1 z ustawieniami zaworu 1, oś TCV2 z ustawieniami zaworu 2, oś SSE z wartościami funkcji celu

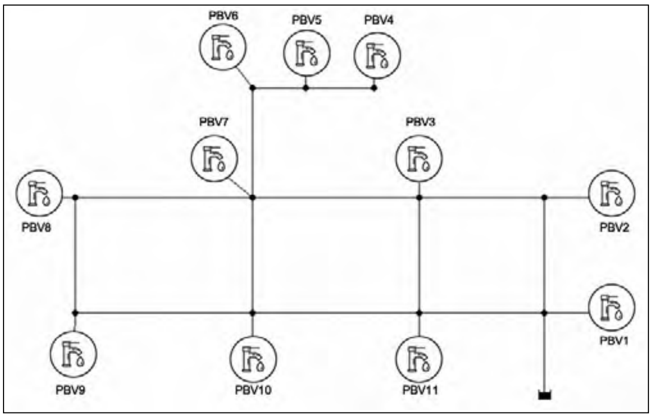
In the first analyses an exhaustive search method (brute force algorithm) was used. This method involves the analysis of all potential solutions of the task in order to select one that meets the task's conditions, with the assumed resolution of decision variables. Results are convergent values for the objective function and decision variables in a range of TCV settings (0–6). Due to the use of an exhaustive search method it was possible to illustrate how changing the TCV settings shapes the goal function. Figure 8 shows values of the goal function SSE within the range of variation of valve 1 and valve 2 settings.

The computational complexity of algorithms performing an exhaustive search is usually very large, often exponential. Using the method for more complex models can be a great challenge in terms of computing power. Therefore, despite the advantages of the very accurate results of an exhaustive search, other methods are sought that return satisfactory results with less use of computing power. In solving optimization problems, the genetic algorithm (GA) method is becoming more and more widely applied. The main advantage is simplicity of implementation and relatively high efficiency with a relatively low cost in computing power. GAs are global optimization methods, which in theory can find the global extreme. A GA method was used to solve the optimization problem for the same example model and goal functions and constraints. The results from both methods are given in Table 2. Taking into account calculation time, the application of the GA was very satisfactory; the algorithm found the best solution with 76 generations and 3625 function evaluations. The results from the GA method confirmed the usability of genetic algorithms in nodal demand control optimization, as they are very close to the results obtained from an exhaustive search.

Case study

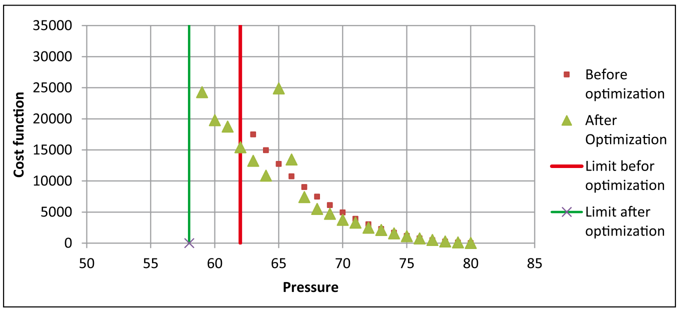
To assess the use of the GA algorithm for determining the valve settings at user nodes, analysis was carried out on a more complex water supply network model. Two situations were analyzed: before optimization, when the valves at user nodes are fully open; and after optimization, with nodal demand control applied. It was assumed that the minimum amount of water to be delivered to consumers is 5% of the water demand ($Q_{min} = 5\%{*}Q_{req}$) being the value of normal consumption. A simplified example model named Network B, consisting of 11 user nodes supplied from one source, is shown in Fig. 9.

Fig. 9.
Water supply network diagram – Network B
Rys. 9. Schemat sieci wodociągowej – Sieć BResults



The aim of using GA was to determine the optimal settings of valves. For

Fig. 10.
Cost function values for different inlet pressures for Network B
Rys. 10. Wartości funkcji kosztów dla różnych ciśnień na zasilaniu dla sieci B



the analyzed case study the cost function was calculated for changed values of the network's inlet pressure. Results from simulations show that the minimum value of the inlet pressure required to guarantee a water supply at user nodes without valve control was 62. The use of valve control optimization allows the pressure to be reduced to 58, while maintaining the minimum water supply service for each user node. The results obtained are presented in Fig. 10. With decreasing network inlet pressure, a difference can be seen in the cost function values. In most cases, for the same inlet pressure value, it is possible to perform an optimization – the objective function value is better with the use of optimization by controlling the valves at the user nodes. Only in two cases (pressure = 65 and 66) does the cost function become worse; this may result from specific conditions in the water network.

Total demand for water in time is constant for all user nodes, and does not vary with inlet pressure changes. As shown in Fig. 11, with decreasing pressure in the network, the water consumption in the analyzed period of time also decreases (before optimization the pressure limit is at 62; after optimization the pressure limit is at 57). Although the total water consumption is reduced, it is assumed that its distribution between user nodes is more even.

Presented below is a detailed analysis of user nodes (Figs. 12–22). Each graph displays node inflow values for a given network inlet pressure as:

- ▬ demand;
- ■ inflow before optimization;
- ◆ inflow after optimization.

For user nodes PBV1 and PBV2, inflow values are equal before and after optimization; this is due to the close proximity of the water supply source (Fig. 12, Fig. 13).

Analyzing the results in detail, it is observed that inflow before optimization is equal to demand at nodes PBV3, PBV5, PBV6, PBV7, PBV10 and PBV11. In these cases, optimization lowers the node inflow values (Figs. 14–19).

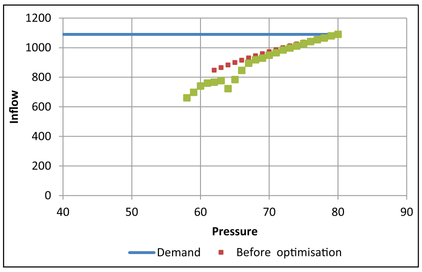


Fig. 11.
Total water inflow as a function of pressure changes before and after optimization in Network B
Rys. 11. Całkowity dopływ wody w funkcji zmian ciśnienia przed i po optymalizacji w sieci B

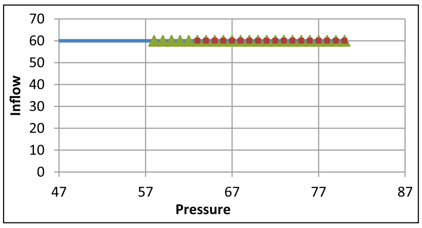


Fig. 12.
Water inflow as a function of pressure changes before and after optimization at PBV1
Rys. 12. Dopływ wody w funkcji zmian ciśnienia przed i po optymalizacji przy PBV1

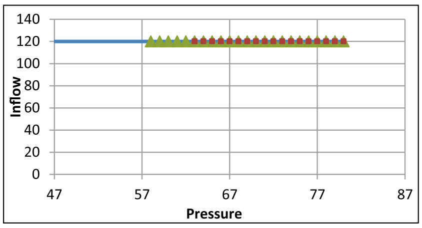


Fig. 13.
Water inflow as a function of pressure changes before and after optimization at PBV2
Rys. 13. Dopływ wody w zależności od ciśnienia przed i po optymalizacji przy PBV2

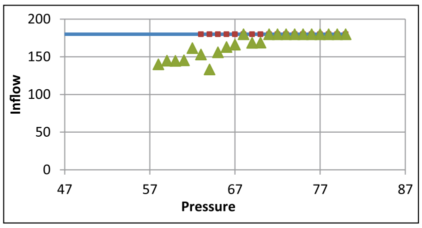


Fig. 14.
Water inflow as a function of pressure changes before and after optimization at PBV3
Rys. 14. Dopływ wody w zależności od ciśnienia przed i po optymalizacji przy PBV3

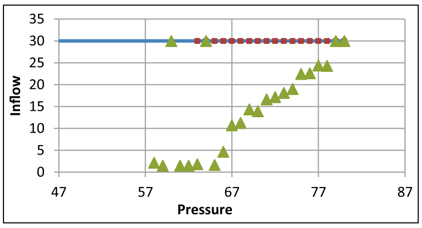


Fig. 15.
Water inflow as a function of pressure changes before and after optimization at PBV5
Rys. 15. Dopływ wody w zależności od ciśnienia przed i po optymalizacji przy PBV5

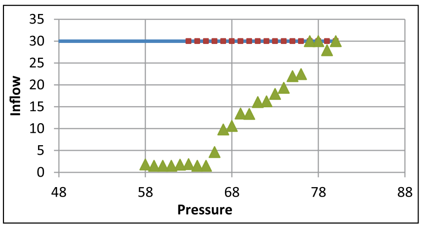


Fig. 16.
Water inflow as a function of pressure changes before and after optimization at PBV6
Rys. 16. Dopływ wody w zależności od ciśnienia przed i po optymalizacji przy PBV6

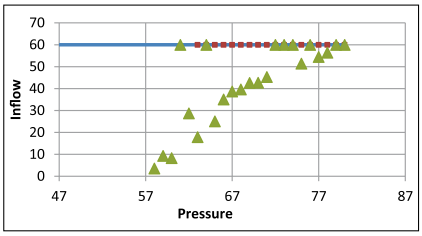


Fig. 17.
Water inflow as a function of pressure changes before and after optimization at PBV7
Rys. 17. Dopływ wody w zależności od ciśnienia przed i po optymalizacji przy PBV7

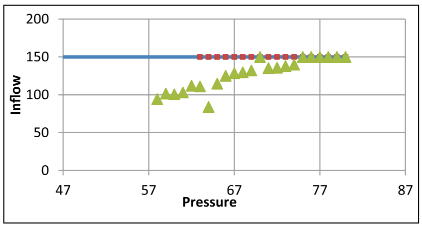


Fig. 18.
Water inflow as a function of pressure changes before and after optimization at PBV10
Rys. 18. Dopływ wody w zależności od ciśnienia przed i po optymalizacji przy PBV10

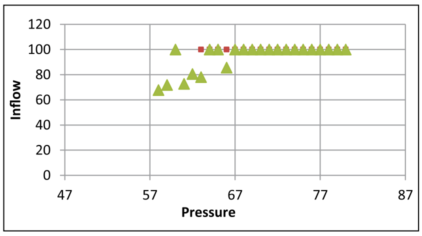


Fig. 19.
Water inflow as a function of pressure changes before and after optimization at PBV11
Rys. 19. Dopływ wody w zależności od ciśnienia przed i po optymalizacji przy PBV11

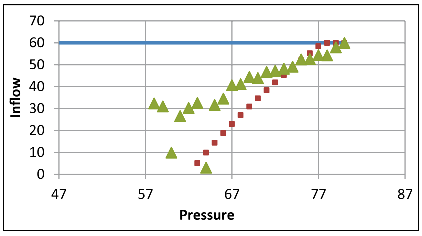


Fig. 20.
Water inflow as a function of pressure changes before and after optimization at PBV4
Rys. 20. Dopływ wody w zależności od ciśnienia przed i po optymalizacji przy PBV4

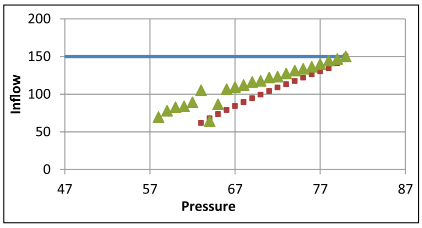


Fig. 21.
Water inflow as a function of pressure changes before and after optimization at PBV8
Rys. 21. Dopływ wody w zależności od ciśnienia przed i po optymalizacji przy PBV8

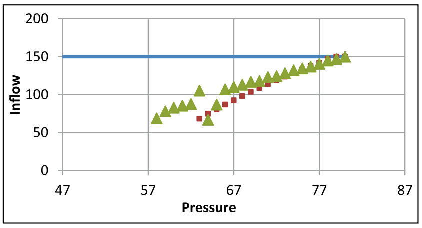


Fig. 22.
Water inflow as a function of pressure changes before and after optimization at PBV9
Rys. 22. Dopływ wody w zależności od ciśnienia przed i po optymalizacji przy PBV9

The greatest changes can be observed in the valves at the user nodes PBV4, PBV8 and PBV9 (Figs. 20–22). These nodes lack a water supply in the case without optimization. The structure of the analyzed water supply network causes significantly greater inflows to the previously mentioned user nodes (PBV3, PBV5, PBV6, PBV7, PBV10 and PBV11). Reducing the inflows to them, by partially closing the valves, makes it possible to increase the inflow to points PBV4, PBV8 and PBV9 and to supply water at the assumed service level.

Discussion

The analysis carried out on a simple model shows that the use of nodal demand control makes it possible to supply water in a minimum quantity to a larger number of residents when a water deficit occurs. Before nodal demand control, the distribution network required a supply with inlet pressure 62 m_{H2O} or higher. Use of nodal demand control enabled the supply pressure to be lowered to 58 m_{H2O} while maintaining the minimum quantity of water supplied (Figure 10). With the use of nodal demand control the total amount of water supplied to all consumers is reduced, due to additional head loss in the network (Figure 11). This is due to the fact that additional resistance must be introduced for some users (Figs. 14–19), which significantly reduces the amount of water supplied to them. On the other hand, it makes it possible to supply water to other recipients (Figs. 20–22), even in a minimal quantity. For some consumers nodal demand control does not affect the amount of water supplied (Figure 12, Figure 13). In two cases (when the pressure is equal to 65 and 66; Figure 10) the value of the objective function with the use of nodal demand control was higher than the value of the objective function without nodal demand control. The results still satisfy the assumed criterion, but are not optimal. This situation may occur when metaheuristic methods of optimization are used.

During optimization the valve settings were determined. These settings can be used to determine the flow coefficient Kv for valves. It is planned to extend the research discussed here with an analysis of the control aspects of certain types of valves serving to implement nodal demand control settings.

In the course of the research, a few technical issues were observed that are worthy of mention:

- For practical reasons, future studies should provide for the sectorization of networks into smaller areas, independently controlled, to avoid the need to simulate flow control per individual customer. The benefits would be optimized calculation time and the need for far less regulating equipment in the network.
- Although the proposed approach should well suit the needs of personal household consumers, a reduction in water supply by 10–15% for industrial consumers may impact their production processes and, in some cases, halt their operations. It should be made clear that in critical situations it is drinking water for the population that has top priority, yet in case of intermittent shortages of water supply usually key customers are treated with priority. The proposed method does not exclude the possibility of extension by different criteria for different nodes.

It should be highlighted, as has been previously discussed [23], that the application of heuristic algorithms may be unsuccessful and there may be cases when the algorithm cannot find an optimal solution.

There are multiple methods of PDD modeling in WDS, using both commercial (WaterGEMS etc.) and freeware applications (EPANET 2.2, WNTR, EPANET-PDD, etc.). Forthcoming research should include a review of these in terms of calculation processing time as well as the optimization of far larger and more complex WDS models.

Genetic algorithms can be widely used in the design, operation and control of water supply systems. Currently, there are many ready-made IT tools that enable relatively easy implementation of optimization using a genetic algorithm. The advantage of this type of method is the ability to quickly find a good solution to a formulated research problem without having to search the entire set of possible solutions. The main disadvantage of genetic algorithms is uncertainty about the solution. Genetically algorithms do not always find the best solution (optimization – in the strict sense, ie the global extreme), especially when there are local extremes of the function.

The time of calculations is crucial in the situation of practical application of optimization results to control the water supply network via SCADA. Generally, genetic algorithms are considered relatively fast, but for large water supply networks, the time to obtain results may be insufficient. To be able to take advantage of the optimization in real-time systems with a very large network, a solution may be preparation of predefine control scenarios, or the use of hybrid methods – also using other optimization methods, e.g. neural networks.

Summary and conclusions

The aim of the research was to test the possibility of using a genetic algorithm as a support tool for determining nodal demand control algorithms for water networks. The problem of nodal demand control was presented as an optimization problem. The genetic algorithm was implemented using the EPANET-Matlab toolkit. The main conclusions from the work are:

- Nodal demand control makes it possible to manage a water distribution system when a water deficit occurs. With the use of nodal demand control it is possible to provide a water supply (at least at a minimum level) for more users by means of properly set node valves.
- The genetic algorithm is an effective tool for determining valve settings for nodal demand control. In two cases the value of the objective function after optimization was higher than without nodal demand control. The result still meets the criteria, but is not optimal. This situation may occur with metaheuristic methods. There is a need to test different optimization methods for solving the model demand control problem and to compare the effectiveness of algorithms.
- The aim of the article was to show the possibility of using the genetic algorithm to control the nodal demand in the water supply network, and to assess its effectiveness, the results were compared with the methods of the full review. The possibility of using other optimization methods for hydraulic networks is a planned direction of further research, especially a comparison of the advantages and disadvantages of these methodologies for water networks of various sizes.
- The developed method allows the calculation of valve settings, and the

proposed algorithm can be implemented at the operations level of a water supply system. In the case of a production system, reduction valves can be installed at important points of the network, for example at the beginning of the pressure zone in a water distribution system or at connections with large customers.

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