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Optimization of Energy Consumption in the Pumping Station Supplying Two Zones of the Water Supply System

Martyna Świętochowska * and Izabela Bartkowska

Faculty of Civil Engineering and Environmental Sciences, Bialystok University of Technology, Wiejska 45E Street, 15-351 Bialystok, Poland; i.bartkowska@pb.edu.pl
* Correspondence: martyna.swietochowska@wp.pl

Abstract: Water supply pumping stations are among the main energy-consuming elements in the water supply system. The energy optimization of a pumping station can significantly affect the energy consumption of a water utility. This article deals with the energy optimization of water pumping stations. The work assumes several variants of optimization of water supply pumping stations through changes in the water supply system, pressure changes in the pumping station, and modification of the number of pumps. After analyzing the network, conducting field tests, and creating a model of the water supply network, the network was calibrated in order to reproduce the existing water network as accurately as possible. Then, a variant analysis was performed, and the best optimization method for the pumping station was selected. In two variants, there was a decrease in electricity consumption; in three there, was an increase; in one, there was no change. By connecting the DMA zones and modifying the pressure in the pumping station, the energy consumption of the pumping stations was reduced. On this basis, it was found that it is possible to optimize the water pumping station by modifying the pumping station and work related to the network layout.

Keywords: pumping station; water distribution system; water supply; water distribution system model; fire flow test; model calibration

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1. Introduction

As the quality of life increases, people's need for water increases dramatically. The optimization problem is very important to water utilities [1,2].

Water supply pumping stations are an indispensable element of any water supply system. They provide not only water supply to each recipient, but also the required pressure on the water supply network for firefighting purposes. The cost of energy is one of the most important components of the price of treated water. They include, among others, costs of pumping and transporting water [3–5]. Global trends in electricity savings and constantly growing electricity prices force you to look for savings at "every step".

The issue of optimizing the pump station includes issues related to the operation, design, and modernization of the water distribution system. Particular attention should be paid to the following:

1. basic tasks of the water supply network,
2. tasks related to fire protection,
3. tasks related to water loss reduction,
4. optimization of electricity consumption,
5. optimization of costs of modernization and maintenance of pipes and devices (pumps, hydrants, gate valves, water meters, etc.)

The basic task of the water distribution system is to provide consumers with water with the right pressure, the right volume, and good quality [6].

Another task of the water distribution system is to provide water for fire protection purposes. Polish law requires that the DN80 overground hydrant must meet the following requirements [7]:

1. for settlement units over 2000 inhabitants:
    1.1. flow (Q) $\geq$10 dm$^3\cdot$s^{-1},
    1.2. static pressure (Ps) $\leq$1.6 MPa,
    1.3. dynamic pressure (Pd) $\geq$0.2 MPa;
2. for settlement units under 2000 inhabitants:
    2.1. flow (Q) $\geq$5 dm$^3\cdot$s^{-1},
    2.2. static pressure (Ps) $\leq$1.6 MPa,
    2.3. dynamic pressure (Pd) $\geq$0.2 MPa.

The pumping station should deliver water to the highest and most unfavorable places in the network. The minimum internal diameter of the pipes used for fire protection purposes should be the following [7]:

1. for a branched network—125 mm,
2. for the ring network—100 mm.

Water loss reduction has a positive effect on the optimization of the pumping station's operation. Reducing the volume of actual losses reduces water consumption from the environment, reduces the flow in the pipes, and reduces the linear resistance, i.e., lower pressure at the outlet from the pumping station. This is important especially in months with high failure rate of the network, which are most often during periods of increased water consumption in the network or periods of temperature decrease [8]. The reduction in pressure in the network directly contributes to the reduction in the UARL (unavoidable annual real losses) level [9]. It also leads to a reduction in electricity consumption. Proper water metering allows for a reduction in apparent losses and provides information on the characteristics of the water consumption. It is important to correctly select the flow measurement devices and the possibility of including them in the monitoring of the water supply network (e.g., remote reading of water meters, DMA measurement points with reading via GSM/GPRS/IoT) [10,11]. The data from the loggers provide the information necessary to control the operation of the pumping station (flow and pressure) and provide information for the preparation of the pattern for the computer model [12,13].

Optimization of electricity consumption is realized through activities related to the replacement of pumps, change of the pumping station operation, modernization of the pipe system, computer modeling of changes in the network operation, and selection of solutions that guarantee the best economic and technical effects [14].

One of the other methods of optimizing the operation of the water pumping station is the construction of the pumping station–network–tank cooperation systems [15]. The main pumping station feeds the network with constant efficiency. The tanks are filled at minimum flow hours. During the hours of maximum consumption, the tanks ensure an increased demand for water. Field tanks bring many benefits, such as the following:

1. possibility of applying variable electricity price tariffs,
2. selection of pumps for lower parameters,
3. constant flow in the main lines,
4. reduction in water hammer in the water supply network,
5. the possibility of using PAT microturbines in the water supply network for energy recovery and supplying monitoring or control points [16].

The construction of field tanks requires considerable investment outlays: design, building permit, purchase or lease of construction site, construction cost, and changes to the pumping system. The construction of field tanks was not approved by the management of the water supply company at the stage of preparing the plans/variants and was not simulated in the research.

Optimizing water pumping stations in terms of ensuring flow and pressure with minimal energy costs may take into account the improvement of other parameters [17], e.g., health and hygiene criteria (acceptable drinking water quality) [18], social–cultural criteria [17], and environmental criteria (emissions of CO_2 (kg/year)) [18]. Optimization of pumping stations can bring savings in both electricity consumption and carbon dioxide emissions, in addition to protecting water resources [19].

Possibilities of the water supply network to provide the town with water for fire protection purposes are checked during hydrant tests. Branched networks are especially exposed to failure to meet fire protection requirements. The hydrant tests performed in the tested network showed that one of the zones supplied from the water pumping station did not provide the required flow and pressure from the hydrants. This is a very common case that causes decisions to change the water supply network. The management staff often decides to carry out various types of investments, e.g., replacement of pumps, expansion of the pump set, construction of new parallel water pipes, changing the diameter of the supply pipes, or increasing the pressure at the outlet of the pumping station. These decisions are made depending on the financial capabilities and knowledge of the staff. The development of science and engineering has provided new solutions, methods, and techniques that provide technical and economic foundations for making informed and optimal decisions. Due to the occurrence of a situation where one of the zones does not meet the fire protection requirements, it was decided to conduct tests and use the available computer techniques to check possible solutions, and then select the optimal solution in terms of the criteria set.

The article presents the optimization of the water pumping station in terms of its costs and generating network efficiency. The research described in the article shows how electricity consumption will change after calibration of the water supply model in various variants in relation to the existing state.

2. Materials and Methods

The main goal of previous studies was to optimize the operation of the pumping station: maximizing pumping efficiency, reducing electricity consumption, and providing flow and pressure in hydrants in the event of a fire.

In order to analyze the optimization of energy at water pumping stations, field tests were carried out; then, a hydraulic model of the water supply network was prepared and calibrated in accordance with the assumed variants. Preparation of the base variant is described in Figure 1. In addition to optimizing the operation of the pumping station and reducing energy consumption, a necessary condition is to ensure a minimum pressure for firefighting in the water supply network [20].

The research and simulations on the optimization of the pumping station and the water supply network were carried out according to the process presented in Figure 2.

The water pumping station is equipped with a set of three identical pumps. The pump set is controlled by means of the variable-speed pump controller which is permanently set at the outlet pressure from the pumping station. The DMA 1 zone is located about 40 m above the pumping station. The DMA 2 zone is located about 30 m above the pumping station. The zone's main pipe is a 225 mm PVC. Then, the main pipe turns into two pipes: a 225 mm PVC to supply the DMA2 zone and a 110 mm HDPE to supply the DMA1 zone. DMA 1 and DMA 2 zones supply about 1500 inhabitants.

The field research included measuring the pressure on the hydrant and measuring the hydrant's efficiency. Aboveground and underground hydrants were used for the measurements. Measurements were made at two measurement points, at the end of zones (DMA 1 and DMA 2; Figure 3).

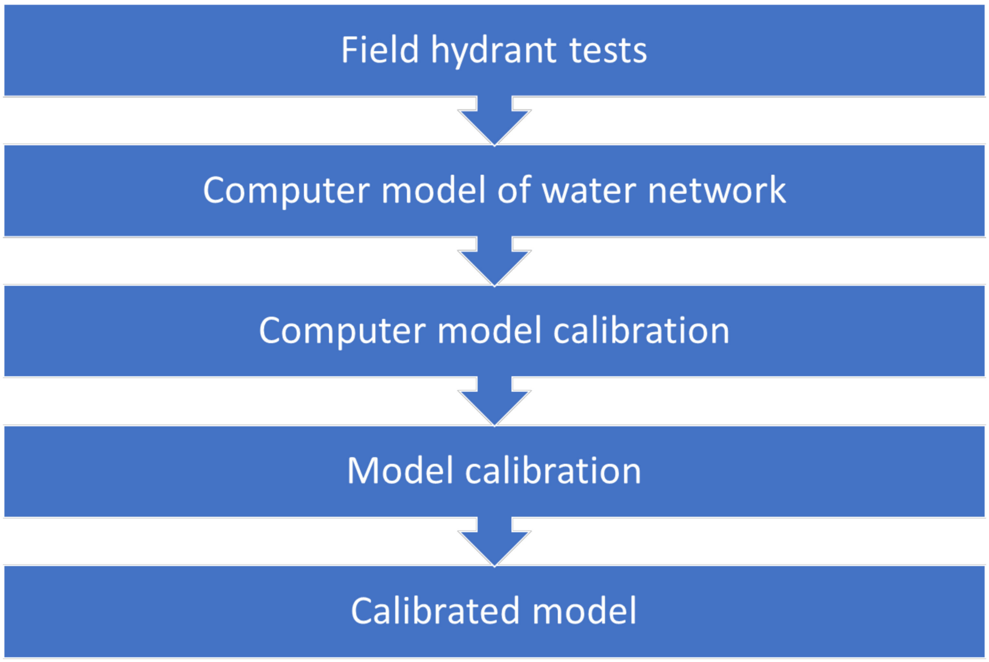

Figure 1. Basic variant preparation diagram (current state) for further analysis and optimization.

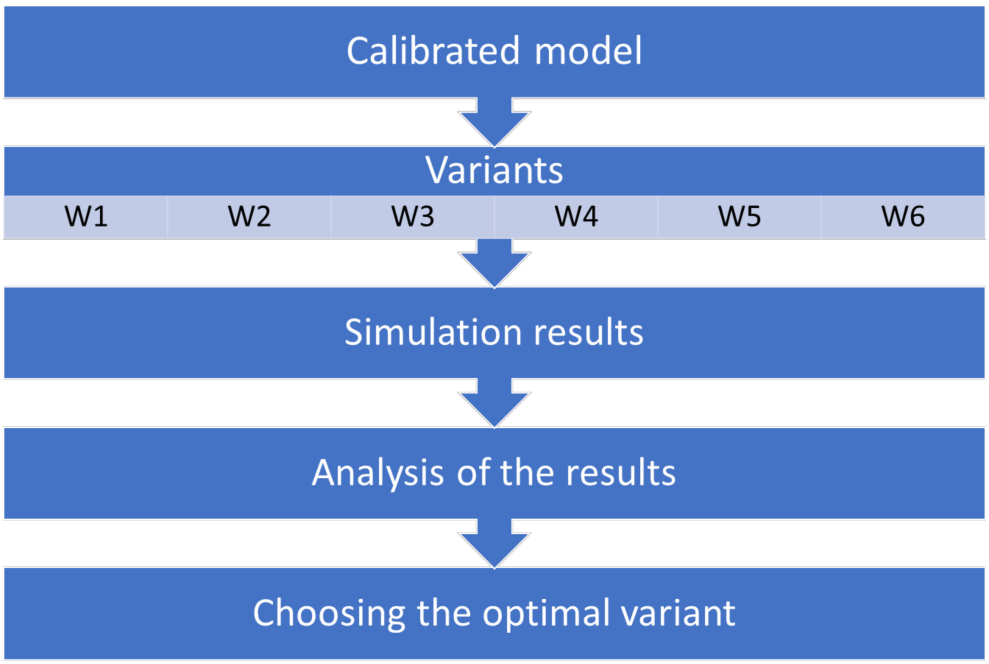

Figure 2. Diagram of the pumping station operation optimization research process.

Pressure data loggers with a measuring range of 0–20 bar and an accuracy of 0.1 FS were used to measure the pressure. The measurement points were underground and aboveground hydrants located in two zones of the system. Hydrant efficiency was tested using HYDROTEST measuring devices. The device enables the measurement of static pressure before opening and dynamic pressure after opening the hydrant. Measuring nozzles located in the device make it possible to measure the intensity of the outflow from the hydrant while measuring the dynamic pressure [21,22].

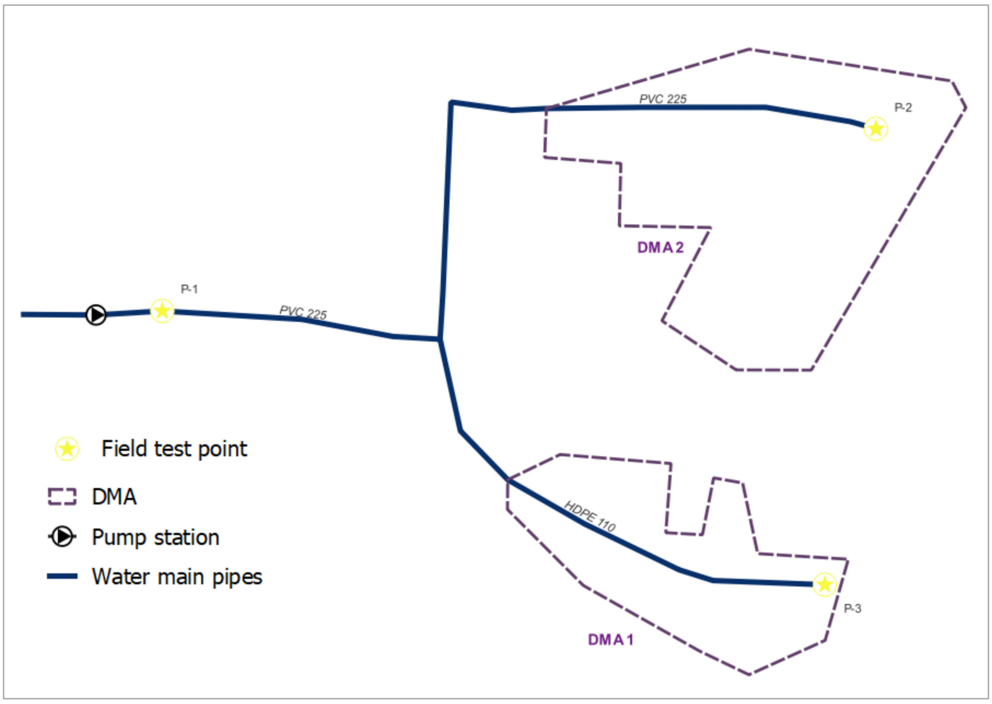

Figure 3. Diagram of the analyzed water supply network with division into measurement areas.

According to the results of hydrant tests, the water system operation was simulated using the EPANET software. Water system operation simulation, i.e., mathematical modeling of the water supply network, is based on the most accurate representation of the network operation in a computer system. It is described by linear and nonlinear algebraic equations. In order to formulate these equations, it is necessary to prepare the structure of the water supply network and the characteristics of the facilities, i.e., lengths and diameters of pipes, gate valves, valves, and pumping stations [23]. In EPANET, water system modeling is a collection of links connected to nodes. These connections are illustrated by pipes, pumps, and control valves. The nodes are junctions, tanks, and reservoirs. The EPANET program enables, among other aspects, tracking water flow in pipes and pressure changes in individual network nodes [24]. After the water network model was established, its calibration was started. Calibration was performed on the basis of the results of field measurements. The calibration consisted of entering the actual values of flow and pressure into the model and checking the correctness of the model. According to the data from the measurement point P-1, the characteristics of the flows at the outlet of the pumping station were determined (Figure 4). Figure 5 shows the simulation of hydrant tests. This simulation was performed for hours with the lowest and highest water consumption.

In order to assess the credibility of the model of the water network with the actual state of the network, a comparative assessment of the results of measurements and pressure simulations in two zones was carried out (Figures 6 and 7). The correlation plot shows the dispersion of the observed and modeled values. A better centering of points on the graph around 45° denotes a better fit of measurement and modeling results.

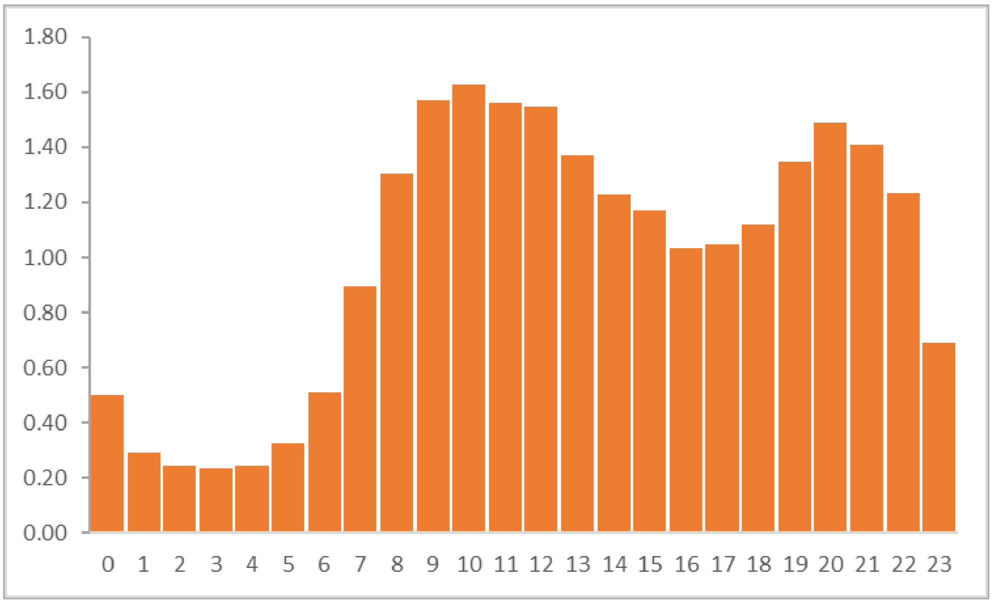

Figure 4. Pattern at measure point no. P-1, where flow was measured in the outlet of the pumping station.

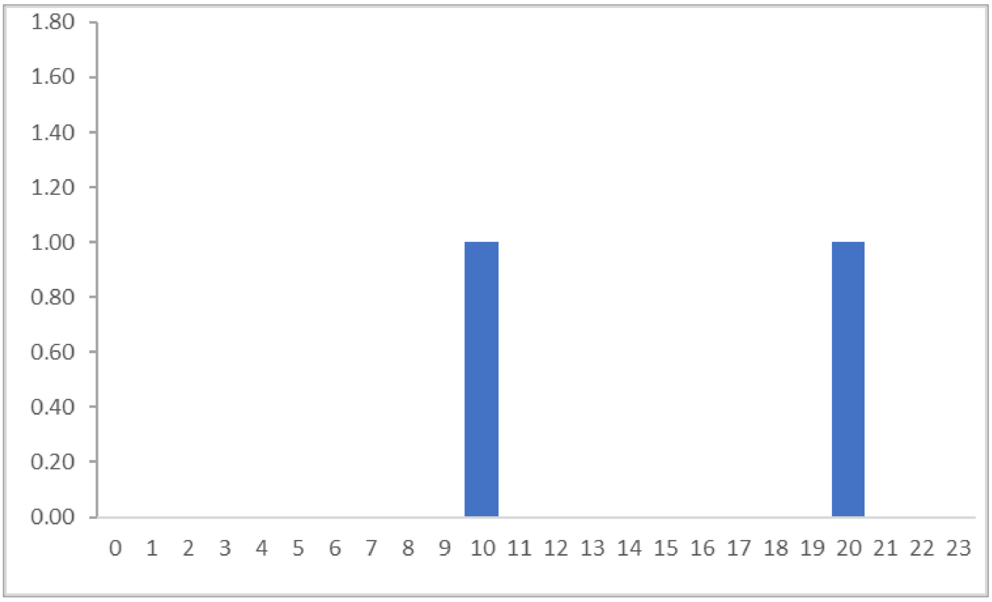

Figure 5. Pattern for hydrant test simulation in computer model.

According to the pressure calibration correlation analysis, it was found that the water network model can be considered correct.

In order to optimize the operation of the pumping station, six variants of the existing water supply network were assumed. These variants included connecting two zones with each other, reducing or increasing the operating pressure of the pumps, and adding another set of pumps (Figure 8).

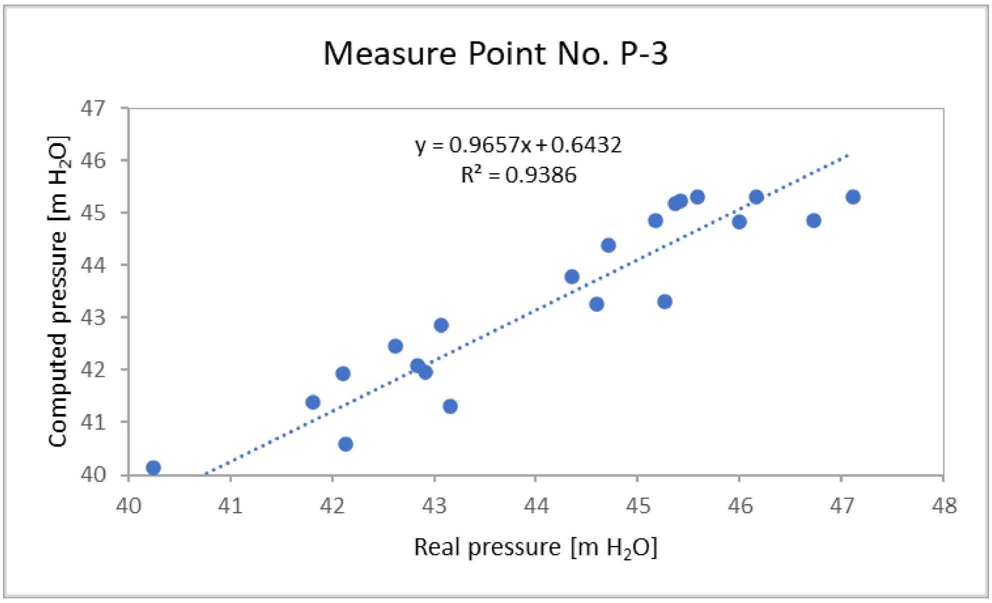

Figure 6. DMA 1 pressure calibration graph.

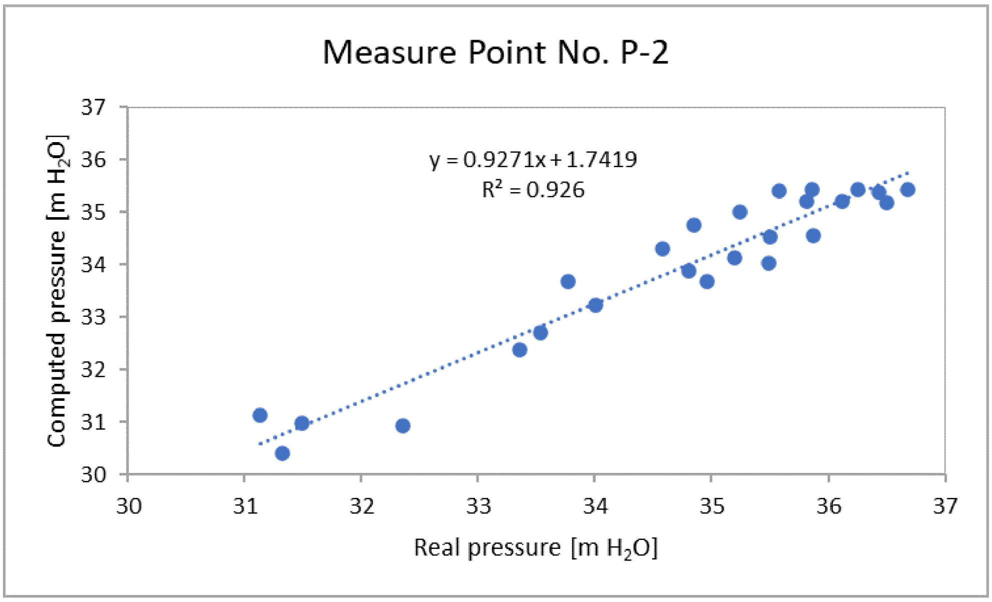

Figure 7. DMA 2 pressure calibration graph.

The first variant is the base variant called W0. This state is present at the output pressure of 0.66 MPa from the pumping station. The pumping station consists of three pumps with a power of 5.5 kW each, with the operating characteristics shown in Figure 9 (hydraulic pump curve) and Figure 10 (efficiency pump curve). DMA 1 and DMA 2 zones are not connected. The pipe supplying the DMA 1 zone is made of 110 mm HDPE (outer diameter). The pipe supplying the DMA 2 zone is made of 225 mm PVC (outer diameter). The pressure in the pipes from DMA 1 zone is approximately 0.35 MPa. The pressure in the DMA 2 zone is approximately 0.45 MPa. When water is drawn from a hydrant in the DMA 1 zone, the pressure drops below 0.2 MPa. The pressure in the DMA 2 zone when water is drawn from the hydrant is reduced to approximately 0.31 MPa.

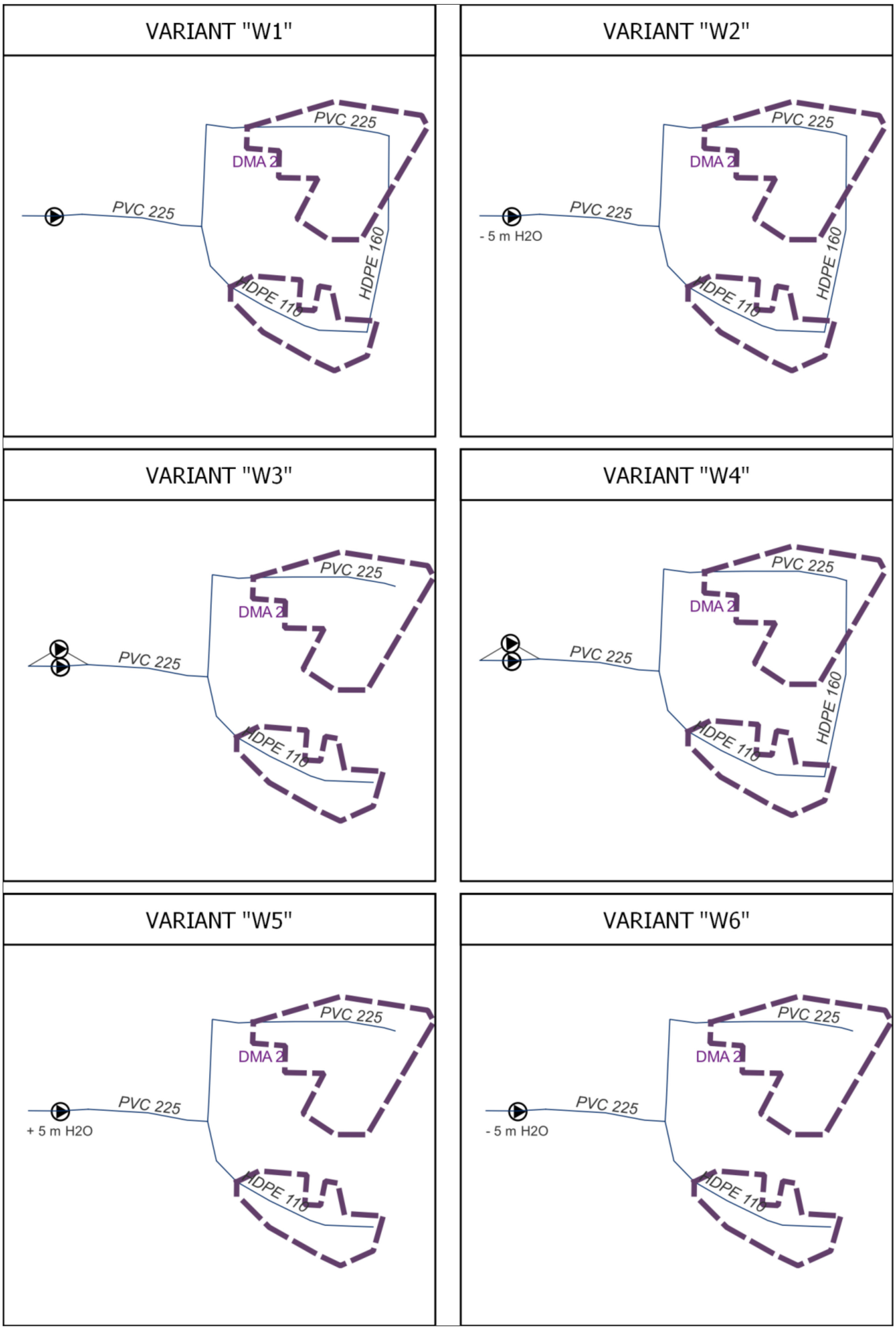

Figure 8. Variants of water supply network modification.

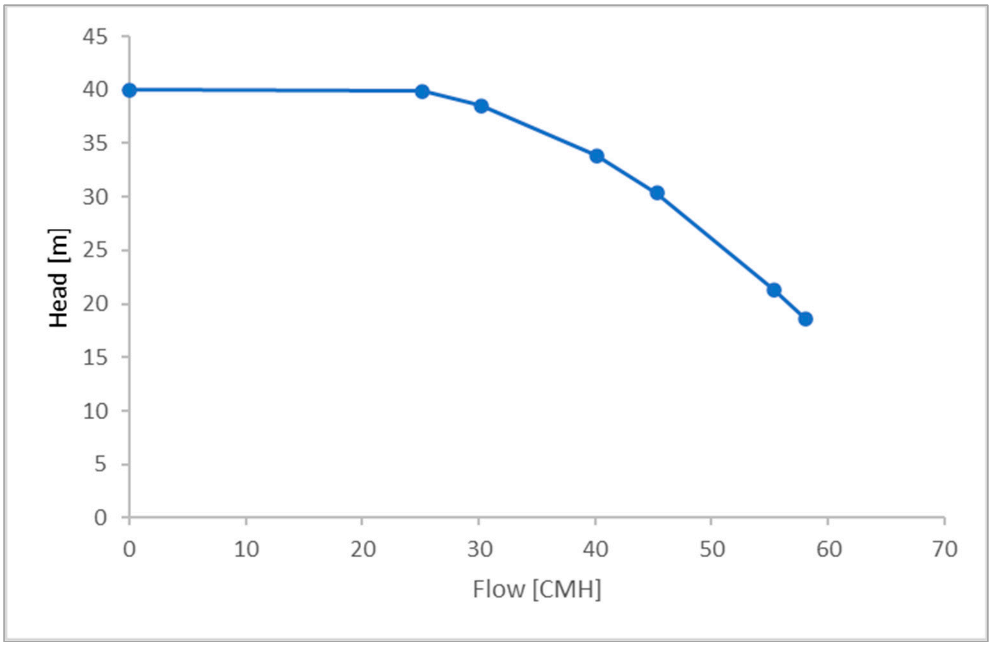

Figure 9. Hydraulic pump curve.

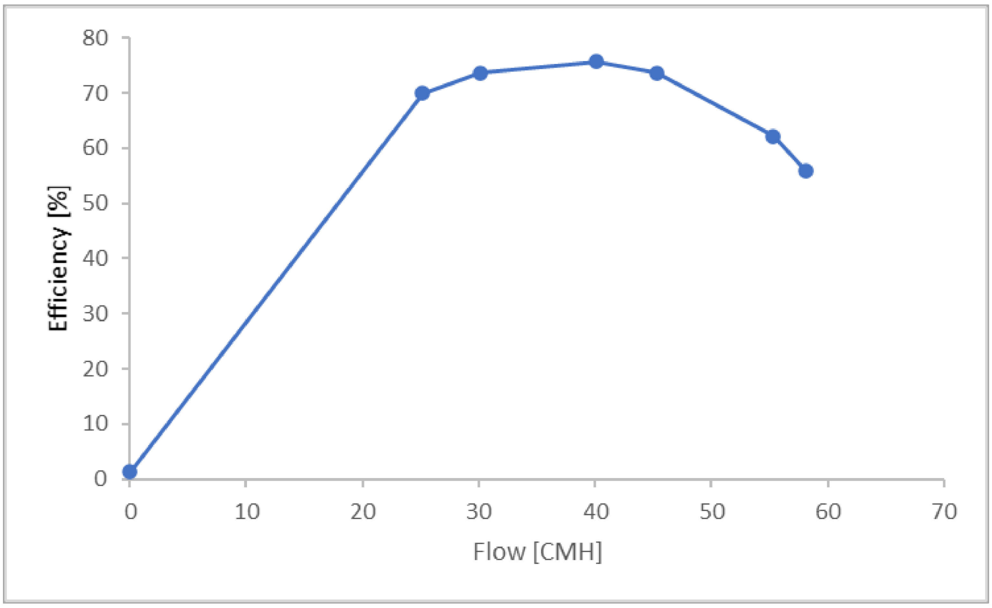

Figure 10. Efficiency pump curve.

Variant W1 assumes connecting two zones with each other. The pipe connecting the zones is planned as 160 mm HDPE (outer diameter). The operating parameters of the pumping station are the same as in variant W0.

Variant W2 assumes connecting two zones of the water supply network, with a simultaneous output pressure of the pumping station reduction to 0.61 MPa. The pipe connecting the zones is planned as 160 mm HDPE (outer diameter).

Variant W3 assumes adding an additional pump. The pipe system is the same as in the W0 variant.

Variant W4 assumes the connection of two zones of the water supply network with the simultaneous addition of an additional pump. The pipe connecting the zones is planned as 160 mm HDPE (outer diameter).

Variant W5 assumes increasing the pressure on the pump to 0.71 MPa. The pipe system is the same as in the W0 variant.

Variant W6 involves a reduction in pressure in the outlet of pumping station to 0.61 MPa. The pipe system is the same as in the W0 variant.

3. Results

3.1. The Results of Electricity Consumption

Through the proposed methodology, the assumed variants, and calculations of costs, an optimization of the pumping station's operation with the required pressure for fire-fighting purposes was conducted. Figure 11 shows the average efficiency of the pumping station in the assumed variants.

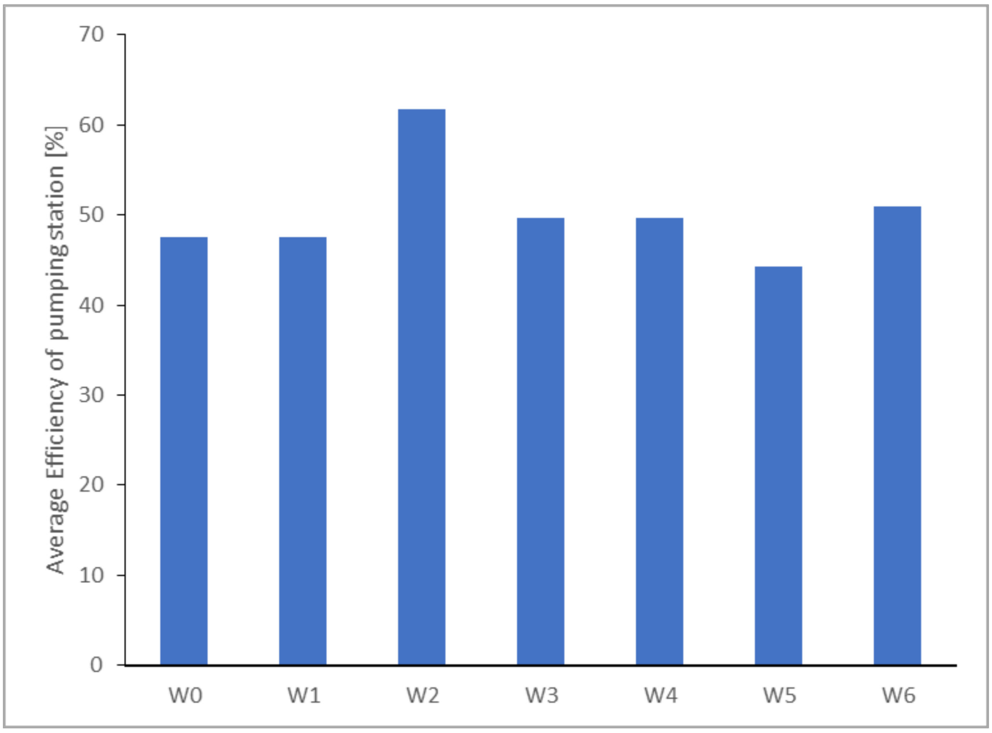

Figure 11. Pumping station efficiency curve.

The pumping station designed in the W1 variant had the same efficiency as the analyzed pumping station in the W0 variant. Pumping stations in variants W2, W3, W4, and W6 had higher efficiency than the pumping station in variant W0. The pumping station in the W5 variant had a lower efficiency than the pumping station in the W0 variant.

The changes in electricity consumption in the simulation variants are shown in Figure 12. The electricity consumption in the W1 variant was the same as in the initial variant; the proposed changes did not change the energy consumption. In the W3, W4, and W5 variants, after the performed calculations, an increase in electricity consumption was observed in relation to the initial variant. In the W2 and W6 variants, a reduction in electricity consumption was observed as compared to the initial variant. The lowest electricity consumption in the pumping station occurred in variant W2, in which the zones of the water supply network were connected. This allowed reducing the pressure by 5 m H_2O. The decrease in electricity consumption compared to the initial simulation variant was over 34%. The greatest increase in electricity consumption in the pumping station occurred in the W5 variant. In the W5 variant, the pressure at the outlet of the pumping station was increased by 5 m H_2O.

According to changes in energy consumption in the proposed variants, the costs of electricity consumed by pumping stations over 10 years were simulated (Figure 13). The energy consumption of the pumping station in variants W0 and W1 was the same. In variants W3, W4, W5, and W6, electricity consumption over 10 years was higher than in the initial variant. The W5 variant would use approximately 48% more electricity than the output pumping station. On the other hand, the pumping station in the most advantageous variant, W2, would consume about 37% less electricity than the output pumping station over a period of 10 years.

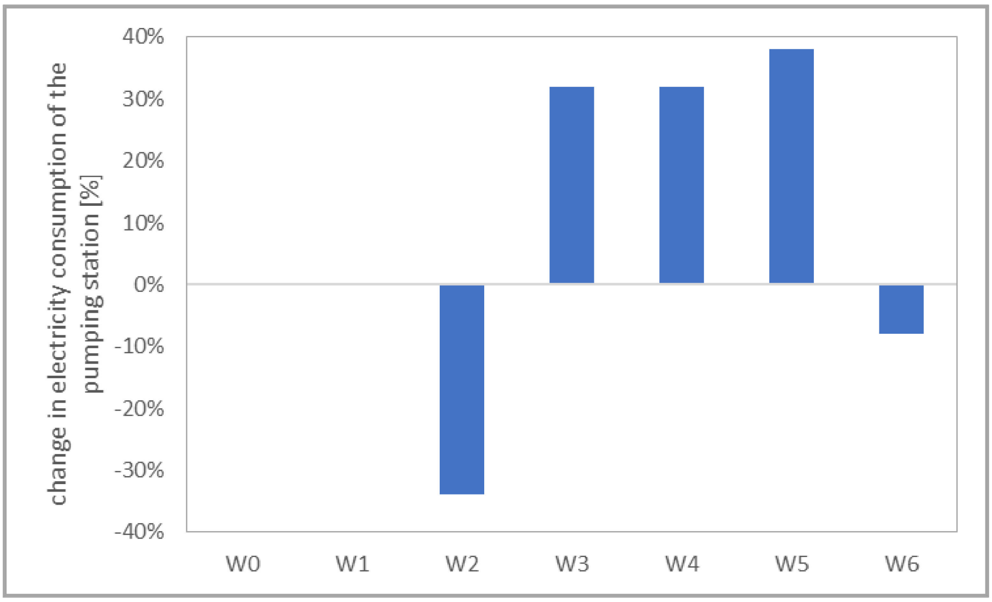

Figure 12. Percentage changes in electricity consumption in the pumping station in the analyzed variants of the water supply system operation [25].

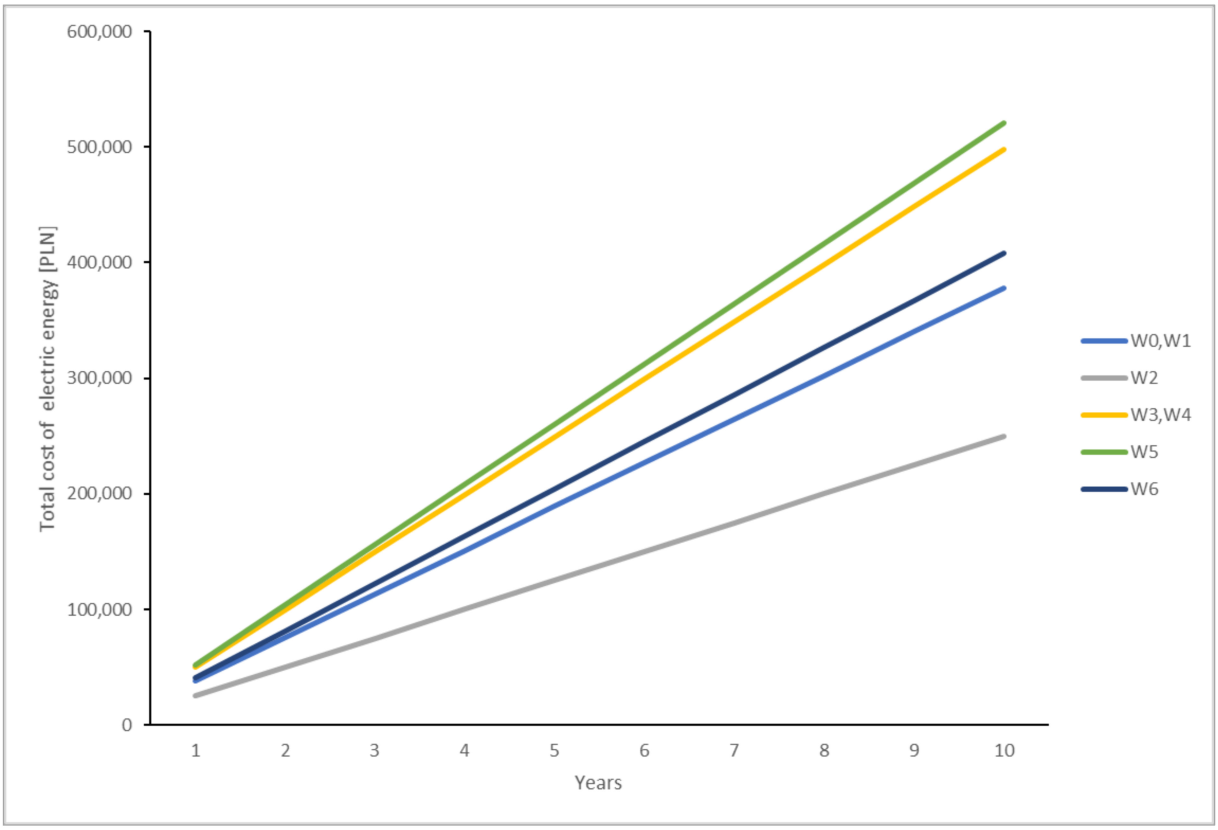

Figure 13. Simulation of pumping station operating costs over 10 years.

On the basis of the performed calculations and the analysis of the results, it was found that it was possible to optimize the operation of the water supply pumping station while maintaining the requirements for the minimum pressure required for firefighting purposes. The most advantageous option of optimizing the pumping station is to connect two zones of the water supply network with a simultaneous reduction in the pressure of the water pumped into the water supply network. The least favorable variants are those with an additional pump set added.

3.2. The Results of Optimization Variants by the Criteria

The prepared variants of the pumping station in the water supply system were aimed at finding a solution to the problem of too low pressure in the water supply network during the fire protection demand and a reduction in electricity consumption due to pumping.

A set of three criteria was selected to evaluate the computer simulations performed:

1. criterion 1—ensuring the minimum pressure during firefighting (the main criterion),
2. criterion 2—reduction in costs of pumping water (electricity consumption by the pumping station),
3. criterion 3—investment costs (construction of new pipes, purchase of additional pumps).

For criterion 1, the ratings were as follows:

(a) 0—minimum pressure below 0.2 MPa at the critical point of zone DMA 1.
(b) 1—minimum pressure over 0.2 MPa at the critical point of zone DMA 1.

For criterion 2, the ratings were as follows:

(a) −1—increase in pumping costs (increase in electricity consumption by the pumping station),
(b) 0—pumping costs at the same level as in variant W0,
(c) 1—reduction in pumping costs (reduction of electricity consumption by the pumping station).

For criterion 3, the ratings were as follows:

(a) −1—investment costs due to construction of a new pipe or purchase of an additional pump,
(b) 0—no investment costs.

Table 1 shows the comparison of variants in terms of meeting the main test criteria. It compares two factors, i.e., ensuring the required pressure for firefighting purposes and reducing energy costs.

Table 1. Comparison of variants in terms of the assumed goals.

Variant	Providing the Required Pressure for Firefighting Purposes	Reducing Energy Costs	Result
W0	0	0	0
W1	1	0	1
W2	1	1	2
W3	1	−1	0
W4	1	−1	0
W5	1	−1	0
W6	0	1	1

4. Discussion

Variant W0—the initial network layout—was used as the reference point for further analysis. Variant W1 provided the required pressure for firefighting, but did not reduce energy costs. In variant W2, the required pressure for firefighting purposes was ensured and energy costs were reduced. Variant W3 provided the required pressure for firefighting, but increased energy costs. In variants W4 and W5, as in variant W3, the required pressure for firefighting purposes was provided, but energy costs were increased. Variant W6 did not provide the required pressure for firefighting, but reduced energy costs. Due to the lack of the required pressure for firefighting purposes, variant W6 was considered a variant that should not be taken into account at all. Summarizing the results obtained in the described analysis, it was found that variants W1, W2, W3, W4, and W5 were those ensuring the required pressure for firefighting purposes. However, only variant W2 met the second required goal—reducing energy costs. Accordingly, variant W2 was considered to be an option that fulfills the two objectives pursued. This variant provided the required pressure and reduced energy costs.

An important aspect that should be considered, in addition to meeting the assumed goals, is the analysis of costs related to the purchase of additional pumps and the expansion of the water supply network.

Table 2 illustrates the comparison of investment costs related to the implementation of the assumed variants. Due to the earlier rejection of variant W6 as not meeting the required assumption, variant W6 was omitted for this comparison. Variant W0—the initial network layout—was used as the reference point for further analysis. Variant W1 met at least one of the assumed goals and generated additional costs related to the construction of the water supply network. Variant W2 met at least one of the assumed goals, reduced energy costs related to the operation of the pumps, and generated additional costs related to the construction of the water supply network. The W3 variant fulfilled at least one of the assumed goals, increased the costs related to the operation of the pumps, and generated additional costs related to the construction of the water supply network. The W4 variant fulfilled at least one of the assumed goals, increased the costs related to the operation of the pumps, and generated additional costs related to the construction of the water supply network. The W5 variant met at least one of the assumed goals, increased the energy costs related to the operation of the pumps, and did not generate additional costs related to the construction of the water supply network. Summarizing the obtained results, it was found that the W2 variant is the most economical in terms of additional costs related to the variant implementation. An important aspect that should not be forgotten when optimizing the operation of a pumping station is the cost associated with the implementation of a new solution. One should conduct a financial analysis and check that the costs of the new solution will not exceed the savings caused by the optimization of the pumping station.

Table 2. Comparison of the total sum of investments.

Variant	Ensuring the Assumed Goals	Pump Purchase Costs	Costs of Building a Water Supply Network	Result
W0	0	0	0	0
W1	1	0	−1	0
W2	1	1	−1	1
W3	1	−1	−1	−1
W4	1	−1	−1	−1
W5	1	−1	0	0

It is worth noting that connecting zones with a new pipe brings many benefits. The connection of two zones increases the reliability of the system in terms of water supply; in case of failure of the main water supply, water is supplied from the other side. The combination of the two zones reduces the stagnation of water on the end pipes in the zones. The connection makes it possible to reduce the internal diameters of the pipes required for the fire protection network from 125 mm internal diameter to 100 mm internal diameter. The performed measurements and computer simulations showed that, in the case of a branched network, pipes with DN <100 mm do not allow for the required outflow of water from the hydrant and the required pressure for fire protection purposes.

5. Conclusions

The goal of the research was achieved. As a result of the conducted research and analyses, the W2 variant was selected as the most optimal in terms of the benefits of reducing electricity consumption, while ensuring the required pressure and the necessary investments in infrastructure.

The use of computer techniques (computer models of the water supply network) is ideal for assessing the variants of planned investments. Computer simulations can reduce investment costs. The basis for the simulation should be a calibrated model.

Computer simulations based on water supply network models in conjunction with the analysis of results based on evaluation and acceptance criteria are a good tool for making decisions on the basis of technical and economic parameters.

Water supply networks with a ring system enable the achievement of better fire protection results than branched networks.

Lowering the pressure in the pumping station has a positive effect on the reduction in pumping costs, but requires other adjustments to be accepted by the service personnel for implementation.

Adding extra pumps to ensure flow and pressure may be the worst option in terms of investment cost and the cost of pumping water.

Optimizing the operation of a water pumping station is a complex issue and requires attention not only to energy costs, but also requires comprehensive planning due to the pumping and water supply system.

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References

1. Mala-Jetmarova, H.; Sultanova, N.; Savic, D. Lost in Optimisation of Water Distribution Systems? A Literature Review of System Design. *Water* **2018**, *10*, 307. [CrossRef]
2. Sen, Z. Water Structures and Climate Change Impact: A Review. *Water Resour. Manag.* **2020**, *34*, 4197–4216. [CrossRef]
3. Pulido-Calvo, I.; Gutierrez-Estrada, J.C. Selection and operation of pumping station of water distribution systems. *Environ. Res. J.* **2011**, *5*, 1–20.
4. Briceño-León, C.X.; Sanchez-Ferrer, D.S.; Iglesias-Rey, P.L.; Martinez-Solano, F.J.; Mora-Melia, D. Methodology for Pumping Station Design Based on Analytic Hierarchy Process (AHP). *Water* **2021**, *13*, 2886. [CrossRef]
5. Gutiérrez-Bahamondes, J.H.; Mora-Meliá, D.; Iglesias-Rey, P.L.; Martínez-Solano, F.J.; Salgueiro, Y. Pumping Station Design in Water Distribution Networks Considering the Optimal Flow Distribution between Sources and Capital and Operating Costs. *Water* **2021**, *13*, 3098. [CrossRef]
6. Available online: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20010720747 (accessed on 30 November 2021).
7. Available online: http://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20091241030 (accessed on 30 November 2021).
8. Gwoździej-Mazur, J.; Świętochowski, K. Evaluation of Real Water Losses and the Failure of Urban-Rural Water Supply System. *J. Ecol. Eng.* **2021**, *22*, 132–138. [CrossRef]
9. Lambert, A.O.; Brown, T.G.; Takizawa, M.; Weimer, D. A Review of Performance Indicators for Real Losses from Water Supply Systems. *AQUA* **1999**, *48*, 227–237. [CrossRef]
10. Gwoździej-Mazur, J.; Świętochowski, K. Analysis of the water meter management of the urban-rural water supply system. *E3S Web Conf.* **2018**, *44*, 1–8. [CrossRef]
11. Thornton, J.; Sturm, R.; Kunkel, G. *Water Loss Control*; McGrow-Hill: New York, NY, USA, 2008.

12. Gwoździej-Mazur, J.; Świętochowski, K. Non-Uniformity of Water Demands in a Rural Water Supply System. *J. Ecol. Eng.* **2019**, *20*, 245–251. [CrossRef]
13. Świętochowski, K. Limiting water losses through flow monitoring on the hydrophore example. *Technol. Wody* **2017**, *5*, 20–28.
14. Farley, M.; Wyeth, G.; Ghazali, Z.; Istandar, A.; Singh, S. *The Manager's Non—Revenue Water Handbook. A Guide to Understanding Water Losses*; USAID: Bangkok, Thailand, 2008.
15. Creaco, E.; Galuppini, G.; Campisano, A.; Ciaponi, C.; Pezzinga, G. A Bi-Objective Approach for Optimizing the Installation of PATs in Systems of Transmission Mains. *Water* **2020**, *12*, 330. [CrossRef]
16. Sambito, M.; Piazza, S.; Freni, G. Stochastic Approach for Optimal Positioning of Pumps as Turbines (PATs). *Sustainability* **2021**, *13*, 12318. [CrossRef]
17. Romero, L.; Pérez-Sánchez, M.; Amparo López-Jiménez, P. Improvement of sustainability indicators when traditional water management changes: A case study in Alicante (Spain). *AIMS Environ. Sci.* **2017**, *4*, 502–522. [CrossRef]
18. Hellström, D.; Jeppssonb, U.; Kärrmanc, E. A framework for systems analysis of sustainable urban water management. *EIA Rev.* **2000**, *20*, 311–321. [CrossRef]
19. Luna, T.; Ribau, J.; Figueiredo, D.; Alves, R. Improving energy efficiency in water supply systems with pump scheduling optimization. *J. Clean. Prod.* **2019**, *213*, 342–356. [CrossRef]
20. Ścieranka, G. *Internal Fire Hydrant Systems—Legal Status*; Rynek Instalacyjny: Warsaw, Poland, 2012; Volume 9.
21. Biatech Ltd. *Hydro-Test: Users Manual*; Biatech Ltd.: Zaścianki, Poland, 2020.
22. Świętochowski, K. The impact of testing fire hydrants on water loss. *Instal* **2018**, *11*, 41–43.
23. Stachura, M.; Fajdek, B.; Studziński, J. Management and control of water networks using mathematical models. *Appl. Comput. Sci. Stud. Mater.* **2013**, *4*, 11–18.
24. Rossman, L.A. *EPANET 2: Users Manual*; U.S. Environmental Protection Agency: Cincinnati, OH, USA, 2000.
25. Świętochowska, M.; Bartkowska, I.; Gwoździej-Mazur, J. Energy Optimization of the Pumping Station. *Environ. Sci. Proc.* **2021**, *9*, 37. [CrossRef]