Jacek DAWIDOWICZ • Andrzej STUDZIŃSKI

IMPACT OF STORAGE TANKS IN WATER DISTRIBUTION SYSTEM OF THE CITY KROSNO ON ENERGY CONSUMPTION AND COSTS IN WATER PUMPING STATIONS

Jacek DAWIDOWICZ (ORCID: 0000-0003-1742-9463) – Bialystok University of Technology
Andrzej STUDZIŃSKI (ORCID: 0000-0002-6551-9490) – Rzeszow University of Technology

Correspondence address:
Wiejska Street 45A, 15-351 Bialystok, Poland
e-mail: j.dawidowicz@pb.edu.pl

ABSTRACT: The aim of the presented study is to evaluate the impact of water supply tanks that cooperate with the water distribution system on the energy costs of water supply pumping stations. Network tanks accumulate a supply of water at night with low water intakes, making it possible to design a smaller pumping station. To achieve the above goal, a model of the water distribution system of the city of Krosno was prepared and numerical simulations were carried out using the EPANET program for various variants with an additional water tank at various locations. For each variant, the daily cost of pumping station operation, as well as the average and maximum electricity consumption, were read. A comparison of the results shows a positive impact on the reduction in the energy costs of water pumping stations.

KEYWORDS: water distribution systems, pumping stations, storage tank, electrical energy consumption, pumping costs

Introduction

Access to energy has a decisive impact on the functioning and sustainable development of societies. With the development of cities and industries, it is becoming increasingly difficult to ensure energy security. The increase in energy costs has a negative impact on the development of industry and the comfort of the residents. For many years, the topic of reducing energy consumption was not the most important topic, but in recent years, this has changed radically. The Energy Efficiency Act, supported by directives from the European Union, creates a strong impulse to save energy. One way is to improve the energy efficiency of various processes that accompany the processing and use of energy. Pump installations consume significant amounts of energy on a national scale. Of particular importance was the improvement in the operation of water pumping stations in water distribution systems to reduce energy consumption and, thus, reduce operating costs. This problem has become important due to the significant increase in electricity prices in recent years. Many different types of methods have been proposed to solve this problem. An aspect that can lead to a reduction in the cost of pumping water in distribution systems is the possibility of introducing retention reservoirs, which allow the use of night hours with reduced water consumption to create a water supply, which will then be used during the hours of highest abstraction during the day. This reduces the size of the pumping station, as the pumps do not have to be adjusted to the maximum water intake.

Two types of energy losses can be distinguished in water distribution systems (Jędral, 2007):

- unavoidable losses, which result from general causes, because the efficiency of any real physical process is less than 100%,
- unnecessary losses resulting from improper technical solutions and/or improper operation.

Unnecessary losses, that is, losses that can be eliminated or reduced, are most often caused by the following reasons (Jędral, 2007):

- unfavourable structure of pumping installations,
- inadequate pumping system concept,
- improper selection of pumps,
- changes in the operating conditions of the installation over the years,
- improper installation solution in terms of hydraulics,
- an irrational, excessively energy-consuming way of regulating efficiency,
- poor technical condition of the pumps,
- improperly selected (too large) electric drive motors,
- too low efficiency of drive motors,
- errors in the operation of pumps and pump installations.

Unnecessary losses, which cause excessive energy consumption of liquid transport, are often higher than unavoidable losses. The value of unnecessary losses is the amount of potential savings in industry, energy, and municipal management, among others, as a result of improving the operating processes of operating pumps.

In this study, the impact of storage tanks on the electricity consumption of water pumping stations was analysed. To achieve the above goal, a model of the water distribution system of the city of Krosno was prepared, and numerical simulations were carried out using the EPANET program (Rossman, 2000) for various variants with an additional water tank at various locations. For each variant, the daily cost of pumping station operation was read, as well as the average and maximum electricity consumption. A comparison of the results shows a positive impact on the reduction in the energy costs of water pumping stations.

An overview of the literature

Water distribution systems are characterised by high complexity, in which the cooperation of elements affects the reliability of the water supply and the costs of operation of the entire system. One of the important elements is the storage tanks, which can occur in various places in the water distribution system. Tanks have a significant impact on the operating costs of the pump stations that supply the system, but their implementation is associated with significant investment costs. A very

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important aspect is the appropriate location of the storage tank and the design of its volume. The methodology of designing water distribution systems with network tanks is described in the article (Prasad, 2010). The article (Hallmann & Suhl, 2016) proposes a method to support the tank planning process in water distribution systems. This method uses a combination of network reduction, mathematical optimisation, and hydraulic simulation. The research discussed in the paper (Trifunovic et al., 2015) aims to integrate storage tanks into the optimisation process, as well as to determine their impact on the total cost and reliability of the network. A tool called NORAT (Networks Optimisation and Reliability Assessment Tool) was used to determine the required storage volume, optimise pipe diameters and tank heights, and finally calculate the total cost of delivery. NORAT further evaluates the hydraulic reliability of the network. The tool was tested on a synthetic network using different combinations of topography, feed schemes, and locations of water sources and storage tanks. The results demonstrate NORAT's ability to use storage tanks in both the optimisation and reliability assessment processes. The paper (Guerrero-Angulo et al., 2006) proposes a method for designing a drinking water network with several tanks and water supply sources, using the design procedure of their components, taking into account the hydraulic interrelationships between them, the constant depths in the tanks at the beginning of the design process, and the variable depth at the end, as well as the different performance requirements of the components at each stage of the method.

The article (Amirabdollahian & Mokhtari, 2015) discusses research on the optimal design of loop water distribution networks with complex systems with storage tanks. Using the Fuzzy Genetic Algorithm, the genetic algorithm selects a viable network, while fuzzy reasoning evaluates the quality of each potential solution's water supply. Then, a new method was presented for the optimal design of the water distribution network in two stages of tank consumption and filling periods. Many articles present the results of works aimed at reducing electricity consumption and thus operating costs in water pumping stations. The thesis (Fang et al. 2010) deals with the design of multi-vessel systems with multiple supply pumping stations. In the first stage, the operation of each tank is determined according to the electricity tariff. In the second stage, a genetic algorithm analyses the problem of pump scheduling to ensure the appropriate efficiency of the pumping station. Significant energy savings can be achieved by carefully scheduling pump operation. The paper (Luna et al., 2019) presents a hybrid optimisation method to improve the energy efficiency of the water supply system toward more sustainable water management with respect to the water-energy nexus. A genetic algorithm was used to optimise the pumping schedule during the day. Knowing the water consumption a priori, it is possible to define the optimal pump condition for a specific time interval (e.g. every 1 hour), minimising operating costs. A water network model developed in the EPANET hydraulic simulator was used to evaluate the solutions. Many articles used machine learning methods to optimise pump schedules, e.g. genetic algorithms, and ant algorithms. Genetic algorithms have been used in many works to optimise the pumping station work schedule (Fu et al., 2016; Blinco et al., 2014; Chen et al., 2021; Cimorelli et al., 2020; Makaremi et al., 2017). The article (Mambretti, 2011) developed a method to optimise the water distribution network using a genetic algorithm and applied it to the Milan water supply network. This network is very complex, and there are no tanks, since the hydraulic pressure is maintained by the action of 31 pumping stations. Using real data, the operation of the entire network and pump station is simulated, with a real schedule, using software using EPANET. The model was used to optimise the operation of the pump station. In the paper (Dadar et al., 2021), the main objective of the presented research is to increase the operational efficiency of pumping stations by developing a model to reduce energy costs in municipal water supply systems. The optimal operation of the pumping station was determined using a genetic algorithm to achieve minimum energy costs. This paper presents a new management model for the optimal design and operation of water pumping systems in a real case study for the city of Gonabad, Iran. Ant colony optimisation (ACO) is a stochastic meta-heuristic for combinatorial optimisation problems that is inspired by the foraging behaviour of some ant species. A paper (López-Ibáñez et al., 2008) developed the application of the ACO structure for optimal pump scheduling. The proposed representation was adapted to the structure of the optimisation of ant colonies and solved for optimal pump schedules. Minimising electricity costs was considered a goal while meeting the limitations of the system. Instead of using the penalty function approach for restriction violations, restriction violations were ordered by severity and solutions were ranked according to that order. The proposed approach was tested on a small test network and a large real network. The paper (Barán et al., 2005) discusses the work on the

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application of multi-criteria evolutionary algorithms (MOEAs) to solve the problem of optimal pumping schedule with four objectives that need to be minimised: electricity cost, maintenance cost, peak maximum power, and tank level fluctuations. Six different MOEA algorithms were implemented and compared. To account for hydraulic and technical constraints, a heuristic algorithm was developed and combined with each MOEA algorithm deployed. The results indicate that the Strength Pareto evolutionary algorithm achieves better overall performance than other MOEA algorithms for the parameters considered in the test problem, providing a wide range of optimal pumping schedules to choose from. The problem of building optimal schedules for pump operation in advance of the day for branched water supply networks with a pumping station to tanks at different locations and at different levels was considered in the article (Bonvin et al., 2016). It is a type of water distribution system characteristic of rural areas. To solve the above problem, a number of sophisticated heuristic algorithms have been designed to solve this difficult problem. The paper (Celi et al., 2017) analysed the required capacities of two pumping stations that supply the water distribution system from different sides of the network. Pumping station capacities are analysed according to the demand curve of the network. The energy consumption of each source is evaluated by the product of the flow supplied and the minimum required head. The inflow distribution between the sources is then optimised, and the minimum head heights from the setpoint curve are obtained. The methodology was applied in two cases, one synthetic network and one real network, using numerical models prepared with the EPANET program. In fixed-speed pump systems, one approach is to optimise pump switching on and off by reducing pumping cycles (Yin et al., 1996). Other considerations looked at variable speed pumps (VSPs). They allow a better fit between the pumping system curve and the demand curve of the network, leading to a reduction in energy consumption (Lingireddy & Wood, 1998; da Costa Bortoni et al., 2008; Viholainen et al., 2013). The paper (Bene & Hős, 2012) presents a method to solve the problem of filling the tank at the least cost using a variable-speed pump in the case of a very simplified hydraulic system. The simplified model can be used as a tutorial or reference problem for pump-schedule optimisation problems. In the paper, a project to optimise industrial water supply pump stations is presented that takes into account the impact of ambient temperature on operating costs (Jia et al., 2020). In the paper (Swietochowska & Bartkowska, 2022), an analysis of several variants of water supply pumping stations was carried out through changes in the water supply system, changes in pressure in the pumping station, and modifications of the number of pumps. In two variants, there was a decrease in electricity consumption; in three, there was an increase; there was no change in one. By combining DMAs and modifying the pressure at the pumping station, the energy consumption of the pumping stations has been reduced. On this basis, it was concluded that it is possible to optimise the pumping station by modifying the pumping station and the works related to the network layout. The article (Zheng & Huang, 2016) discusses an optimal mathematical model investigating a large number of distributed water supply systems fed by a two-stage pumping station. Taking into account the water demand in rural areas and the time-dependent electricity prices that will affect operating costs, a mathematical model was developed to minimise electricity consumption during the operation of the system. The paper (Reis et al., 2023) reviews and systematises the literature on operational control strategies to reduce energy consumption and costs in water supply systems.

In the available literature, no items have been found considering the impact of the location and parameters of the network tanks on the energy consumption of pumping stations and thus the costs of pumping water.

Research methods

The task of a water supply system is to supply good quality water at the appropriate pressure, continuously and reliably. Due to technical limitations related to water resources and the capacity to supply the network, water supply systems are often supplied from more than one source. A common element of a water distribution system is a storage tank that cooperates with the entire water supply system. Storage tanks are designed to store excess water during nighttime hours when water consumption by recipients is reduced and then to supplement supplies during periods of increased consumption during daytime hours. An additional task of some water supply tanks is to equalise the

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pressure in the supply area, which changes at different times of the day depending on water consumption. Tanks are also used to store water supplies in the event of a fire and to ensure a water supply in the event of a failure. In the case of water distribution systems without expansion tanks, water supply pumping stations must be adapted to maximum water consumption, which is why the pumping stations must have a capacity adapted to significant consumptions, often occurring in a very short period of time during the day. The introduction of expansion tanks allowed for the accumulation of water during night hours, which would be used during peak consumption hours. This allowed for the use of smaller pumping stations with lower capacity, which should result in lower electricity consumption and, consequently, lower operating costs of the pumping station. The impact of additional storage tanks on electricity consumption costs was analysed for the water distribution system of the city of Krosno.

The city of Krosno and its neighbouring towns are supplied with water by the Municipal Utility Company – Krosno Municipal Holding. Water and sewage in the city of Krosno are carried out by Krosno Waterworks. The water supply system of the city and 11 communes of the Krosno, Sanok, and Brzozów counties consists of three Water Treatment Plants (WTP), which are located in the towns of Szczepańcowa, Iskrzynia, and Sieniawa, and a water supply network with a length of almost 800 km. The Water Treatment Plants (WTP) have two pumping stations that work alternately. The number of water connections in the city is almost 8 thousand. The water supply network includes 5 hydrophores and 4 pressure reducers, and two two-chamber expansion tanks are also connected (Studziński et al., 2022).

To analyse the impact of storage tanks on the operating costs of water pumping stations, a numerical model of the water distribution system of the city of Krosno was used, prepared using the EPANET program.

The costs of electricity used to ensure the correct operation of the water supply system are mainly due to the energy consumption of the pumps. However, electricity bills contain variable components that depend on consumption and fixed components that are independent of consumption. The total price of energy depends on many components, including ordered power, commercial fees, distribution fees, etc. For this analysis, the simulation of energy consumption was assumed on the basis of the energy cost per kilowatt hour. The cost of electricity was assumed on the basis of data from PGE Polska Grupa Energetyczna S.A. According to energy supplier data, from January 1 to March 31, 2025, the maximum electricity price was PLN 0,6930/kWh (excluding VAT and excise duty). This applies to local government units and entities performing public tasks (PGE Polska Grupa Energetyczna, 2025).

It was assumed that the pumping station was equipped with pumps with constant rotational speed, and in each variant, the characteristics were verified in such a way that the pumping station operated at a point close to the nominal parameters, characterised by the highest efficiency.

EPANET generates an Energy Report that displays statistics about the energy consumed by each pump and the cost of this energy usage over the duration of a simulation (Rossman, 2000). The Energy Report table lists the following statistics for each pump in the network:

- Percent Utilisation means that percent of the time that the pump was operating,
- Average Efficiency,
- Average power consumption (kWh) per cubic meters pumped,
- Average rate of energy usage (kilowatts),
- Peak rate of energy usage (kilowatts),
- The total cost.

First, a numerical simulation was performed with calculations of electricity consumption and daily pumping costs for the basic variant, without additional storage tanks. Then, simulations were performed for three alternative locations of the additional storage tank. Based on the tank capacity at the hour of maximum water consumption, the pumping station capacity was reduced accordingly, to store the supply of the water distribution network from all sources with the water consumption. On this basis, the electricity consumption and daily pumping costs for the variants with an additional tank were calculated.

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Results of the research

The diagram of the initial model of the water distribution system (variant 1) of the city of Krosno is shown in Figure 1. The results of the calculations for the above variant are presented in Table 1. The total cost of the pumping station for all water intakes in variant 1 is PLN 2407.68. The highest cost of the pumping station is generated in the WTP Sieniawa and is 1396.41. This is dictated by the operating conditions of the above pumping station. It is located at a considerable distance from the city, which results in high pressure on the pumping station, and it is also the basis of the water supply of the entire city. Therefore, in the second variant, a storage tank was introduced in the central part of the water distribution system (Figure 2), which replenishes water shortages after the reduction in the pumping station capacity in WTP Sieniawa. The operation of the reservoir was modelled in such a way that it cooperated with the water distribution system and the pumping stations. The results of the calculations for a system with an additional tank are presented in Table 2. The total cost of pumping water in the system is PLN 2021.24, which means that the introduction of an additional tank and the appropriate adjustment of the pumping station capacity in WTP Sieniawa allowed us to reduce pumping costs throughout the system by 16%. The cost of the pump in the WTP Sieniawa in the second variant is PLN 1021.38. In the third variant, a second additional tank was introduced on the opposite side of the system from the water pump station (Figure 3). The results of the calculations of the energy consumption and pumping costs for the third variant are presented in Table 3. The tank has been modelled in such a way that it works properly with the water distribution system. For this purpose, it was necessary to adjust the efficiency of all pump stations in the system, i.e. WTP Sieniawa, WTP Iskrzynia(1), WTP Iskrzynia(2) and WTP Szczepańcowa. In the third variant, energy consumption has been reduced by 27%. The total cost of pumping amounted to PLN 1748.85, while in individual pumping stations the costs of pumping stations amounted to, respectively (in brackets cost reduction compared to variant 1): WTP Sieniawa PLN 755.47 (reduction of 46%), WTP Szczepańcowa 423.67 (reduction of 2%). WTP Iskrzynia(1) (reduction of 1%) WTP Iskrzynia(2) (reduction of 1%).

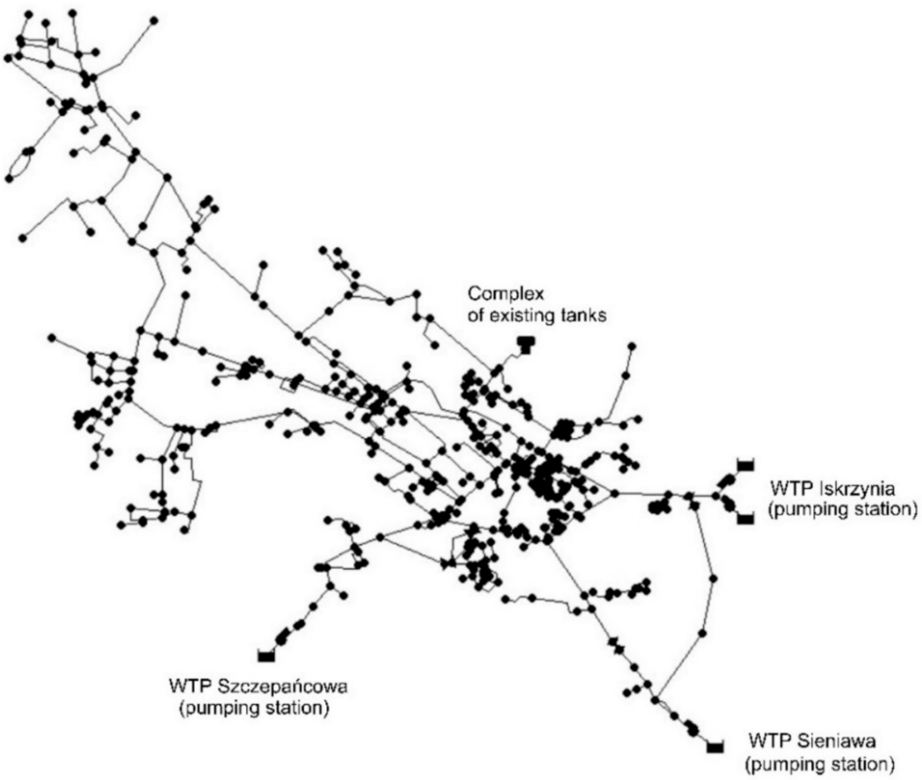

Figure 1. Basic diagram of the water distribution system of the city of Krosno without additional tanks (variant No. 1)

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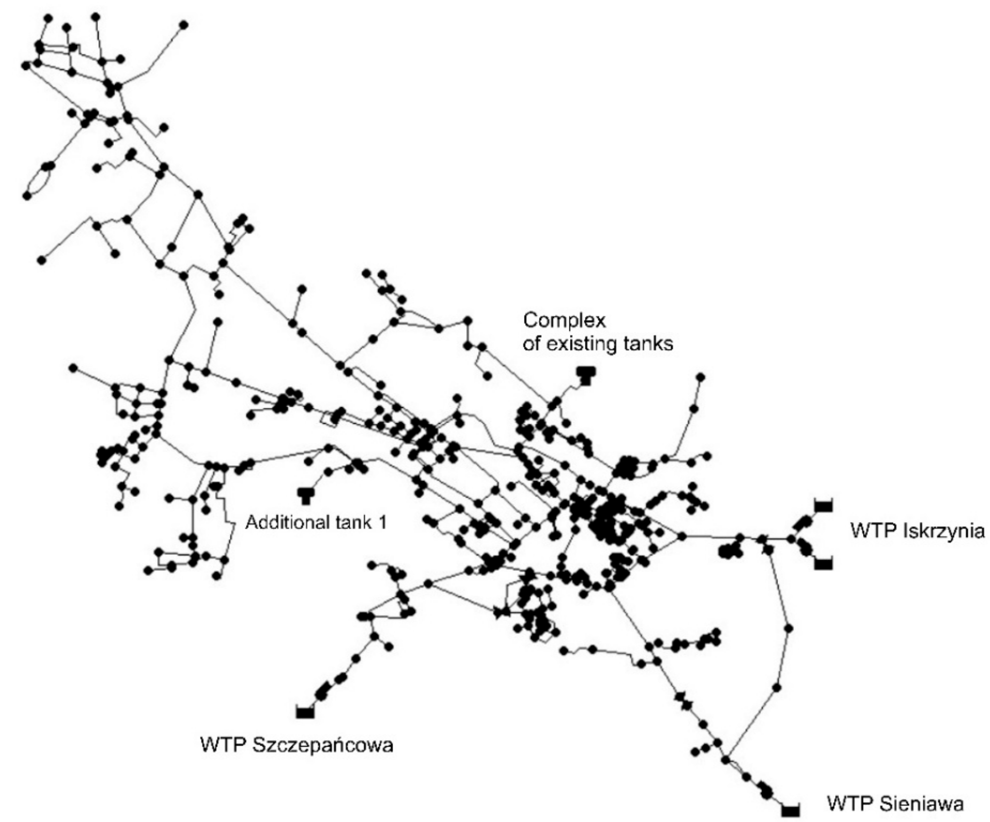

Figure 2. Diagram of the water distribution system of the city of Krosno with one additional tank (variant No. 2)

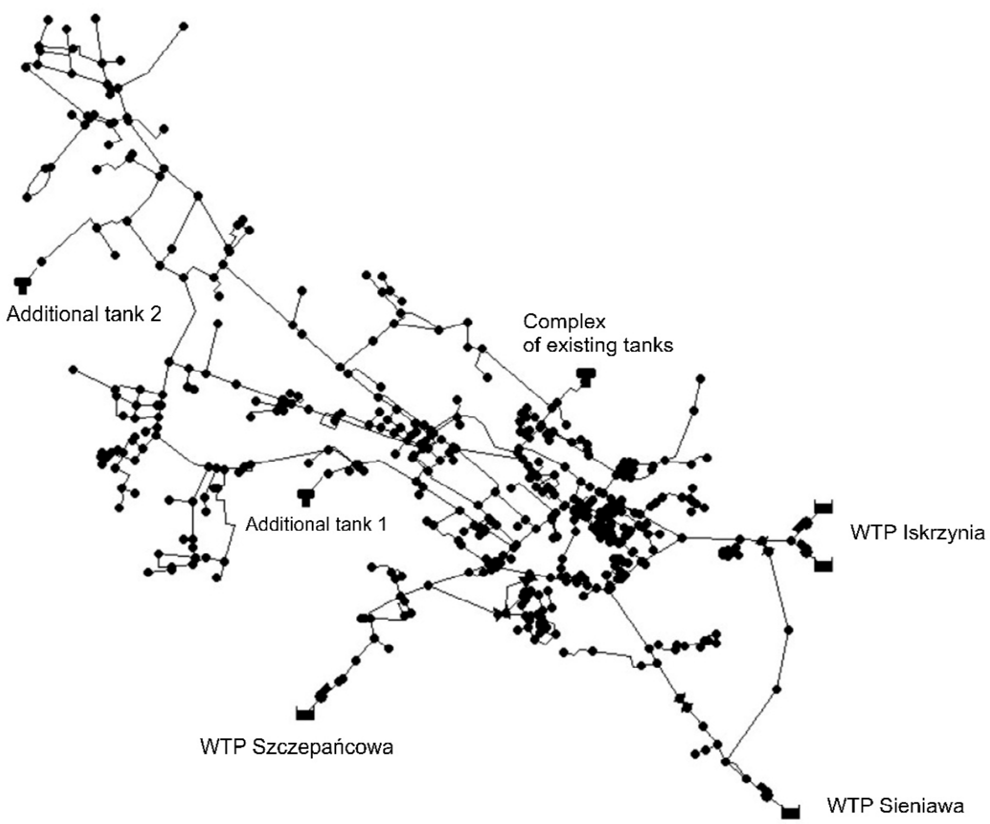

Figure 3. Diagram of the water distribution system of the city of Krosno with two additional tanks (variant no. 3)

Table 1. Energy Report for basic variant no. 1 without an additional tank

Pump	Percent Utilization	Average Efficiency	Average power consumption	Average rate of energy usage	Peak rate of energy usage	Cost/day
-	%	%	kWh/m3	kWh	kWh	PLN
WTP Sieniawa	100	75.0	0.22	83.96	106.06	1396.41
WTP Szczepańcowa	100	75.0	0.21	26.11	26.41	434.27
WTP Iskrzynia (1)	64.58	75.0	0.15	41.83	42.07	449.35
WTP Iskrzynia (2)	35.42	75.0	0.14	21.67	21.67	127.65
Total Cost						2407.68

Table 2. Energy Report for basic variant no. 2 with an additional tank

Pump	Percent Utilization	Average Efficiency	Average power consumption	Average rate of energy usage	Peak rate of energy usage	Cost/day
-	%	%	kWh/m3	kWh	kWh	PLN
WTP Sieniawa	100	75.0	0.18	61.41	85.46	1021.38
WTP Szczepańcowa	100	75.0	0.21	25.60	26.94	425.73
WTP Iskrzynia (1)	64.58	75.0	0.15	41.60	42.07	446.80
WTP Iskrzynia (2)	35.42	75.0	0.14	21.62	21.67	127.34
Total Cost						2021.24

Table 3. Energy report for variant no. 3 with two additional tanks

Pump	Percent Utilization	Average Efficiency	Average power consumption	Average rate of energy usage	Peak rate of energy usage	Cost/day
-	%	%	kWh/m3	kWh	kWh	PLN
WTP Sieniawa	100	75.0	0.16	45.42	57.13	755.47
WTP Szczepańcowa	100	75.0	0.21	25.47	26.89	423.67
WTP Iskrzynia (1)	64.58	75.0	0.15	41.32	42.07	443.82
WTP Iskrzynia (2)	35.42	75.0	0.15	21.37	21.57	125.89
Total Cost						1748.85

Conclusions

The results obtained from the simulation of the Krosno city water distribution system for the basic variant and with additional storage tanks indicate that the tanks have a clear impact on reducing pumping costs, assuming that the pumping station efficiency will be adjusted to water consumption. The introduction of storage tanks without correcting the efficiency of the pumping station will not result in a reduction in electricity consumption and pumping costs. The analyses carried out indicate that the decisive influence on the reduction of pumping costs in both analysed variants is played by the water pumping station in WTP Sieniawa. The expensive investment in the storage tank should be combined with the analysis of the city water collection curve and appropriate adjustment of the pumping station operation schedule to ensure the correct cooperation between the tank and the water supply pumping stations. The larger the storage tank that cooperates correctly with the water distribution network, the greater the savings in electricity at the water supply pump station.

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An improperly located tank with low water exchange will not provide energy benefits and pumping costs.

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The contribution of the authors

Conceptualisation, J.D. and A.S.; literature review, J.D.; methodology, J.D. and A.S.; formal analysis, J.D. and A.S; writing, J.D. and A.S.; conclusions and discussion, J.D. and A.S.

The authors have read and agreed to the published version of the manuscript.

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Jacek DAWIDOWICZ • Andrzej STUDZIŃSKI

WPŁYW ZBIORNIKÓW WYRÓWNAWCZYCH W SYSTEMIE DYSTRYBUCJI WODY MIASTA KROSNO NA ZUŻYCIE ENERGII I KOSZTY POMPOWNIA WODY

STRESZCZENIE: Celem prezentowanego artykułu jest ocena wpływu wyrównawczych zbiorników wodociągowych współpracujących z systemem dystrybucji wody na koszty energii przepompowni wodociągowych. Zbiorniki sieciowe gromadzą zapas wody w nocy przy niskich poborach wody, co umożliwia zaprojektowanie mniejszej przepompowni wody. Aby osiągnąć powyższy cel, przygotowano model systemu dystrybucji wody miasta Krosna oraz przeprowadzono symulacje numeryczne z wykorzystaniem programu EPANET dla różnych wariantów z dodatkowym zbiornikiem wody w różnych lokalizacjach. Dla każdego wariantu odczytano dobowy koszt eksploatacji przepompowni oraz średnie i maksymalne zużycie energii elektrycznej. Porównanie wyników pokazuje pozytywny wpływ zbiorników wyrównawczych na sieci wodociągowej na obniżenie kosztów zużycia energii w przepompowniach wodociągowych.

SŁOWA KLUCZOWE: systemy dystrybucji wody, systemy pompowe, zbiornik wyrównawczy, zużycie energii elektrycznej, koszty pompowania

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