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## RECONSTRUCTION OF REAL OPERATING CONDITIONS IN A WATER DISTRIBUTION SYSTEM AND ANALYSIS OF EVENTS AND HYDRAULIC EFFECTS USING NUMERICAL MODELING

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**ABSTRACT:** This research study employs mathematical modelling to reconstruct the real operating conditions of a water distribution system by examining the structure of water supply and consumption in the town of Olecko, home to approximately 17,000 residents. The conducted calculations made it possible to develop a model representing the operation of the water supply network and enabled the formulation of rational and optimal decisions affecting the efficient functioning of the entire system under various assumed situational events. The modelling process is presented as a common and effective tool supporting rational and optimal management of water distribution systems. At the same time, numerous possibilities of computer-based modelling and processing of accurate real-world data are demonstrated. The scope of the study included an analysis of the network model in terms of the fundamental quality parameters that the network should meet, such as flow velocity, pressure, unit head losses, water age, and operating conditions during simulated events such as system expansion or failure distributed across the assumed time variants. The research was closely related to the use of mathematical modelling, taking into account both economic and design aspects from the perspectives of the user and the system operator. The study also presents a situational variant related to a planned modernisation aimed at improving the performance of the system through the expansion of the water network with new pumps and pipeline sections. The EPANET software, distributed by the U.S. Environmental Protection Agency (US EPA), was used for the simulations.

**KEYWORDS:** mathematical model, dynamic model, computer modelling, water distribution system, water ages, fresh water flows

## Introduction

One of the main challenges faced by modern water distribution engineers is the correct design and implementation of water supply networks, their optimisation, and the ensuring of the infrastructure's longevity. The primary function of a water supply system is to abstract, treat, and distribute water of adequate quality, pressure, and quantity to meet the demands of both individual consumers and industrial enterprises. (Walski et al., 2003). This activity is a municipal responsibility, as regulated by the Polish Water Supply and Sewage Act (2001).

Water supply systems are designed for long-term operation, assuming changes in water consumption and hydraulic parameters over time (Trębicka, 2022). Today, tools exist to analyse systems at the design, operational, and modernisation stages, which help improve them at each level (Kanakoudis & Gonelas, 2015).

The urban water supply system is an open system, forming part of the global, natural water cycle, but not constituting its complete, closed loop (Machell & Boxall, 2013). A deep understanding of their internal structure is essential to propose sustainable development strategies. Given the rising demand associated with the growing populations of numerous urban agglomerations, enhancing water supply systems has become a necessity (Sangroula et al., 2022). Urban water safety is directly tied to both ecosystems and socio-economic systems, highlighting the importance of optimising systems to meet consumer needs (Butler et al., 2016).

Two key concepts underpin urban water supply: treatment technology and distribution technology (Sitzenfrei et al., 2020). The former refers to all filtration and purification systems used to ensure water quality and quantity in a short time, and is considered a technological innovation (Trębicka, 2023). The latter involves new materials, equipment, and systems that provide uninterrupted distribution, known as new water technology (Prest et al., 2021). Proper selection of system components, network design, and operational modelling enables efficient delivery of quality water in the required quantity and pressure (Sitzenfrei et al., 2012).

In Poland, the creation of water supply simulation models is widespread. EPANET, developed by the U.S. Environmental Protection Agency, is a key tool. It enables hydraulic simulations and analysis of water flow in pressure networks, supporting optimisation at all stages: design, construction, and operation (Rossman, 2000).

Recent developments in water distribution modelling emphasise not only hydraulic efficiency but also sustainability, resilience, and adaptability to local conditions. In this context, the development of a calibrated hydraulic model for a medium-sized urban system offers valuable insights into the dynamics of water consumption, pressure management, and the network's operational reliability (Egito et al., 2023). Such studies are particularly important for small and medium-sized towns, where modernisation efforts must balance technical feasibility with economic constraints. (Friedman et al., 2010).

This study focuses on the water distribution system of the town of Olecko in northeastern Poland, which serves approximately 17,000 inhabitants. The model developed using EPANET reproduces real operational conditions, enabling a detailed assessment of the system's hydraulic performance and the effectiveness of its existing infrastructure (Muranho et al., 2012). The research provides a foundation for further optimisation of water distribution and supports sustainable management of municipal water resources. (Shokoohi et al., 2017).

## Research methods

For over 20 years, the Water Supply and Sewerage Company (PWiK Ltd.) in Olecko (Poland) has supplied the town with water. The history of the water supply system dates back over 100 years, with the first components of the system commissioned in 1907.

As multi-family housing expanded and water supply infrastructure developed, water consumption increased significantly. Rural residents were supplied by both municipal waterworks and local intakes. One of the first components of the system, a water tower, still regulates network pressure and serves as a reserve potable water tank, with a capacity of 1,000 m<sup>3</sup>.

The town and municipality of Olecko are supplied with water drawn from five deep wells located at depths ranging from 45 to 74 meters. Due to elevated concentrations of iron and manganese, which result in an unpleasant hydrogen sulfide odour, the water requires treatment.

Treated water is stored in a 1-million-litre clean water reservoir at the station. From there, it is distributed via a pump set and the water tower, which functions as a pressure stabiliser and buffer tank. Further distribution to surrounding areas occurs via intermediate pressure-boosting stations located in Sedranki, Moźne, and Łęgowo.

The treated water meets quality standards set by the Ministry of Health. The water network includes 230,184.80 m of pipes, with 24,862.00 m of water connections. In total, the network and connections extend to 343,342.10 m. The main materials include: stoneware (16,661.10 m), PVC (16,435.20 m), PE (155,085.50 m), PVC (124,936.80 m), steel (10,412.20 m), and cast iron (18,831.30 m).

The first stage in representing the water supply network in Olecko was importing the map background into the EPANET program. The map background was generated in the QGIS program based on the water supply network map obtained from the District Office in Olecko. After importing the map background into EPANET 2.2, a model representing the Olecko water supply network was created, as shown in Figure 1. Data about the network, such as pipe diameters, node elevations, and lengths of segments between nodes, were read from the map and entered manually into the program. Accurate water demand spatial allocation for water networks modelling using a new approach. A reservoir for drinking water and a water tank were included in the scheme; in Olecko, this is a water tower. The network system consists of 80 nodes and 121 segments between nodes.

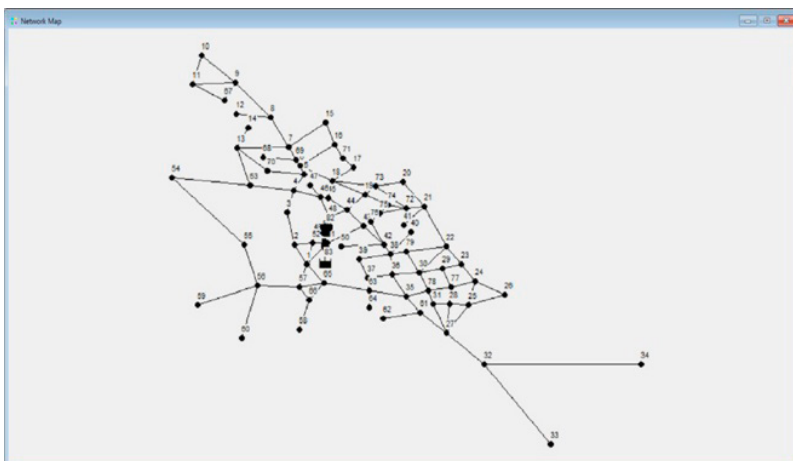


Figure 1. Model of the Olecko water supply network in the EPANET program

The calibration of the hydraulic model of the water distribution system was performed to adjust the simulation results to actual operating conditions. The calibration process involved comparing simulated values with measured data obtained from selected points in the network, including pressure and flow rate measurements.

During calibration, the following parameters were primarily adjusted: the friction factor  $f$  in the Darcy–Weisbach equation, dependent on pipe roughness and the Reynolds number, nodal demand coefficients (based on daily consumption data), pump operating parameters and tank water levels. Measurement data were obtained from pressure loggers and flow meters installed at key locations within the system. The obtained model enabled a reliable analysis of the system's operation under both normal and emergency conditions.

To create a digital model, the daily water demand for individual elements of Olecko's land development was calculated. The calculations were performed in Excel, with the total water demand amounting to  $Q_{dmax}=11734.6 \text{ m}^3/\text{d}$ . The results obtained during the peak consumption period (7-8 AM) were divided by the corresponding number of nodes and assigned to each node.

The calculation of water demand in the hydraulic model of the water distribution network was carried out in accordance with national guidelines, including the Regulation of the Minister of Infrastructure of 14 January 2002 on average water consumption standards (2002) and the Polish Standards for water supply systems (e.g., PN-EN 806, PN-92/B-01706). In addition to traditional unit

consumption values, the integrated indicator method was applied, allowing for a synthetic representation of demographic and functional factors influencing the actual water consumption in different urban areas.

In practice, the values of these indicators were implemented in the model as correction coefficients assigned to individual network nodes, providing a more realistic representation of the spatial variability of water demand (Pietrucha-Urbanik & Studziński, 2019).

To ensure the model best reflects real water demand conditions, a water consumption time pattern was established, as shown in Figure 2, based on maximum consumption.

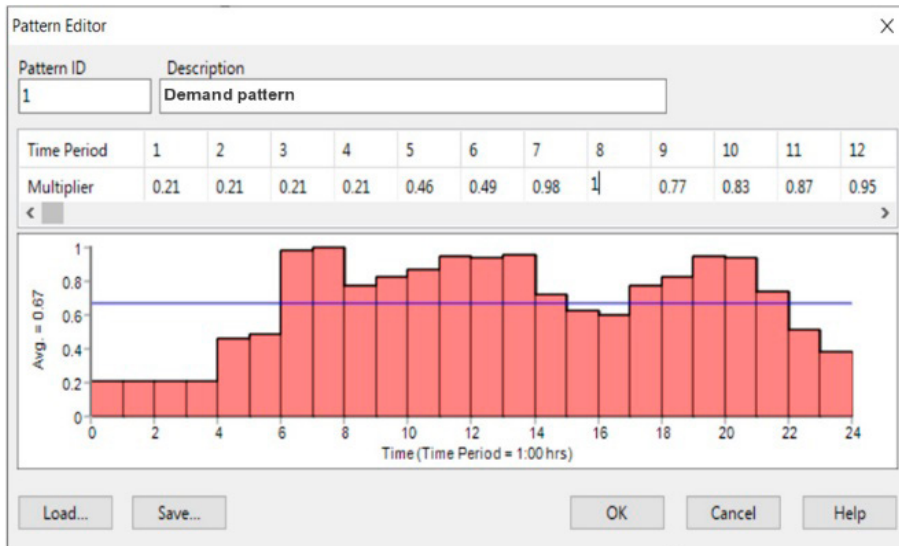


Figure 2. Time pattern

## Results of the research

The first parameter that was checked is the pressure in the network presented in Figure 3. According to the conditions set by the Minister of Infrastructure in the regulation, the minimum height of the water column in the network is 20 m, i.e. 2 atmospheres.

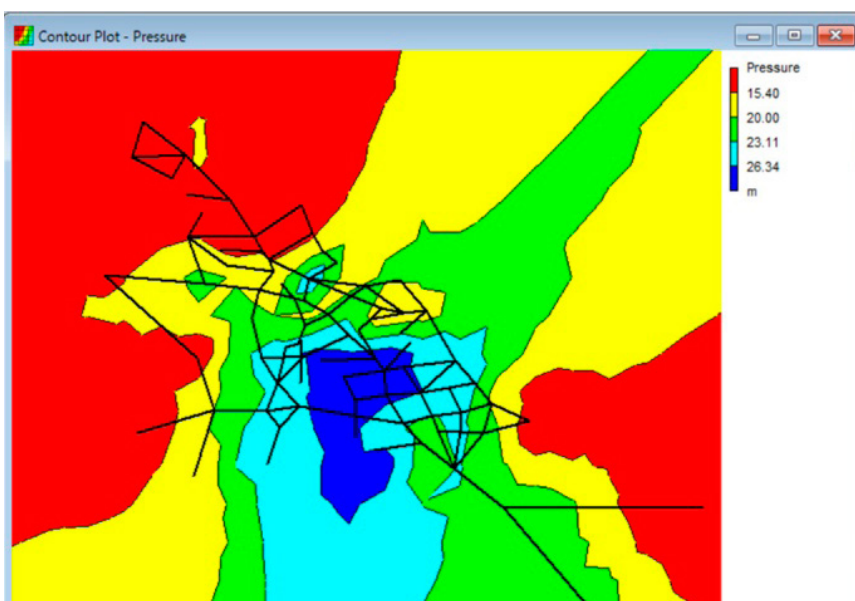


Figure 3. Pressure distribution at the time of maximum demand

In the generated model, areas can be observed where the height of the water column ranges from 15.40 m to 26.34 m. The pressure prevailing in the network is related to the terrain elevation, local extractions, and the location of the water reservoir, which, in the case of the water supply network, is the water tower located in the city centre. It is possible to observe areas that do not meet the conditions specified in the minister's regulation. Therefore, solutions have been proposed to improve the situation in specific areas.

The following Figure 4 shows the correlation between pressure distributions and the elevations of the existing water supply network. The node elevations range from 153.78 m to 178.61 m. The height difference between the extreme nodes is 24.83 m.

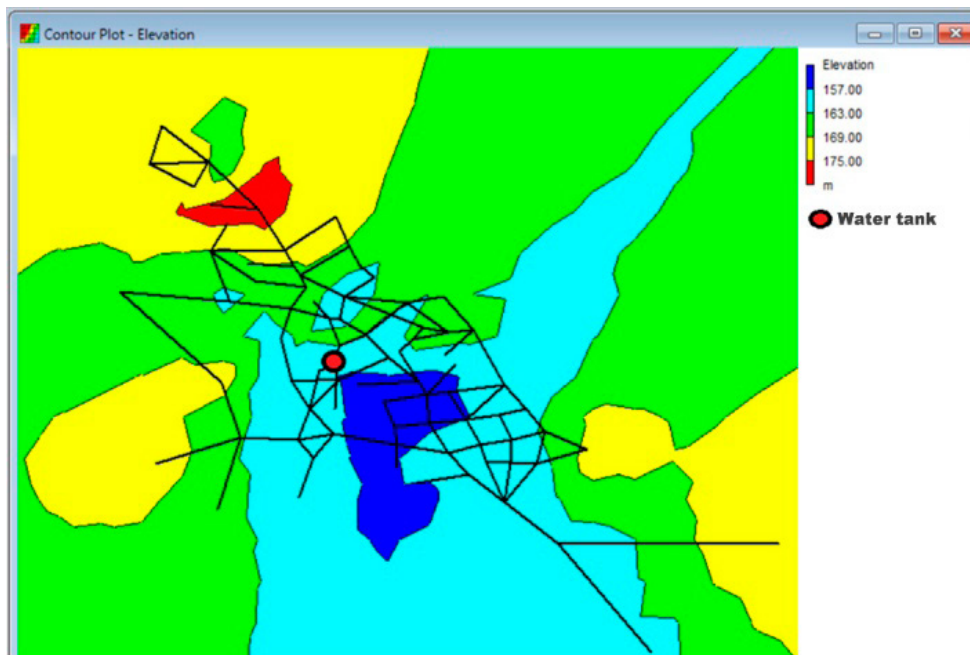


Figure 4. The elevation layout of the water supply network

Another important element that affects the operation of the water supply network is the velocity of water flow in the pipelines. The velocity of water flow in the water supply network significantly affects: water quality, energy efficiency, pipe durability, and water pressure. All these factors influence the performance, costs, and quality of water supply services, so it is important to maintain an appropriate flow velocity in the water supply network. In the hydraulic calculations of the water distribution network, flow velocity criteria were adopted in accordance with the PN-EN 805:2025-07 standard. The recommended velocity values in distribution pipes range from 0.5 to 1.5 m/s, while in transmission (trunk) mains they range from 0.6 to 2.0 m/s. The minimum velocity should not be lower than 0.2–0.3 m/s in order to prevent sediment deposition and to maintain appropriate water quality.

These velocity ranges were applied as reference criteria during the calibration and verification of the EPANET hydraulic model to ensure that simulated operating conditions reflected realistic and normative flow parameters within the network. The distribution of flow velocities in the water supply network is presented in Figure 5.

The model shows the distribution of speeds in the water supply network. In the model, areas can be distinguished where the speeds are higher and lower, depending on the land use in the area. Speeds in the pipes are related to the withdrawals and diameters of the pipes. From the model, it can be inferred that the speeds in the pipes are highest in the areas of multi-family residential buildings and industrial areas.

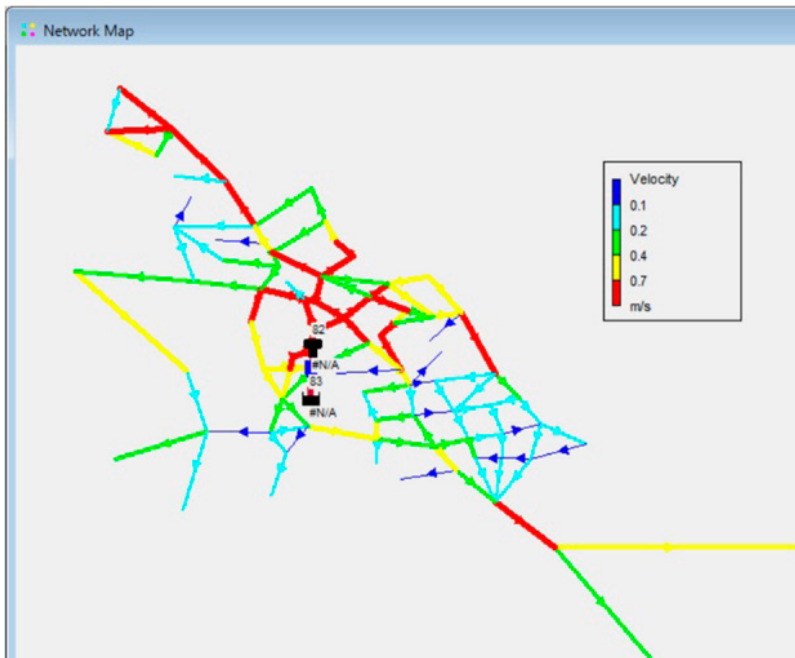


Figure 5. Distribution of speeds in the water supply network

Figures 6, 7, and 8 illustrate the distribution of flow velocity in the pipes in relation to water demand and pipe diameter. The demand distribution remains largely within the same range throughout the model, with several peaks observed at two locations on the outskirts of the town. The flow appears to be higher in some pipes with larger diameters, although increased flow rates can also be observed in smaller-diameter pipes.

This pattern indicates that the hydraulic performance of the network is influenced not only by pipe diameter but also by the spatial distribution of water demand and network topology, which together determine the direction and magnitude of flow and affect head losses in individual sections.

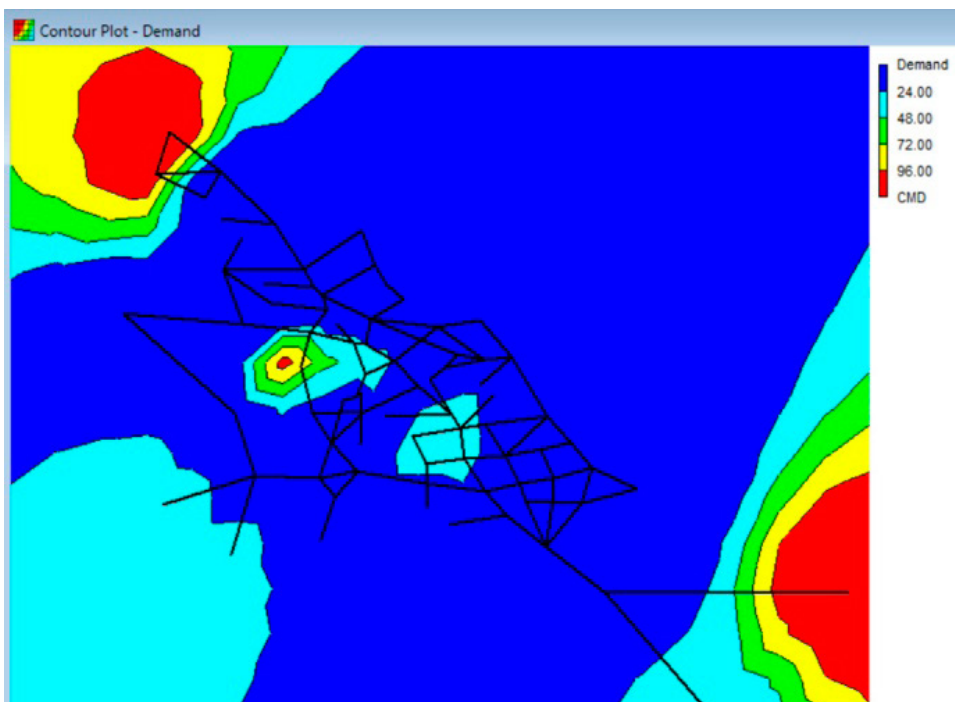


Figure 6. Distribution of water demand in the water supply network

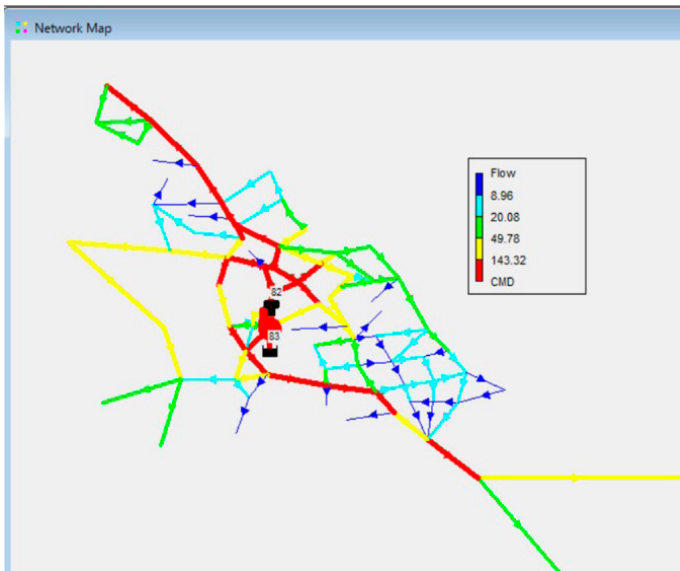


Figure 7. Distribution of flows in the water supply network



Figure 8. Diameters of water supply network pipes

Water age study in the Epanet program is a very important tool in the design and analysis of water supply systems. Water age is the time that has elapsed from the moment the source water leaves to the moment it reaches a specific junction in the water supply system. By studying water age, one can determine how long water stays in pipes and reservoirs, which allows for the assessment of the effectiveness of mixing and water distribution processes. In Figure 9, the result of water age modelling assuming a 72-hour extraction.

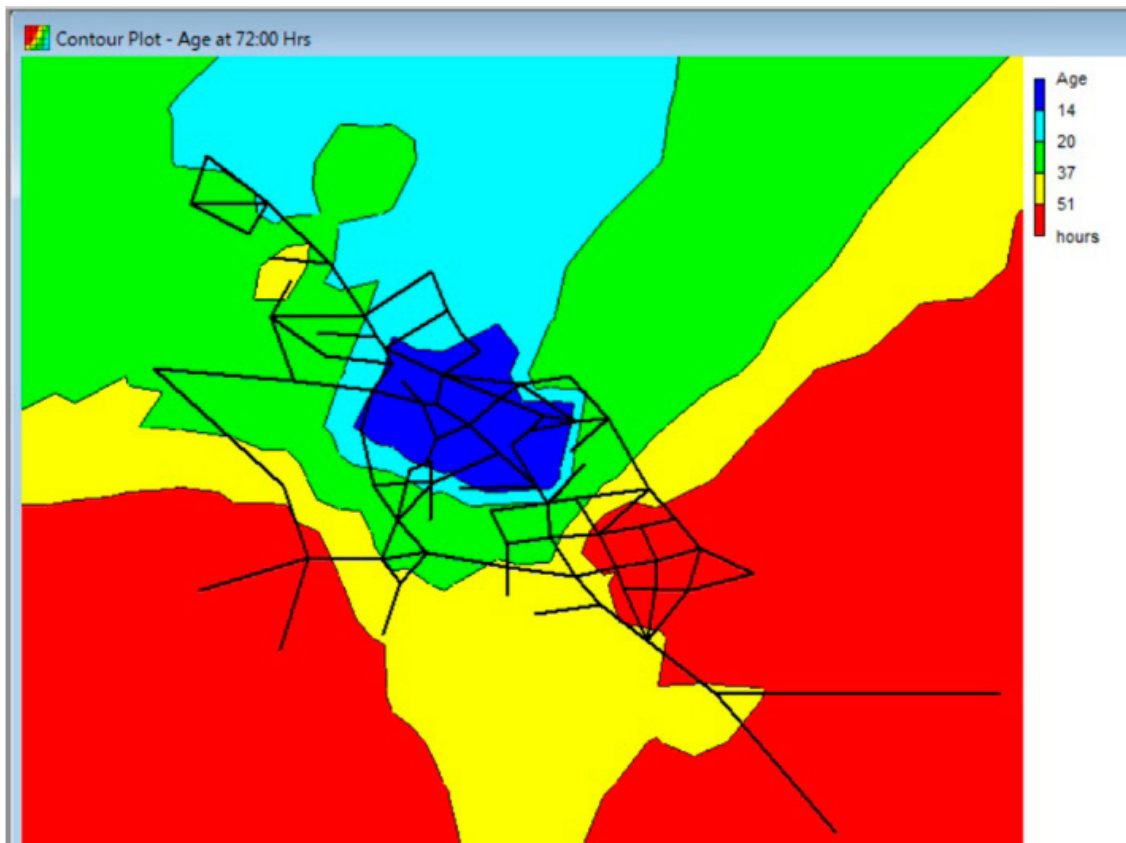


Figure 9. Age of Water

In the generated model, it can be observed that the water in the centre, i.e., closest to the intake, is the freshest. The greater the distance from the water intake point, the older the water becomes.

After analysing the water supply network model in Olecko, it was determined that it is necessary to implement solutions that allow for increasing the pressure in areas where it is insufficient to meet the requirements set forth in the aforementioned regulation. To this end, additional pumps and pipelines were used to locally increase the pressure in the network, as shown in Figure 10. The pumps were designed between nodes 6-60, i.e., on the outskirts of the centre, on the main line supplying the northern part of the city, and between nodes 32-43, at the outlet to the industrial zone, which generates a high demand. Additional pipelines were designed between nodes 34-26 and 55-59 to close the network's circuits in low-pressure areas. Figure 11 shows the effects of using additional pumps and pipes on the models used above.

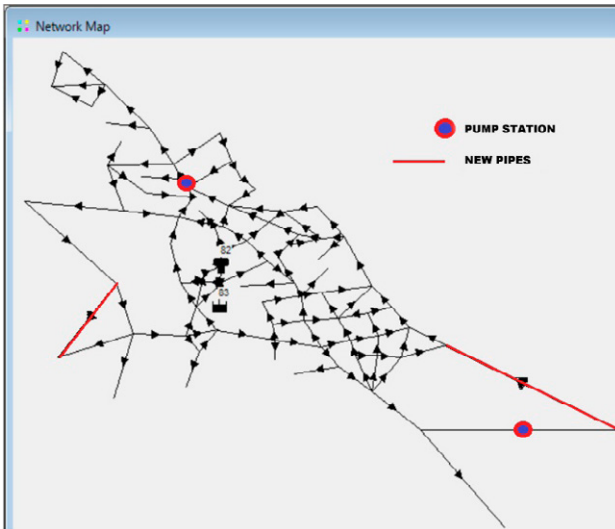


Figure 10. Location of additional pumps and pipes

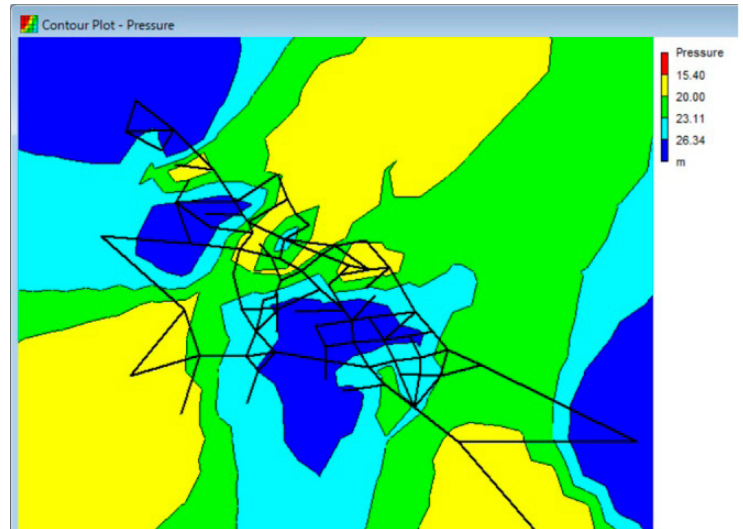


Figure 11. Pressure distribution after the application of additional pumps

After the application of additional pumps and conduits at crucial points, significantly fewer low-pressure areas were observed in the model, and all those below 1.5 atm were eliminated, as shown in Figure 12.

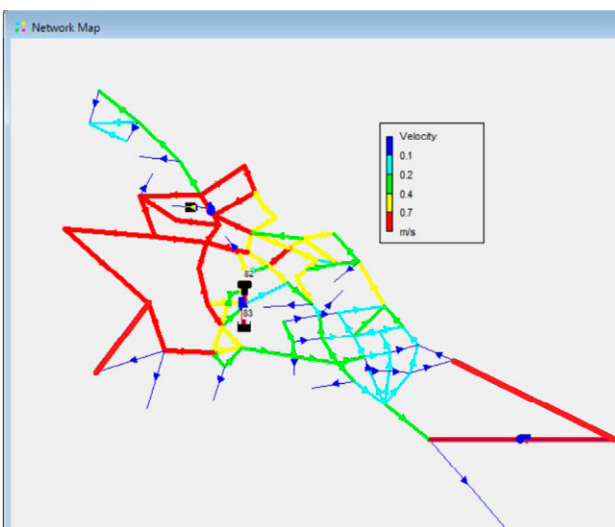


Figure 12. Water speeds up after the use of additional pumps and pipes

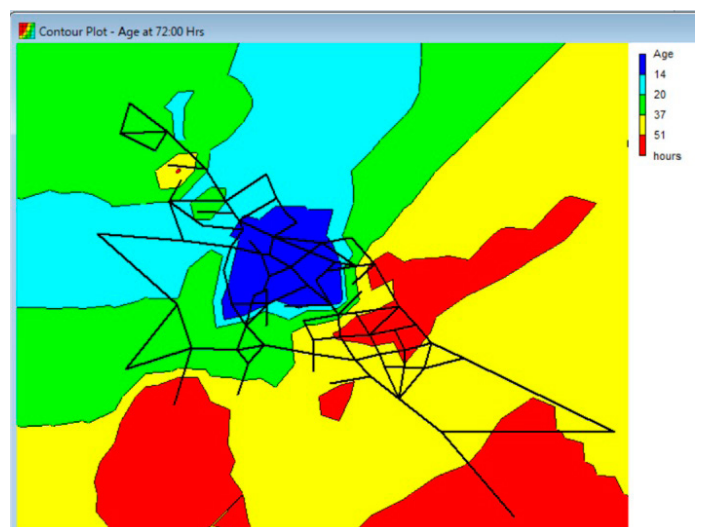


Figure 13. Age of water after the application of additional pumps and pipes

After the implementation of additional pipes and fittings, a slight increase in flow velocity in the pipes was observed, which, at previously relatively low speeds, is a desirable phenomenon.

In the model shown in Figure 13, an improvement in water quality can be observed by reducing its age in the areas where additional pumps and pipes were applied. In other areas, the age of the water remained similar.

## Conclusions

The aim of this article was to recreate the actual working conditions of the water distribution system in the city of Olecko, as well as to assess the likelihood of hydraulic effects of selected events. The model was created using EPANET 2.2 software. Data concerning water consumption was calculated in Excel. The current base maps were provided by the Olecko County Office and imported into EPANET using QGIS. In the first stage, a base map of the water supply network was created using QGIS, which allowed for the representation of all water networks and pipes that make up the system.

After entering the required data, the EPANET 2.2 program generated a series of tables, graphs, and maps that enabled the analysis of the operational parameters of the water supply network in the analysed city. Based on the research conducted, the following conclusions can be made:

- The analysis involved two simulations, the first assuming a realistic flow of the water supply network, and the second assuming the addition of two additional pumps and two sections to close the network.
- The application of the second approach produced the desired effects, which means providing the required pressure to all nodes in the network without exceeding allowable values.
- The average water flow velocity has slightly increased, which still has a minor positive effect on the water supply network and may still lead to water stagnation.
- In the case of the water age, an improvement was observed after the installation of two pumps and two segments closing the rings in the system; however, at the final sections of the network, the water was still clearly older.
- The results of the analysis suggest the need for monitoring in terms of physicochemical and bacteriological aspects, as well as flushing the network pipes to improve water quality in the terminal sections, where local water stagnation may occur.

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## ODTWARZANIE RZECZYWISTYCH WARUNKÓW PRACY SYSTEMU DYSTRYBUCJI WODY ORAZ ANALIZA ZDARZEŃ I SKUTKÓW HYDRAULICZNYCH Z WYKORZYSTANIEM MODELOWANIA NUMERYCZNEGO

**STRESZCZENIE:** Niniejsza praca badawcza wykorzystuje proces modelowania matematycznego w celu odtworzenia rzeczywistych warunków pracy systemu dystrybucji wody poprzez analizę struktury zaopatrzenia w wodę oraz jej zużycia w mieście Olecko, zamieszkanym przez około 17 000 osób. Przeprowadzone obliczenia umożliwiły opracowanie modelu przedstawiającego funkcjonowanie sieci wodociągowej oraz pozwoliły na podejmowanie racjonalnych i optymalnych decyzji wpływających na efektywne działanie całego systemu w ramach różnych założonych zdarzeń sytuacyjnych. Proces modelowania przedstawiono jako powszechne i skuteczne narzędzie wspomagające racjonalne i optymalne zarządzanie systemami dystrybucji wody. Jednocześnie zaprezentowano liczne możliwości komputerowego modelowania oraz przetwarzania dokładnych danych rzeczywistych. Zakres badań obejmował analizę modelu sieci pod kątem podstawowych parametrów jakościowych, które sieć powinna spełniać, takich jak prędkość przepływu, ciśnienie, jednostkowe straty hydrauliczne, wiek wody oraz warunki eksploatacyjne podczas symulowanych zdarzeń, takich jak rozbudowa systemu czy awaria, rozłożonych w przyjętych wariantach czasowych. Badania były ściśle powiązane z wykorzystaniem modelowania matematycznego, uwzględniającego zarówno aspekty ekonomiczne, jak i projektowe, z perspektywy użytkownika i operatora systemu. W pracy przedstawiono również wariant sytuacyjny dotyczący planowanej modernizacji mającej na celu poprawę funkcjonowania systemu poprzez rozbudowę sieci wodociągowej o nowe pompy i odcinki rurociągów. Dodatkowo przeprowadzono analizę wieku wody przed i po zastosowaniu dodatkowych elementów. Do symulacji wykorzystano oprogramowanie EPANET, dystrybuowane przez U.S. Environmental Protection Agency (US EPA). Dodatkowo przeprowadzono analizę wieku wody przed i po zastosowaniu dodatkowych elementów.

**SŁOWA KLUCZOWE:** model matematyczny, sieć wodociągowa, zaopatrzenie w wodę, dynamiczny model, komputerowe modelowanie, system dystrybucji wody, wiek wody, przepływy wody