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USE OF HYDRAULIC MODEL IN REAL WATER LOSS REDUCTION AND WATER DISTRIBUTION NETWORK OPERATIONAL COST LOWERING

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ABSTRACT: Most of the small water companies supplying a small number of consumers with water are struggling with the extremely tight budget, often making any large-scale modernisation impossible. In effect network managed by these companies is often very leaky and unreliable. One possible and cheap way of leakage reduction is the reduction of average pressure in the network. Thanks to new computing technologies, the device selection process for pressure reduction is accurate and easy to do. This study uses the hydraulic model to select required pressure reducing valves and correct locations accurately and adequately approximate the resulting absolute water loss reduction thanks to this approach.

KEYWORDS: hydraulic, modelling, water loss, leakage, cost of exploitation, loss reduction

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Introduction

Water losses are expected in any water distribution system over its lifecycle. The simplest way to define them is by calculating a non-revenue water (NRW) level. It equals unbilled authorised consumption plus actual losses and apparent losses (Pearson, 2019). According to The European Federation of National Associations of Water Services (2021), the mean values for non-revenue water are 25% (2696 m^3/km/y) in EurEau member countries. In some cases, reported average NRW level exceeds 30%, like Bulgaria, Italy, Malta, Romania, and Slovakia. Figure 1shows the reported average NRW level in EurEau member countries.

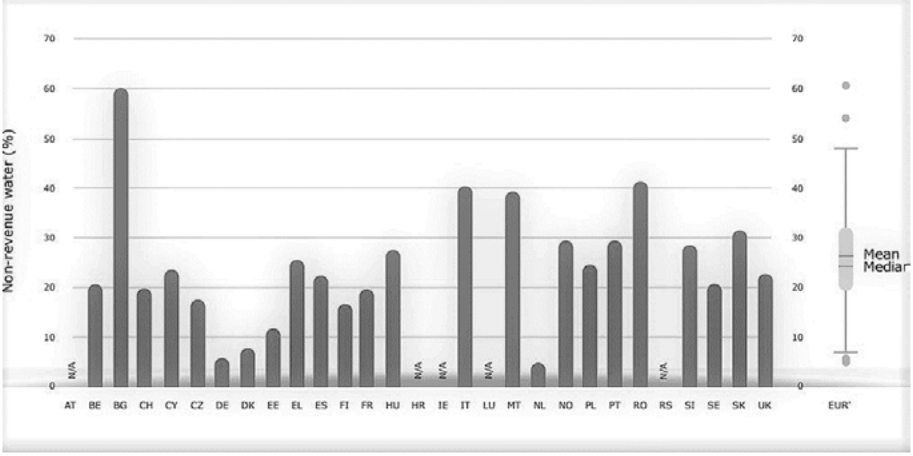

Figure 1. The average non-revenue water level reported in EurEau member countries

Source: The European Federation of National Associations of Water Services (2021), p. 22.

High water loss level in distribution networks is one of the key challenges facing water utilities Dawidowicz et al. (2021). From an economic point of view, water that never reaches customers must be treated and transported, generating additional operating costs and causing carbon dioxide emissions that could have been prevented Trębicka (2016). Moreover, negligence in the management of the water supply network also affects social and technical issues like water supply interruptions and low-pressure Gwoździej-Mazur et al. (2019).

According to Baader et al. (2011), actual losses usually represent the most critical component of water losses in developed countries. Actual water losses are associated with leakages on transmission and distribution mains, storage tank overflows and service connections. Practice shows that the best

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results in leakage level reduction are obtained by applying several integrated methods. One of them is widely used pressure management, which aims to:
- lower the amount of water lost due to pipe bursts and breaks,
- decrease the background leaks, which are related to minimum night flow,
- reduce the frequency of failures.

According to McKenzie and Wegelin (2009), reducing the water pressure in a water system can be achieved in a number of ways:
- fixed outlet pressure control,
- time-modulated pressure control,
- flow modulated pressure control.

Nowadays, hydraulic models are increasingly used to assist in operating water supply systems, including PMA (pressure management areas) zones planning Świętochowska et al. (2021).

The hydraulic model creation process includes several steps:
- representation of water system geometry, including:
    - filling internal diameters,
    - estimating roughness based on material and date of commissioning,
    - verification of connections,
    - localisation of closed valves;
- demands allocation and defining water consumptions patterns;
- recreation of water supply facilities operation;
- model calibration.

Most hydraulic models require some calibration for even basic uses, and numerous model adjustments are often required (Walski, 1986). Before any analyses are carried out, simulated results must be compared to the field's pressure and flow rate data. The model can be considered reliable if the collected time series are consistent with the simulated ones.

The calibrated model enables the user to leverage relatively few field observations into a complete picture of what is occurring in the distribution system. It allows viewing computed parameter changes over simulation time in every node point of the water distribution system. This helps to plan the future location of pressure-reducing valves (PRV), identify critical points with the lowest pressure and adjust pressure reducing valve settings. Simulated flowrates may be used to correctly choose the PRV nominal diameter to ensure the device's correct operation.

An important feature of the hydraulic model is also simulating the response of leaks to changes of pressure in a water distribution system or specific pressure management area Gwoździej-Mazur et al. (2021). It can be carried out by adding the emitter coefficient to network nodes. According to Lewis et al. (2020), emitters are used to model flow through sprinkler systems and irrigation networks. They can also simulate leakage in a pipe connected to the junction. The pressure determines the flow rate through the emitter at the node:

$$q = Cp^{\gamma}, \tag{1}$$

where:
q – flow rate through emitter,
p – pressure,
C – discharge coefficient,
γ – pressure exponent (for nozzles and sprinkler heads γ = 0.5).

Figure 2 shows the dependence of Epanet 2.2 simulated leakage outflow rate to pressure and selected emitter coefficient values.

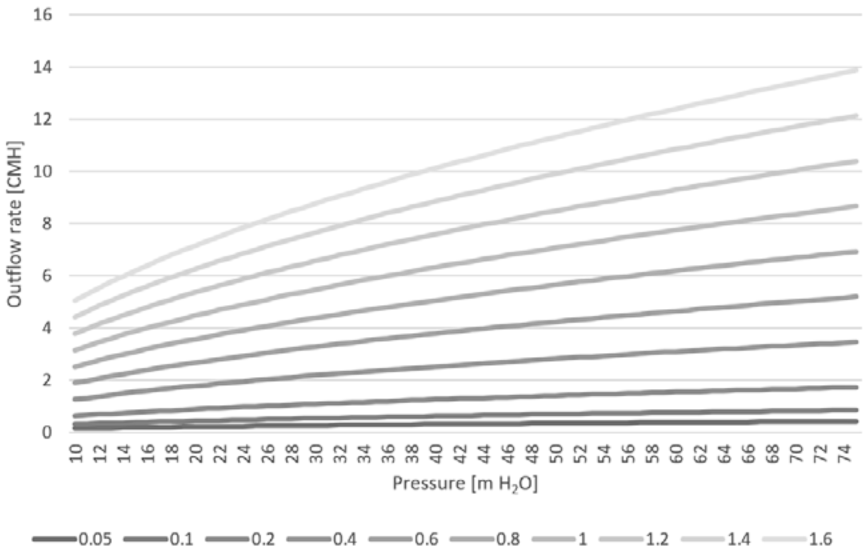

Figure 2. Dependence of Epanet 2.2 simulated leakage outflow rate to pressure and selected emitter coefficient values

Source: author's work.

Without disturbing customer service, network models can be used to replicate the behaviour of an actual system under a variety of hypothetical scenarios like checking different pressure reduction methods and valve settings. Each approach can be evaluated to determine the savings from leakage reduction. If more than one pressure management zones are designed, and funds are limited, it is possible to split the project into stages and set a priority on each one of them.

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Methodology

To conduct the study, one hydraulic model consisted of two sub-models. Both of them represent existing municipal water supply systems in Silesian voivodeship. Each of them supplies at least one village. According to a census done in 2011, village A has around 3014 inhabitants and has an area of 7.1 km^2. Sub-model B supplies around 4000 inhabitants, and the total pipe length is approximately 44 km. Data about several inhabitants comes from a census done in 2011. Models were created with the use of Quantum GIS which is under an open-source license. After models were built, they were exported into the simulation software Epanet, also under an open-source license issued by USEPA.

Both models' demands were allocated using the Voronoi polygon method. This method allows for quick and accurate aggregation of water demands. Sum of demands in both models is represented in Table 1.

Table 1. Sum of demands and total supplied the population of both sub-models

Sub model	Total water demand [CMD]	Number of inhabitants
A (one village)	161.106	3014
B (one village and part of neighbouring village)	328.197	4000

Source: author's work.

Model A

Network A is connected to an external water supply main with a diameter of 1000 mm by a pipe with a diameter of 150 mm. This connection supports all normal and emergency demands that arise in the system. That water source is managed and owned by different water companies. The network manager buys water from that company at a price of 2.51 PLN/m^3. Submodel A includes the whole water supply network, which has a total length of 15.35 km of pipes. The total number of links for this sub-model equals 726, and the number of nodes equals 717. The average link length is around 21.40 m. This means that most of the water supply connections to individual recipients are represented in the model. All allocated demands have one demand pattern, which represents single-family housing.

Figure 3 shows a graphical representation of submodel A extent, complexity and structure. The white diamond symbol with a numeric label represents the location of the planned pressure reduction valve that will reduce the total pressure of water flowing to the system, located on the network water supply point. Current pressure at the supply point is maintained

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around the value of 6 bars. Thus, reducing stress will lessen water seepage caused by pipe leakage.

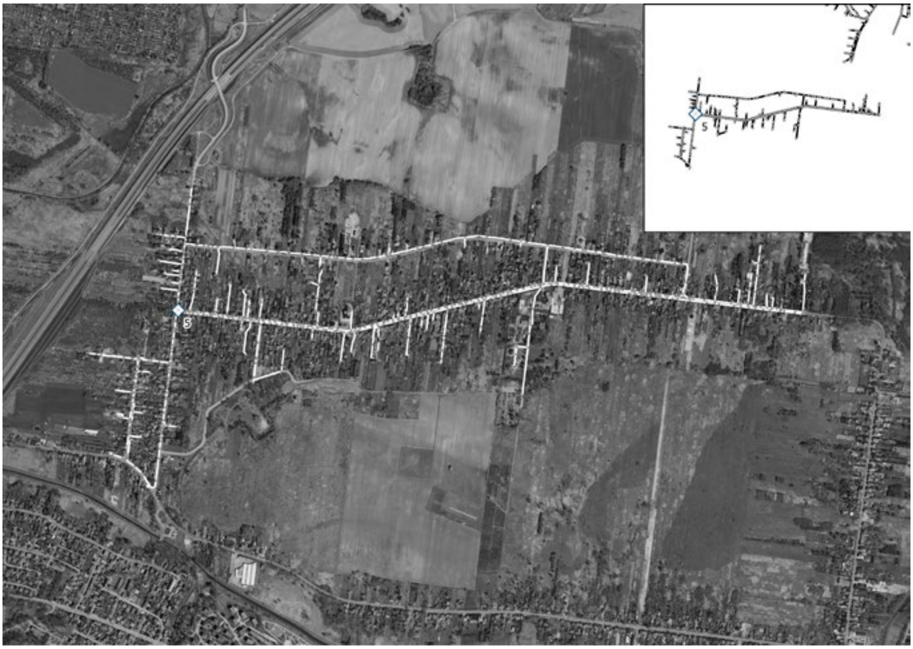

Figure 3. Graphical representation of hydraulic model A range and structure
Source: author's work.

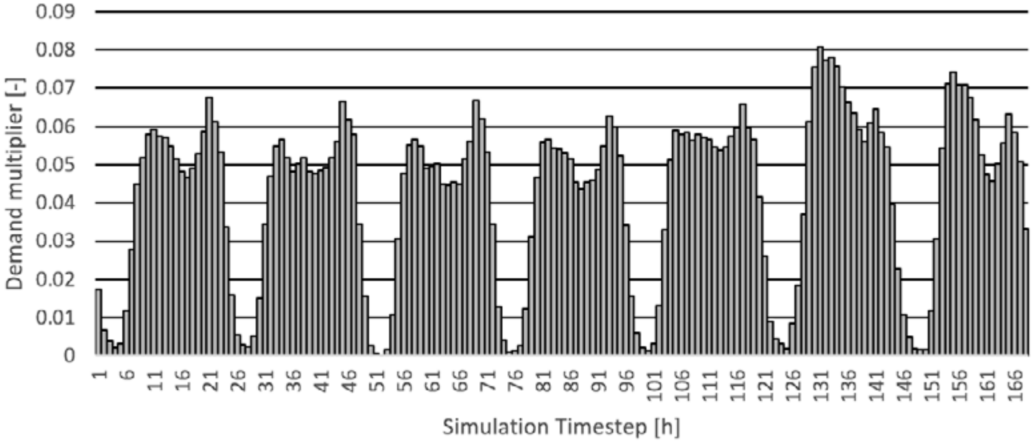

Figure 4. Demand pattern for submodel A representing single-family housing
Source: author's work.

The plot in Figure 4 indicates that the total simulation duration is equal to 168 hours. This allows to simulate different days of the week and achieve higher fidelity of flow and pressure in the system.

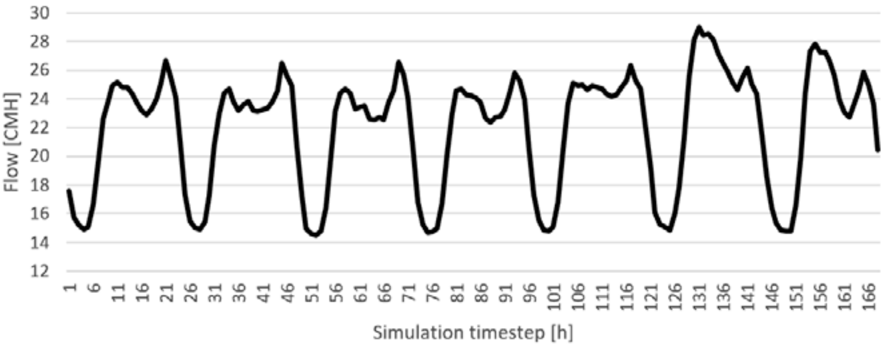

Figure 5. Subnetwork A water inflow on supply point

Source: author's work.

The plot in Figure 5 shows the distribution of water inflow. The most noticeable things are very high night flow values which oscillate around 15 m^3/h. This indicates that there might be a significant leak in the system. On closer examination, it can be concluded that, on average, 528.03 CMD of water flows into the network, and the sum of water leakage is around 366.92 CMD. This indicates the level of losses in grid A of 69.49%. Such water leakage is unacceptable and must be reduced as quickly as possible. The main problem with water leaks in the system is that they are located on individual water supply connections to individual recipients. Most of those connections are either under asphalt or pavement.

Table 2. Estimated simplified supply cost to recipients in subsystem A

Data type	Volume of water [m^3]	Money value [PLN]
Water price of 1 cubic meter	-	2.51
Inflow	192,730.340	483,753.15
Demands	58,803.508	147,596.80
Water losses due to leakage	133,926.832	336,156.35

Source: author's work.

Each year on average, the total inflow to network A is equal to 192 730 m^3. On average, the yearly water demand in the system is approximately 58 803 m^3.

This gives water losses at the level of over 133,926 m^3 and financial losses at a group of over 336,000 PLN. The overview of this data is visualised in Table 2.

Model B

Water fed to the system is similar to in-network A. Network B is connected to an external water supply main with a diameter of 1000 mm by a pipe with a diameter of 150 mm. This connection allows the collection of all regular and emergency demands that arise in the system. Water is sold to the network by the same company and at the same price as in the case of network A which is equal to 2.51 PLN/m^3. Submodel B includes the whole water supply network with 44 km of pipes. The total number of links for this submodel is 1576, and the number of nodes is 1553. The average link length is around 28.33 m. This means that, on average, most individual water supply connections to particular recipients and model complexity are very similar as in the case of submodel A. All allocated demands have one demand pattern, which represents single-family housing.

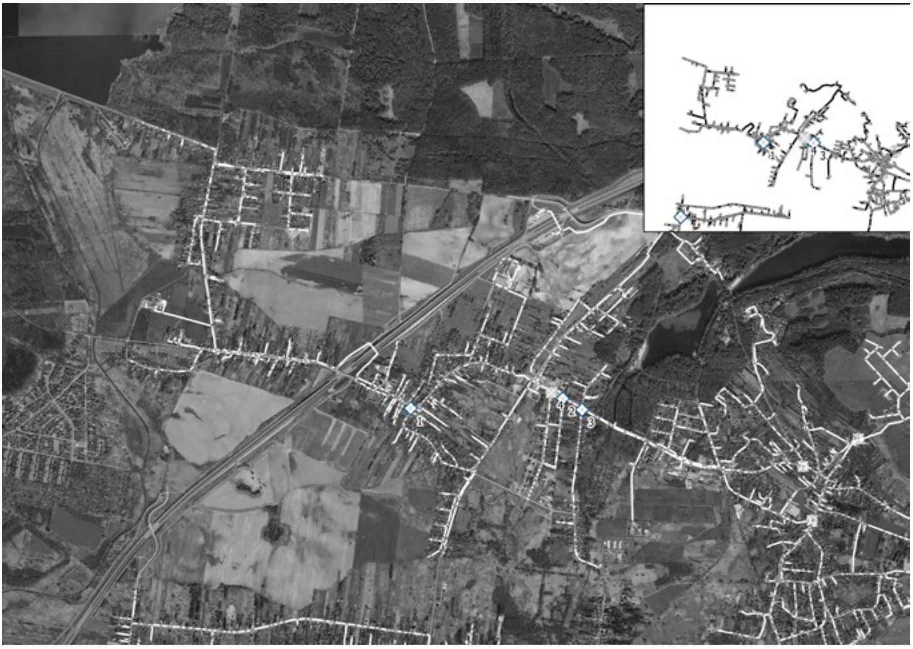

Figure 6. Graphical representation of hydraulic model B range and structure

Source: author's work.

The image in Figure 6 shows a graphical representation of submodel B extent, complexity and structure. A red valve symbol with the number label represents the location of the planned pressure reduction valve location. Red crosses indicate valves that cut off flow to and from foreign systems connected to subsystem B.

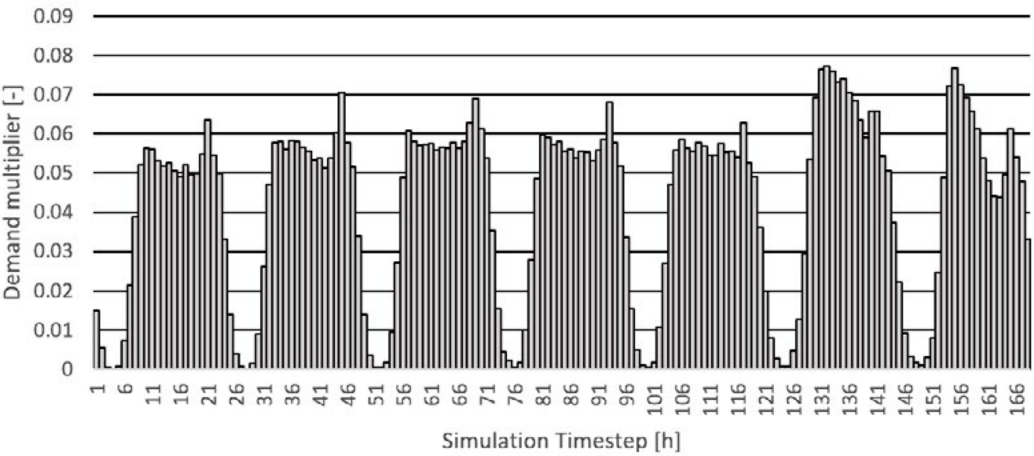

Figure 7. Demand pattern for submodel A representing single-family housing

Source: author's work.

Figure 7 indicates that the total simulation duration equals 168 hours. This demand pattern differs from the one used for subnetwork A. This allows to simulate different days of the week and achieve higher fidelity of flow and pressure in the system.

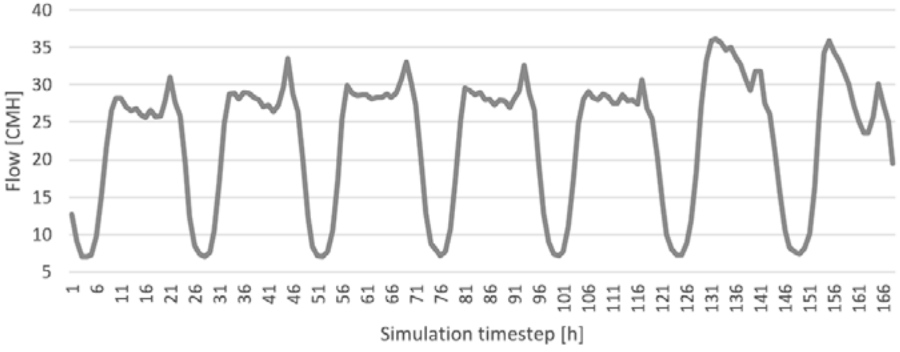

Figure 8. Subnetwork B water inflow on supply point

Source: author's work.

The plot in Figure 8 shows the distribution of water inflow. Like in the earlier case, the most noticeable is the high values of night flow which oscillates around 7 m^3/h. This indicates there is a leak in the system. On closer examination, it can be concluded that, on average, 545.61 CMD of water flows into the network, and the sum of water leakage is around 217.41 CMD. This indicates the level of losses in grid B of 39.85%, which is lower almost by half compared to network A. Difficulties and hurdles with leakage location is identical to submodel A.

Table 3. Estimated simplified supply cost to recipients in subsystem B

Data type	Volume of water [m^3]	Money value [PLN]
Water price of 1 cubic meter	-	2.51
Inflow	199,146.764	499,858.377
Demands	119,791.905	300,677.682
Water losses due to leakage	79,354.8586	199,180.695

Source: author's work.

Each year on average total inflow into network A equals 199,146 m^3. On average, the yearly water demand in the system is approximately 119,792 m^3. This gives water losses at the level of over 79,000 m^3 and financial losses at the level of over 199,000 PLN. The overview of this data is visualised in Table 3.

In total, a water distribution company that manages networks A and B loses over 535,337 PLN each year due to actual water losses in the system. One has to remember that this company supplies around 7000 inhabitants. The combination of the fact that all water provided to the networks is bought from another company and the high level of water leakage causes the managing company not to have enough assets to carry out a thorough modernisation of the pipe network.

The first step in lowering actual water losses should be reducing the overall pressure in both systems. This pressure initially is relatively high for networks on relatively flat terrain and oscillates around 6 bars for network A and reaches up to 6.4 bars for network B. With a low initial investment; it is possible to reduce the cost of the network exploitation.

Water leaks were simulated by applying the emitter coefficient factor, which responds to changes in water pressure in the pipes. Higher the pressure, the more significant the outflow. Usage of this function allows simulating and approximating outflow reduction due to the decrease in the pressure in the system.

As the leak location is unknown in the case of both networks, the safest approach is to apply the emitter coefficient factor to every working node in the model's graph after the main flowmeter. Table 4 shows the sum of emitter coeff. That is spread across all nodes in the models. A total of 716 nodes in model A and 1551 in model B were assigned this parameter. For each node in the model, the A value of the parameter is equal to 0.0026599 and 0.000644 for model B.

Table 4. Summary of emitter coefficient parameters in both models

Submodel	Total value of emitter coeff. Spread on all nodes [-]	Total number of nodes with assigned value of emitter coeff.	Value of emitter coeff. assigned to each node
A	1.897328	716	0.002650
B	0.998844	1551	0.000644

Source: author's work.

Results

Model A

The pipe connecting system A to the supply point has a diameter of 150 mm, minimum flow at this point is equal to 14.50 CMH, and maximum flow is similar to 29.02 CMH. On average, through this pipe flows 22 CMH of water. Table 5 represents flow and pressure reduction values for model variant A. As it can be seen that the optimal diameter for the pressure reduction valve that will supply subnetwork A is equal to 100 mm. This unit will be available to water for firefighting purposes. Plot Figure 9 shows average pressure values for each simulation hour before and after applying pressure reducing valve, which in effect lowers the whole system pressure by 1.44 bar of pressure.

Table 5. Flow parameters for the point of pressure reduction valve installation location

Model variant	Pipediameter [mm]	Minimum flow [CMH]	Maximum flow [CMH]	Averageflow [CMH]	Pressurereduction [bar]	Optimal presure reduction valve diameter [mm]
A	150	14.500	29.022	22.001	1.44	100

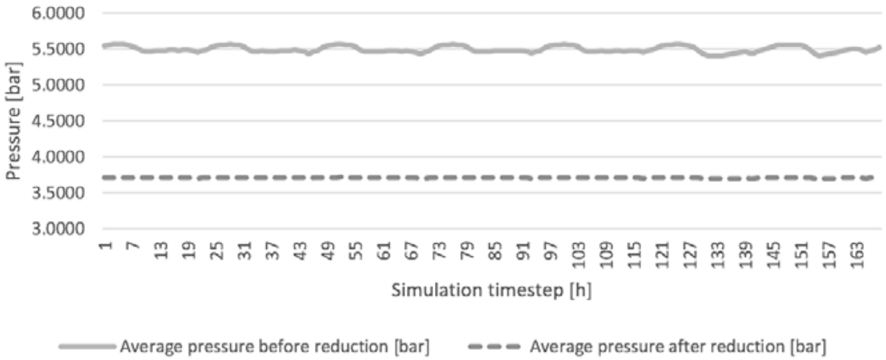

Figure 9. Average pressure for model A before and after reduction of pressure

Source: author's work.

After the average pressure in the network was reduced from around 5.5 bars to 3.7 bars by installing a pressure reduction valve at the chosen point, a decrease in flow was observed. This reduction is represented in Figure 10, showing that approximately 2 CMH reduced nighttime flows and a similar amount reduced daytime flows. The plot in Figure 11shows exact differences for flow before and after pressure reductions which were calculated in simulation software.

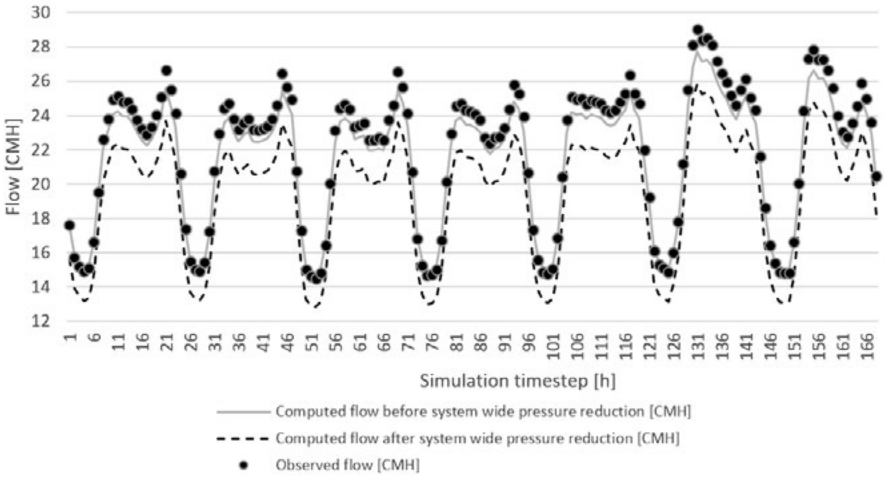

Figure 10. Plot of observed flow at inflow point of subsystem A and computed flow before and after pressure reduction in the network

Source: author's work.

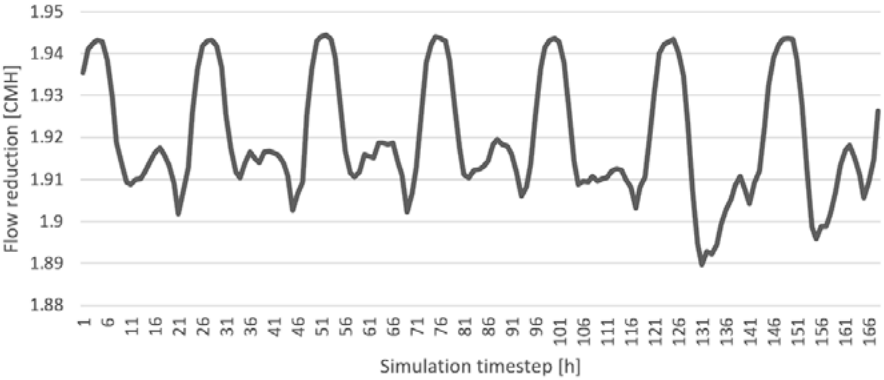

Figure 11. Difference in flow before and after pressure reduction

Source: author's work.

These results indicate that, on average, each day, it is possible to reduce leaks of the subnetwork A by approximately 46 cubic meters. This translates to 42,207 PLN each year. This can be considered a big saving considering that the pressure reduction valve costs a fraction of this value.

Model B

Due to land topography, it is impossible for system B to reduce pressure by applying pressure reducing valve at one point. This means that system-wide pressure reduction is impossible without adding expensive pumping stations Świętochowska et al. (2022). Thus, three points were selected where pressure will be reduced via the installation of pressure reducing valve and 1 point where the closure of the general-purpose valve will cut off the flow. Flow and diameter parameters for each of the said points are represented in Table 6. The plot in Figure 12 shows the average drop in pressure due to taken measures.

Table 6. Summary flow parameters at planned PRV installation and flow cutoff locations

Point	Pipediameter [mm]	Minimum flow [CMH]	Maximum flow [CMH]	Averageflow [CMH]	Pressurereduction [bar]	Optimal pressure reduction valve diameter [mm]
PRV valve 1	150	4.991	22.697	14.542	1.432	100
PRV valve 2	80	0.353	1.102	0.757	1.724	65
PRV valve 3	80	0.324	1.489	0.952	1.704	65
Flowcutoff point	110	-	-	-	-	-

Source: author's work.

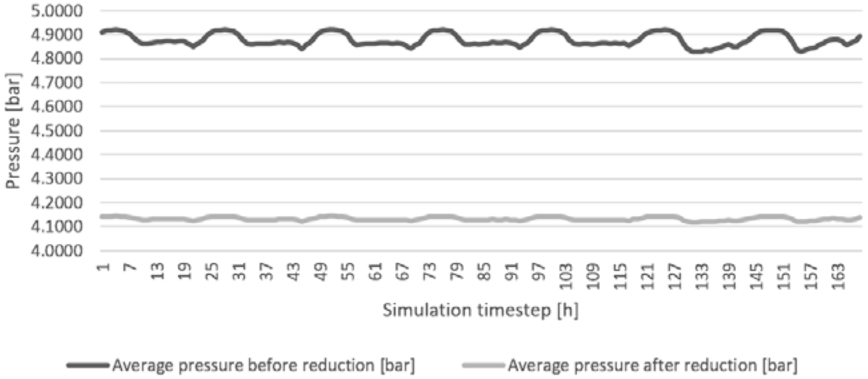

Figure 12. Average pressure for model B before and after reduction of pressure

Source: author's work.

A decrease in flow was observed after the average pressure in the network was reduced from around 4.9 bars to 4.15 at pressure reduction valves and flow cutoff at chosen points. A plot represents this reduction in Figure 13, and it shows that there is an observed reduction of approximately 0.8 CMH throughout the whole day of system work. Action in Figure 14 shows exact differences in flow before and after systemwide pressure reductions.

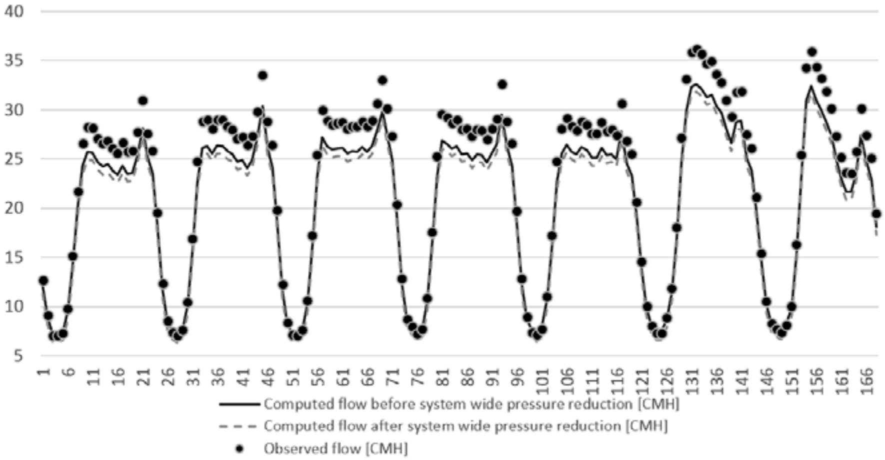

Figure 13. Plot of observed flow at inflow point of subsystem B and computed flow before and after pressure reduction in the network

Source: author's work.

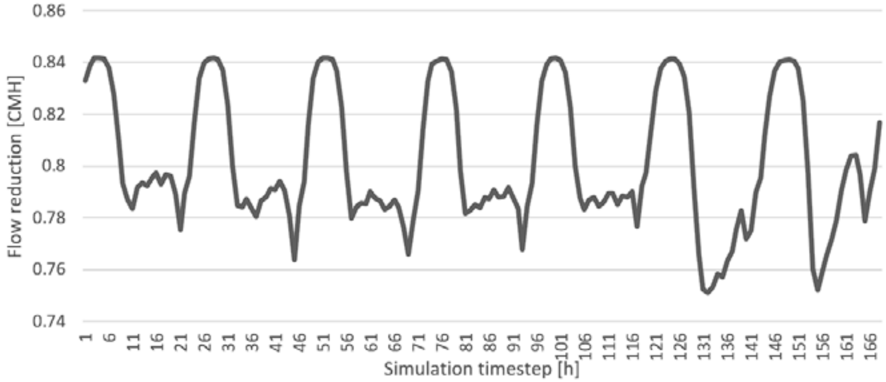

Figure 14. Difference in flow before and after pressure reduction

Source: author's work.

These results indicate that, on average, each day, it is possible to reduce leaks of subnetwork B by approximately 19.23 cubic meters. This translates to 17,625 PLN each year. This, in addition to subsystem A saving, gives 59,832 PLN lowered yearly expense of supplying end-users with water. In the perspective of 10 years, this value increases up to 598,832 PLN assuming that the price of water provided by the external company does not improve, which is unlikely when considering rising costs of energy and new environmental taxes. Such an amount for a small scale water supply company is by no means a small matter considering that all water is bought from external sources.

Conclusions

The use of computer models in water distribution system management is constantly growing. The paper focuses on the feasibility of using hydraulic modelling to estimate absolute loss reduction by implementing pressure management. For this purpose, computer models of two water distribution systems were created – submodel A and submodel B. Both of them belong to one water utility in the Silesian Voivodeship. Pressure reduction methods have been developed and simulated for each water distribution system as model scenarios.

Results have shown that in model A, average pressure in the system was reduced by 32.73% from 5.5 bar to 3.7 bar, which resulted in an expected leakage reduction by 12.88% from 130,407 m^3 per annum to 113,617.2 m^3 per annum. In model B, average pressure in the water distribution network was reduced by 15% from 4.9 bar to 4.15 bar, which may cause leakage reduction by 8.85% from 79,354 m^3 per annum to 72,335 m^3 per annum. The expected savings for implementing pressure reduction in both systems are 59,832 PLN per year (42,207 PLN at submodel A and 17,625 at submodel B).

Based on the research results, we can state that hydraulic modelling can effectively manage pressure in water distribution systems. In the case of splitting the investment into stages, implementation of pressure management in submodel A should be prioritised, as it yields the most significant savings. It also requires less financial investment as it only needs installing one pressure reduction point, unlike the submodel B, where three pressure reducing valves are needed.

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The contribution of the authors

The article was written in collaboration with all authors.

References

Baader, J., Fallis, P., Hübschen, K., Klingel, P., Knobloch, A., Laures, Ch., Oertlé, E., Trujillo, A., R. & Ziegler, D. (2011). *Guidelines for water loss reduction – a focus on pressure management*. Deutsche Gesellschaft für Internationale Zusammenarbeit.

Dawidowicz, J., Bartkowska, I., Kazimierowicz, J., Czapczuk, A., & Walery, M. J. (2021). Model of the c&rt tree for the assessment of the technical variant of the water distribution system. In D. Oraczewska & N. Vrons'ka (Eds.) *Water Supply and Wastewater Disposal: Designing, Construction, Operation and Monitoring: Proceedings of the 4th International Scientific-Practical Conference* (pp. 134–135). Lviv: Lviv Polytechnic National University.

Gwoździej-Mazur, J., & Świętochowski, K. (2019). Non-Uniformity of Water Demands in a Rural Water Supply System. Journal of Ecological Engineering, 20(8), 245–251. http://doi.org/10.12911/22998993/111716

Gwoździej-Mazur, J., & Świętochowski, K. (2021). Evaluation of Real Water Losses and the Failure of Urban-Rural Water Supply System. Journal of Ecological Engineering, 22(1), 132–138. http://doi.org/10.12911/22998993/128862

Mckenzie, R. S. & Wegelin, W. A. (2009). Implementation of pressure management in municipal water supply systems. IWA, pres. Paper 0309.

Lewis, A. Rossman et al. (2020). EPANET 2.2 User Manual. https://epanet22.readthedocs.io/_/downloads/en/latest/pdf/

Pearson, D. (2019). Standard Definitions for Water Losses https://www.iwapublishing.com/books/standard-definitions-water-losses

Świętochowska, M., Bartkowska, I., & Gwoździej-Mazur, J. (2021). Energy Optimization of the Pumping Station, Environmental Sciences Proceedings 9/1, 1–3. https://doi.org/10.3390/environsciproc2021009037

Świętochowska, M. & Bartkowska, I. (2022). Optimization of Energy Consumption in the Pumping Station Supplying Two Zones of the Water Supply System. Energies. 15(1):1–15. https://doi.org/10.3390/en15010310

The European Federation of National Associations of Water Services (2021). Europe's Water in Figures. An overview of the European drinking water and wastewater sectors. https://www.eureau.org/resources/publications/eureau-s-publications/5824-europe-s-water-in-figures-2021/file

Trębicka, A. (2016). Ekonomiczne aspekty monitorowania pracy podsystemu dystrybucji wody podczas symulacji komputerowej. Ekonomia i Środowisko, 1, 107–116.

Walski, T. M. (1986). Case study: Pipe network model calibration issues. Journal of Water Resources Planning and Management, 112(2), 238–249. https://doi.org/10.1061/(ASCE)0733-9496(1986)112:2(238)