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WATER AGE MODELLING AS A TOOL TO IMPROVE THE QUALITY AND REDUCE THE COSTS OF WATER TREATMENT IN POLANICA-ZDRÓJ

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ABSTRACT: The article contains part of the results of the project Protection of Natural Water Resources in Polanica-Zdrój through Intelligent Water and sewage management. The article presents the research results into the water supply network (WDN). The aim of the research was to improve the quality of water and reduce the cost of its treatment by reducing the age of the water. For this purpose, a model was built that takes into account the time in which water stays in a given section from the moment it flows out of the intake and mixes with the water already present in the network. The research was preceded by the construction of a model based on GIS geodetic data and a digital terrain model. On the basis of the simulations and analyses carried out, a solution was proposed to reduce the average age of water in the investigated WDN.

KEYWORDS: hydraulic modelling, gis, water age, water quality

Introduction

This article contains the results of research that is part of a project carried out by our research unit. The project entitled: “Protection of natural water resources in Polanica-Zdrój through intelligent management of water and sewage management” is financed by The National Center for Research and Development in Poland. Project number: POIR.01.01.01-00-0349/19. The entire project includes the creation of an intelligent, integrated water and wastewater management system based on an innovative 3D GIS system and hydrodynamic modelling of water distribution and sewage disposal systems. The object of the research is the municipal water supply network and household sewage system in Polanica-Zdrój. The full subject scope includes the construction of a simulation system for the operation of the water supply network, the construction of a simulation system for the operation of domestic and commercial sewage systems, the construction of scenarios for the operation of systems in the conditions of urban development and climate change, multi-criteria assessment of the economic efficiency of the operation of systems, taking into account social and environmental criteria, development of an integrated management system the system, taking into account the guidelines to increase the efficiency of its operation and work safety. The part of this project described in this article is the results of computer simulations of the operation of the water supply network, which were intended to help find a method and a way to improve the quality of water supplied by the water supply network. The age of water is the time the water stays in the network until it is delivered to the recipient. It is a parameter that determines the freshness of water and affects its quality. The longer the water stagnates in the water supply, the more likely it is that dangerous bacteria will develop in it and create deposits on the walls of the pipes.

The built model considers the time in which the water stays in a given section from the moment it flows from the intake and is mixed with the water already present in the network.

The research on the model was preceded by mapping the WDN based on GIS geodetic data and a digital terrain model. Then, a pressure and flow measurement campaign was carried out, and the model was calibrated.

Analysis of the age of water in the modelled aqueduct showed areas where stagnant water is ageing, having no outlet and not giving way to fresh water. Based on the simulations and analysis, a solution was proposed to reduce the average water age in the WDN pipes of the tested facility.

In the study, the Epanet program was used for modelling, which performs extended hydraulic simulations and simulations of water quality behaviour in pressure networks. During the simulation period, which consists of spe-

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cific time steps, the program makes it possible to observe the flow of water in pipelines, changes in pressure values in nodes, changes in the water level in individual tanks and the distribution of concentrations of chemical compounds within the entire network. The chemical analysis of the program allows you to simulate the age of water and its flow from individual sources.

Water distribution systems in Poland in previous years had a much higher demand for water. Strict fire safety standards that must be met by constructed water supply systems have resulted in the current water supply systems being oversized as demand for water decreases.

Maintaining proper water flow in water supply networks (min. 0.5 m/s) prevents the accumulation of deposits on the walls of water pipes. This has a significant impact on water quality and operating costs of water supply systems (Lahlou). Too low speeds affect the deterioration of water quality and increase the risk of failure. This significantly increases the costs of water treatment and the operation of water supply systems.

An overview of the literature

Geospatial (GIS) data is increasingly being used to optimally manage a city's water and wastewater infrastructure. This allows you to gain an additional analytical tool for planning, designing or obtaining operational data. The integration of hydraulic models of the water supply and sewage networks in one coherent management system based on GIS is particularly important because it enables a holistic assessment of the functioning of the water and sewage management system in the city (Sitzenfrei, 2021).

Decision support systems based on a spatial information system (GIS) associated with a variety of specialised software are becoming a standard in the modern management of a water supply and sewage company. However, research conducted by entities offering commercial solutions in this area shows that only about 40% of companies in the industry use systems of this type, and at the same time, the vast majority are interested in their implementation or development in the near future. In addition, most of the GIS-based management systems used in practice are limited to the inventory of network resources and the integration of multiple databases into one coherent IT system. Only in a few cases systems of this type contain modules that model the operation of the network in dynamic conditions, which results primarily from the additional costs of implementation related to the construction of sufficiently reliable models of water supply and/or sewage systems.

The long-term stagnation in the transfer of modern technologies and technical solutions in Poland has led to an increase in the interest of municipal enterprises in the implementation of IT tools supporting the management of water and sewage management (Malmur et al., 2018). This is mainly due to the need to reduce operating costs, improve the operation of existing networks, and increase the efficiency of company management (Farmani et al., 2006).

A dynamic network model is a highly efficient tool supporting its observation and operation, allowing for making well-founded optimal decisions regarding the operation, modernisation and expansion of the entire water and sewage system of a city or commune (Desta et al., 2022). The precision of the model operation depends to a large extent on the accuracy of the data entered in the digital geodetic bases. Data is entered using selected GIS data and modelling software (Studzinski, 2015). It is also possible to do it in one integrated environment.

Conducting computer simulations of the operation of the water supply network is intended to help in finding a method and a way to improve the quality of water supplied by the water supply network (Wang & Zhu, 2022). Using special software, it is possible to model, e.g. changes in the age of water throughout the distribution system. Fresh water flows into the network from reservoirs or springs. The age of the water in the pipes is a parameter that determines its freshness and affects its quality. The model takes into account the time in which water stays in a given section from the moment it flows from the intake and is mixed with water already in the network (Świętochowska & Bartkowska, 2022).

There are comprehensive management systems available on the market for companies from the water supply and sewage industry, built on the basis of GIS systems and containing modules for computer modelling of water supply and sewage networks. These are solutions from companies such as Bentley Systems (USA), MIKE Powered by DHI (Denmark), and Stanet (Germany). These companies have offices in Poland and implement comprehensive platforms for integrated enterprise management, also using mathematical modelling of the operation of the water supply and sewage networks. However, these solutions require the purchase of costly licenses and maintenance packages run by external companies. Implementation costs often exceed the budgetary capabilities of small water supply companies. Reducing the costs associated with the purchase of licenses and support for the implemented solutions can be achieved through the use of open-source software and the use of the experience of the scientific and research staff. For this purpose, available free modelling and GIS software is successfully used. These environments can be combined using existing platforms or by building your own software (Haghiabi et al., 2018).

Contemporary geoinformation systems designed for water supply and sewage infrastructure are complex platforms integrated with monitoring and

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mathematical modelling tools (Sunela & Puust, 2015). They also cooperate with other IT systems, such as supervisory and information gathering systems – SCADA (Supervisory Control And Data Acquisition), work management systems – WMS (Work Management Systems) or archival documentation management systems – EDMS (Electronic Document Management Systems).

The payback period for the implementation of the GIS IT system shortens with the increase in the size of the water supply and sewage system in use. Before starting modelling, it is necessary to decide on the choice of software and the method of its implementation – a company, an external institution or its own human resources (training specialists to create and use the model).

A functional solution that increases the quality of services in the water supply (Zimoch & Bartkiewicz, 2018) and sewage sector based on the results of hydrodynamic modelling in conjunction with the monitoring network and GIS database allows for:

- in the water supply network – improving the quality of water by selecting the optimal operating parameters, reducing the age, and increasing the average speed of water flow in the pipes (Kourbasis et al., 2020),
- in the sewage network – limiting the amount of infiltration and accidental water and minimising the risk of the network's odour nuisance,
- savings are resulting from abandoning the implementation of inappropriate investments – checking their legitimacy with simulations in the program. Planning "outages" on networks related to flushing, renovation or investments in such a way as not to worsen the standards of water supply to residents or sewage disposal during their duration,
- reduction of operating costs and losses on the network by reducing the efficiency of sources in the period of the smallest partitions (Gwoździej-Mazur & Świetochowski, 2021),
- reduction of operating costs by controlling the operation of the pumping station (proven by simulations in the model) in such a way as to reduce energy consumption and, at the same time, maintain the standards of water supply and sewage disposal to residents (AWWA, 2002),
- obtaining full knowledge in real time about the parameters, i.e., quantity and quality of water supplied at any point in the water supply network or wastewater flows in domestic and commercial sewage systems, and additional knowledge on the interaction of water supply and sewage systems in dynamic conditions (Shamsaei et al., 2013).

Too low velocity of water in the pipes causes deposits on the bottom of the pipelines and decreases the permeability of the pipeline, which causes an increase in pressure and water flow velocity in a given section (Tabesh & Doulatkhah, 2006). At some point, the increase in flow velocity entrains the accumulated sludge and discharges polluted water at the end user. With

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longer sections and low flow velocities, there is also the phenomenon of stagnation of water in the pipes, which may result in the risk of secondary multiplication of bacteria. Hence, the recommendation is that the water velocity should be in the range of 0.5-1.3 m/s.

The implementation of an integrated system in water supply networks should allow for pressure regulation to maintain its value at each point within the required range with an accuracy of ±10% to reduce areas with speed below 0.2 m/s by at least 20% and reduce the average age of supplied water in areas with the longest water age by at least 20%, and reducing water losses by 12%. In the case of sewage networks, the implementation of the developed solutions will make it possible to reduce the inflow of rainwater to the sewage treatment plant and to reduce network fragments operating under pressure during rainy weather by at least 10%.

Research methods

In order to achieve the intended results of the project, the following stages of the project were carried out:

Construction of the hydraulic model of the water supply network

The hydraulic model built in the initial phase, representing the geometry of the network, the height system and the hydraulic characteristics of its elements (in-takes, pumping stations, tanks, etc.), was supplied with data on water consumption registered in the MZK Polanica-Zdroj company database. Preliminary steady-state hydraulic simulations (for average water consumption) revealed a number of inconsistencies in the model generated directly from the GIS database, mainly due to the incorrect assignment of network nodes to sections. After correcting the structure of the model, a formally correct and ready-for-calibration hydraulic model of the water supply network was obtained.

The hydrodynamic model of the water supply network was built in the Epanet program on the basis of data from the GIS system, supplemented with information obtained from employees of the MZK in Polanica-Zdrój. This model has the following structure:

- number of nodes: 4160,
- number of episodes: 4221,
- number of tanks: 5,
- number of control valves: 22.

The model was supplied with information on the water distribution of individual water consumers registered in the MZK databases in Polanica.

The model was developed in the first stage of the QGIS program based on the developed GIS data (Figure 1). Then, the model data was exported to

Epanet (middle window) and to WaterGems (first window). Full compliance with the mapping was obtained in each program. This enables the choice of performing simulations in both programs – commercial – WaterGems and open source –Epanet (Rossman et al., 2020).

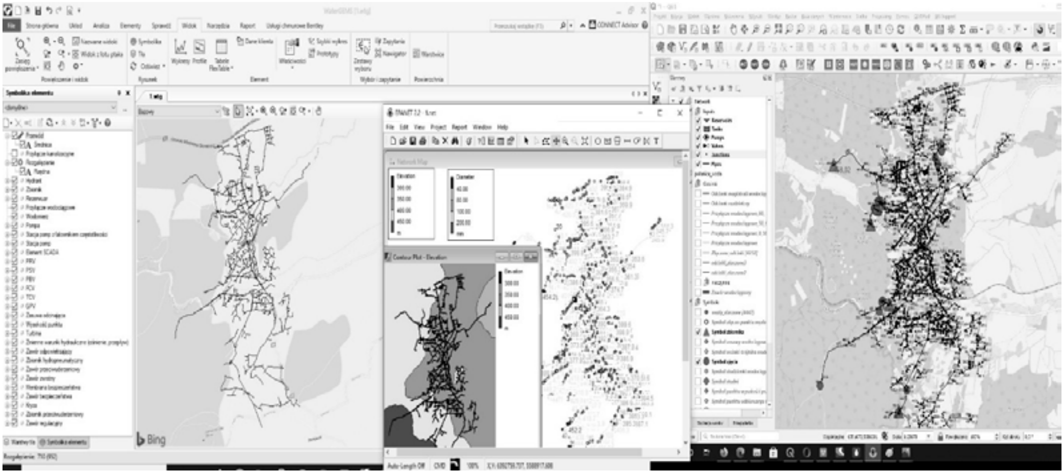

Figure 1. Mapping of the water supply network model in Polanica Zdrój in the WaterGEMS, Epanet and Qgis programs – view of the entire network

Measurement campaigns

For the purposes of calibration and validation of the water supply network model, 4 pressure and water distribution measurement campaigns were carried out in the period October 2020 – June 2021. For each campaign, 20 measurement points on hydrants (pressure) located in different pressure zones of the water supply system and 20 water meters of household connections were used (distribution of water) for different categories of recipients. Examples of measuring stations are shown in Figures 2 and 3.

Calibration of the water network model

The data obtained from the measurement campaigns were used to calibrate and validate the model. On the basis of data from flow recorders mounted on water meters, the characteristics of unevenness of water consumption for different groups of recipients were developed in Figure 4.

Based on the obtained results, a new pattern of dissections was developed (Figure 5), used for further calibration due to the water pressure in the water supply network.

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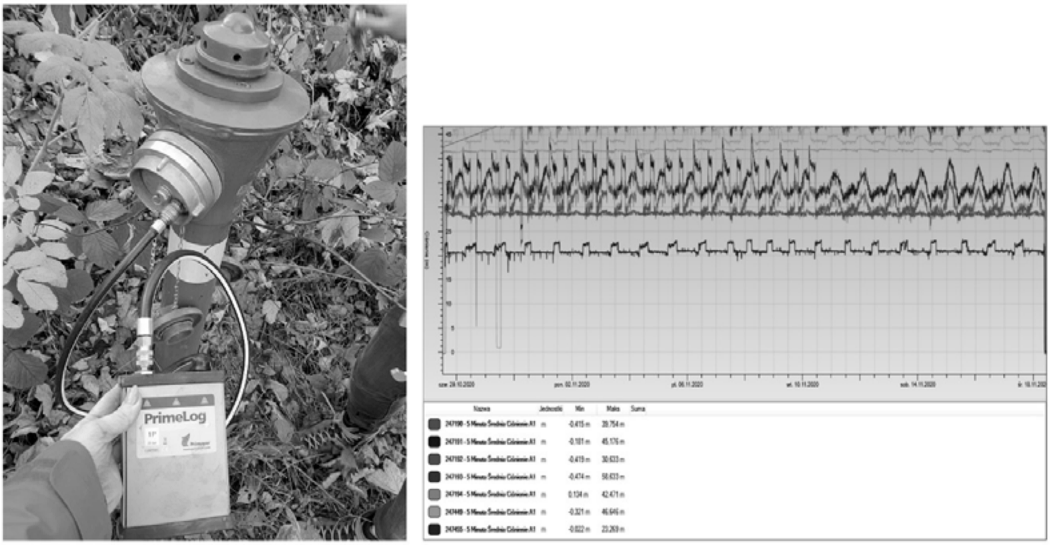

Figure 2. Pressure recorder on the hydrant with the reading device and the pressure reading taken from the device

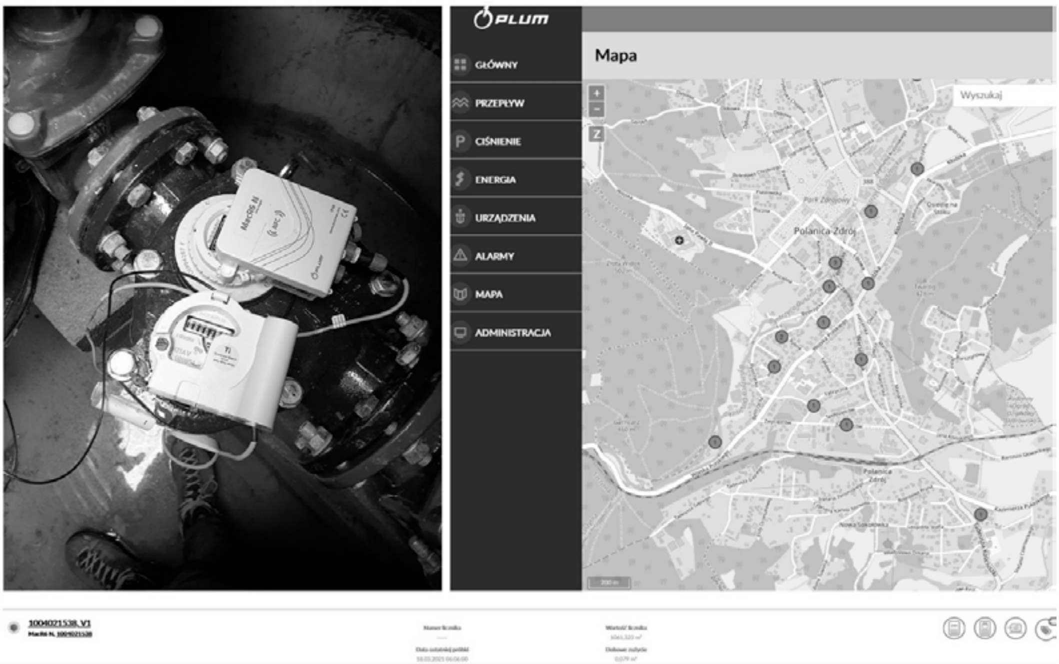

Figure 3. Flow recorders with the device, their location and the flow reading downloaded from the device service website

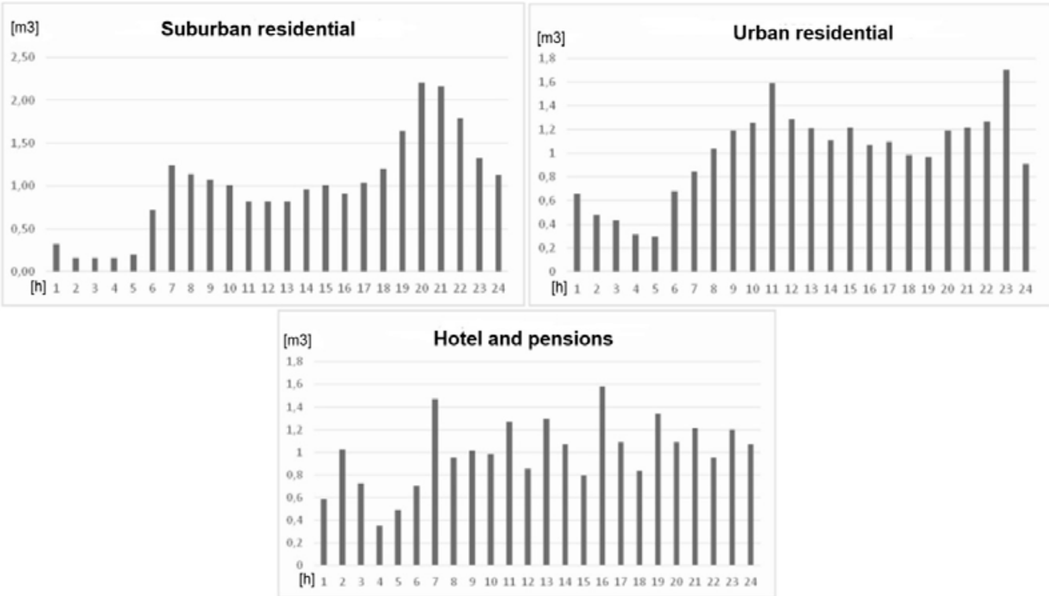

Figure 4. Irregularity of partitioning for the water supply network in Polanica Zdrój

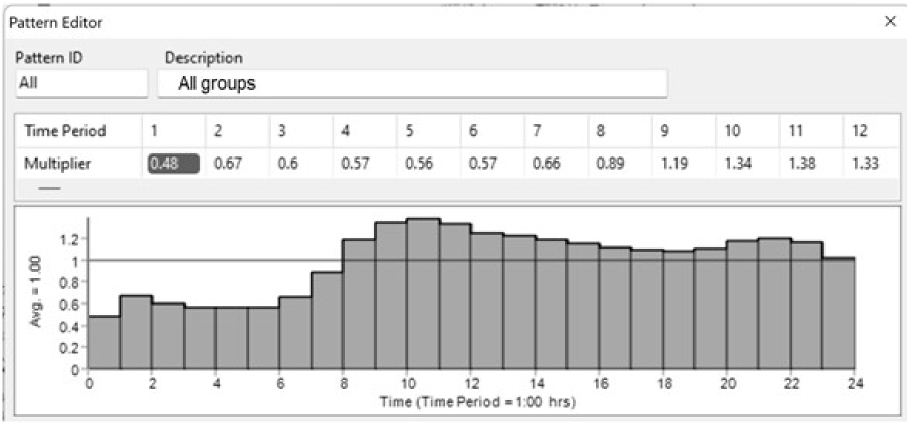

Figure 5. Corrected unevenness of water distribution (averaged for housing)

The second stage of the calibration was the verification of the water pressures obtained from the measurement campaigns with the simulation results. The results of the calibration for campaign 1, generated from the Epanet program, are shown in Figure 6. The data from campaign 2 were not used in the calibration due to the fact that the duration of the campaign was too short. Based on the obtained results, the simulation error does not exceed 10% – Figure 6.

Calibration Report - Pressure

Statistics | Correlation Plot | Mean Comparisons

Calibration Statistics for Pressure

Location	Num Obs	Observed Mean	Computed Mean	Mean Error	RMS Error
150	24	35.43	39.09	3.661	3.910
172	24	29.33	29.30	0.143	0.170
90	24	49.40	53.20	3.795	4.058
70	24	41.51	43.57	2.064	2.191
158	24	44.25	46.28	2.030	2.238
99	24	21.10	21.32	0.600	0.687
83	24	57.70	59.45	1.755	2.107
154	24	38.51	41.48	2.967	3.265
12	24	47.68	50.09	2.412	2.718
133	24	24.17	24.83	0.658	0.705
4755	24	55.56	58.48	2.917	3.200
2294	24	33.16	34.20	1.041	1.106
123	24	43.37	47.20	3.826	3.879
85	24	48.32	49.60	1.279	1.331
78	24	58.52	59.65	1.139	1.288
176	24	47.14	47.53	0.461	0.531
166	24	42.69	39.17	3.524	3.601
72	24	47.07	43.08	3.995	4.073
Network	432	42.49	43.75	2.126	2.633

Correlation Between Means: 0.981

Figure 6. Calibration results for pressure

The last stage was the validation of the model carried out for a different period of the network operation than the calibration. Data on pressures in the water supply network collected in measurement campaigns 3 and 4 were used for validation. The validation results shown in Figure 7 confirmed the assumed accuracy of the model – the simulation error does not exceed 10%.

Calibration Report - Pressure

Statistics | Correlation Plot | Mean Comparisons

Calibration Statistics for Pressure

Location	Num Obs	Observed Mean	Computed Mean	Mean Error	RMS Error
70	24	41.58	43.58	1.998	2.004
123	24	43.29	47.20	3.905	4.039
67	24	62.49	64.65	2.169	2.287
72	24	39.02	43.07	4.046	4.108
4567	24	32.36	34.51	2.148	2.240
150	24	38.96	38.45	0.708	0.774
78	24	57.96	59.45	1.492	1.675
85	24	49.62	49.60	0.427	0.543
154	24	42.10	40.84	1.348	1.570
133	24	22.97	24.87	1.894	1.981
158	24	43.72	46.25	2.531	2.965
90	24	50.58	53.02	2.445	2.876
4755	24	57.67	58.29	0.831	0.912
12	24	50.62	49.45	1.327	1.474
99	24	21.23	21.27	0.580	0.706
Network	360	43.61	44.97	1.857	2.282

Correlation Between Means: 0.990

Figure 7. Validation results for pressure – campaign no. 3

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Results of the research

The age of the water is a function primarily of water demand, system operation and system design. As demand for water increases, the amount of time a given litre of water stays in the distribution system decreases. Demand is related to land use patterns, types of commercial and industrial activities occurring in the settlement unit, weather (i.e. watering lawns) and community water usage habits (i.e. conservation practices, reuse practices). Conservation, in particular the use of reclaimed water on-site or through separate distribution systems, will lead to greater water ageing when all other factors are held constant (Clarke, 2012).

In the study, the Epanet program was used for modelling, which performs extended hydraulic simulations and simulations of water quality behaviour in pressure networks. During the simulation period, which consists of specific time steps, the program makes it possible to observe the flow of water in pipelines, changes in pressure values in nodes, changes in the water level in individual tanks and the distribution of concentrations of chemical compounds within the entire network. The chemical analysis of the program allows you to simulate the age of water and its flow from individual sources (Imran, 2022).

For the purposes of this article, the results of water age modelling in the WDN in the city of Polanica-Zdrój were selected in three variants:

1. Variant 1 – age of water in the tested WDN based on the collected data and the launched model showing the actual state Figure 8. WDN in this variant contains all 4160 nodes. The average age of the water during the 240-hour water simulation is 107.54 hours. Figure 8 shows large zones where its age is longer than 140 hours.
2. Variant 2 – age of water in the tested WDN – simulation after introducing additional pipe connections in order to force better water circulation in the network. Figure 9.

In this variant, the HDN contains all nodes from the simulation of the existing state, but 5 lines have been added to speed up the circulation and exchange of water in the network:

- 1 connection – between node J7522 and J20322, wire number: 123, diameter: 90 mm,
- 2nd connection – between node 2910 and 2918, wire number: 124, diameter: 32 mm,
- 3rd connection – between node 2886 and 2780, wire number: 136, diameter 32 mm,

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- 4th connection – between node 3950 and 4257, wire number: 141, diameter 32 mm,
- 5th connection – between node 3953 and J421, wire number 159, diameter 40 mm.

According to this solution, the average water age during the 240-hour water simulation for the investigated WDN is 96.40 h.

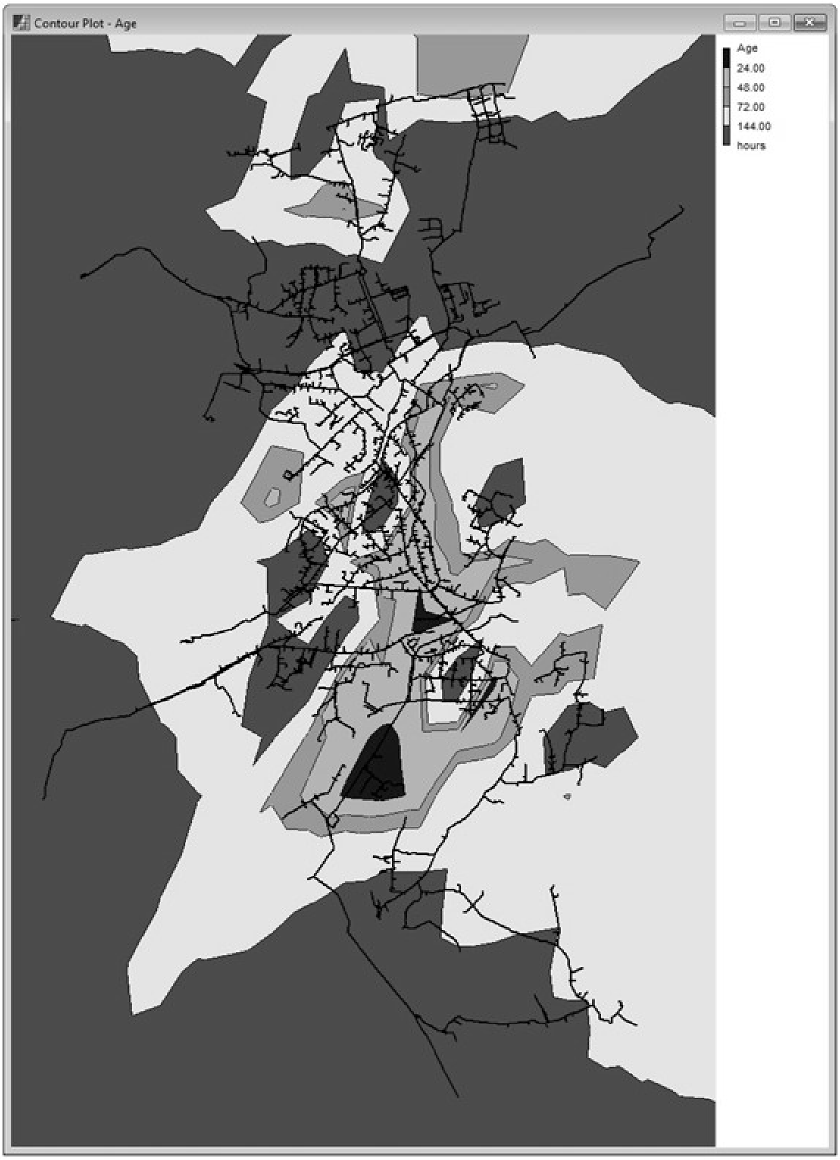

Figure 8. Age of water in WDN Polanica-Zdrój – simulation time 240h. Variant 1

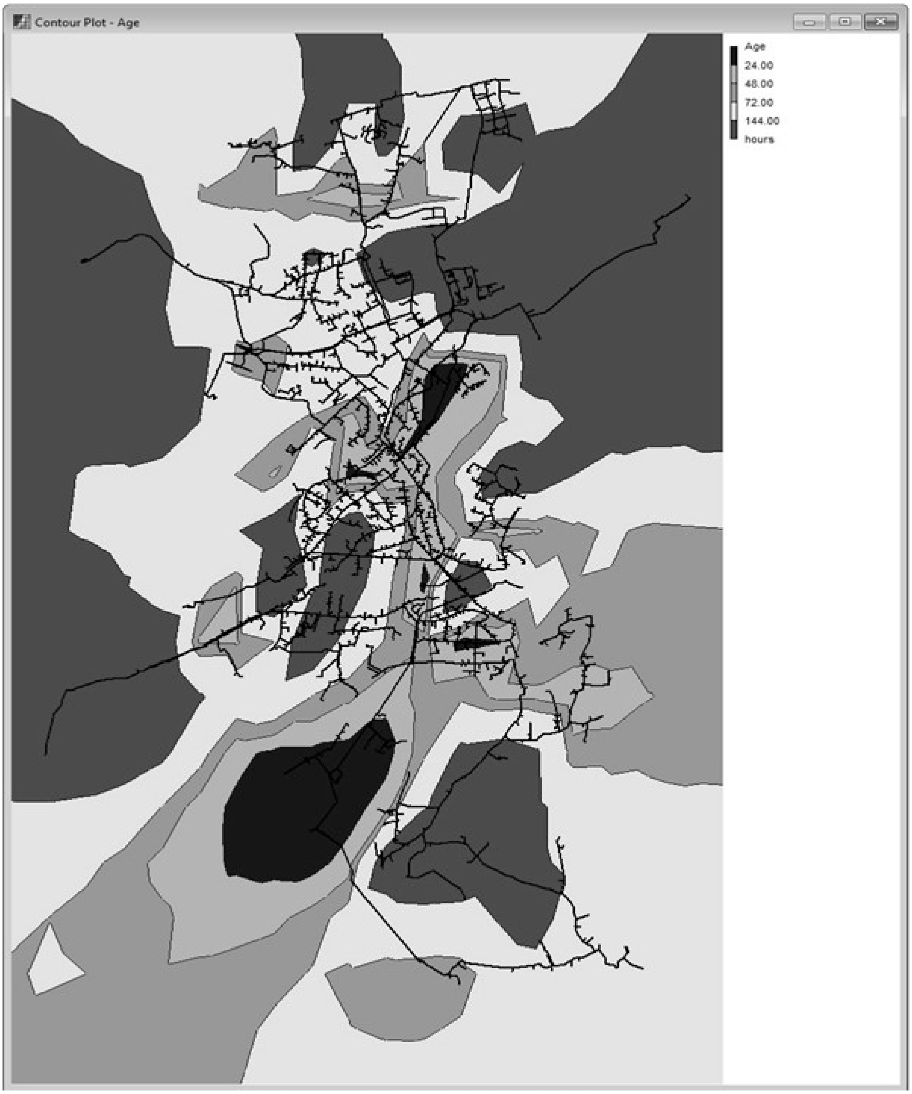

Figure 9. Age of water in WDN Polanica-Zdrój – simulation time 240h. Variant 2

Variant 3 – age of water in the tested WDN – simulation showing the difference in water age in the case of proposed changes aimed at reducing the number of zones with no water flow in the network.

In this variant, the exclusion of zones in which no water partitions were recorded from the network was simulated. Figure 10 shows a clear reduction in the number of zones where the total water age is longer than 140 hours. The average age of the water during the 240-hour water simulation for the investigated WDN is 75.19 hours.

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Figure 10. Age of water in WDN Polanica-Zdrój – simulation time 240h. Variant 3

Discussion and Conclusions

The analysis of water age performed on models of the existing state of the tested water supply network in Polanica Zdrój showed that there are zones with a potentially high risk of deterioration of water biological purity and deposition of sediments at the bottom of the pipes. This is a very unfavourable phenomenon and may result in the risk of secondary multiplication of bacteria. As a result of the simulations, it was found that it is possible to reduce the percentage of the average age of water in the pipes. Table 1. In the example water supply network, in the 240-hour simulation, the age of the water decreased by 10.37% compared to the condition existing in the simulation, taking into account the introduction of additional pipes forcing water circulation in the network. On the other hand, the simulation of excluding dead zones from the network showed that such a solution would theoretically reduce the maximum age of water in the tested network by 30.8%. Table 1 and Figure 11.

Table 1. Percentage reduction of the maximum water age in WDN Polanica Zdroj

	average age of the water	percentage reduction of the maximum water age
Variant 1	107.54	
Variant 2	96.40	10.37
Variant 3	75.19	30.08

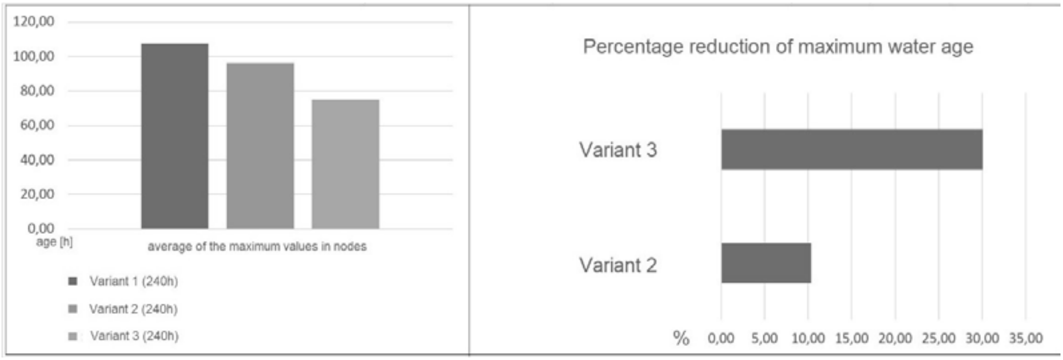

Figure 11. The average age of the water and percentage reduction of the maximum water age in WDN Polanica Zdroj

Using the software used, changes in the age of water in the entire distribution system can be modelled. The age of the water in the pipes is a parameter that determines the freshness of the water. Epanet takes into account the time in which water stays in a given section from the moment it flows from the intake and is mixed with water already present in the network. Computer modeling of water supply networks allows you to obtain economic and technological benefits:

- savings resulting from the abandonment of inappropriate investments – checking their legitimacy with simulations in the program,

- reduction of operating costs and losses on the network by reducing the efficiency 0 of sources in the period of the smallest partitions,
- reduction of operating costs by additional connections forcing water circulation in the network (proven by simulations in the model) or elimination of dead zones from the network without water flow,
- real-time knowledge about the parameters, including the quantity and quality of the water supply at any point in the water supply network.

The simulations carried out showed that it is possible to use computer models of water supply networks to find solutions aimed at improving the quality of water in its distribution systems.

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The contribution of the authors

The article was written in collaboration with all authors.

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