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Analysis of Water Age and Flushing of the Water Supply Network of the Pressure Reduction Zone

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ABSTRACT

The water of appropriate quality introduced in the water system changes its chemical properties. Depending on the chemical properties of water and pipe materials, various phenomena may occur, e.g. corrosion, and biofilm structure. The decreasing water demand in existing water systems leads to a reduction in the water flow velocity in the pipes. Accordingly, the age of the water in the system increases. It is especially visible at connections and long sections of the network. The deteriorating water quality along with the elapsing time of its stay in the pipes makes it necessary to perform appropriate measures, e.g. flushing the network. Water supply services usually perform them intuitively. The choice of flushing sites, times, or flow rates is not measured and verified. The age of the water and the efficiency of flushing can be simulated in computer programs. EPANET provides tools for such simulations. The research aimed to check the effects of flushing the network and the age of water in the pressure reduction zone. This is a case that is particularly prone to the increasing age of water. The research has shown that the network flushing sites used so far contribute to the exchange of water in the main water pipes. The simulations showed the need for the additional flush in new places, and in the tested case, the age of the water in the pipes is as much as the intervals between subsequent rinses.

Keywords: water distribution system, water age, water quality, flushing water systems, pressure zone.

INTRODUCTION

The water in the water supply system must have the appropriate quality specified in the law, it must be sufficiently large to meet the needs of the settlement unit and people, and must be pumped and delivered under the appropriate pressure to reach each recipient [Dz. U. 2001 Nr 72 poz. 747]. Polish regulations on the quality of drinking water, however, do not specify the values related to the time it may remain in the water pipes [Dz.U. 2015, poz. 1989]. Water from the source to the recipient changes its properties. Water in contact with steel or cast iron pipes reacts in various types, for example leading to corrosion and an increase in roughness [Hu, et al, 2018]. The roughness in cast iron pipes may increase by as much as 1 mm per year [Wichowski et al., 2021]. The absolute roughness k of its internal wall increases, but each network has a different increment. This leads to many problems when calibrating computer models [Mallick et al., 2002; Annus and Vassiljev, 2015]. Water in PE and PVC pipes quickly forms a biofilm that can be torn off and transferred to water recipients when changing the flow direction or increasing the water flow velocity (e.g. during network flushing) [Ainsworth, 2013; Zimoch and Bartkiewicz, 2018]. High pressure in the water supply network is one of the reasons for the increased failure rate, and thus increases unit failure intensity λ [fail·km^{-1}·a^{-1}] [Gwoździej-Mazur and Świętochowski, 2021]. Higher pressures have a directly proportional effect on the increase in the volume of UARL, which depends on the length of the water supply network, the number of connections and their length, and the value of the average pressure [Lambert and Hirner, 2000; Gwoździej-Mazur and Świętochowski, 2019]. One way to manage the pressure in the pressure zone is to build pressure reduction points equipped with PRV valves. The use of PRVs reduces water pressure but can increase water age [Kourbasis et al., 2020]. Retrofitting PRV points with flow meters or water meters with a properly selected diameter allows you to generate patterns for the zone. Appropriate selection of a water meter in the main supply point of the zone, and then correctly selected water meters at the recipients help in managing the water balance and reduce the apparent losses of water [Gwoździej-Mazur and Świętochowski, 2018]. Patterns are important because they help in the preparation of computer models of network operation. The amount of water consumption depends on the season, month, day of the week, and time. The hourly non-uniformity may vary from a few to several dozen percent about the same hour on another day of the year [Gwoździej-Mazur and Świętochowski, 2019]. Patterns require normalization [Avni, Fishbain and Shamir, 2015]. Usually, they are averaged to the 1-hour interval. In the case of water quality simulations, the simulation interval is often much shorter than the hydraulic simulation duration [Rossman, 1994]. Computer models, apart from being used to simulate the hydraulic operation of the network, are also used to model water quality [Sunela and Puust, 2015]. This is often overlooked when designing, expanding, and modernizing networks.

Water quality simulation model in EPANET

EPANET has many options for water quality modeling. Lagrangian time-based used in EPANET's water quality simulator allows for an approach to track the fate of discrete parcels of water as they move along pipes and mix at junctions between fixed-length time steps [Rossman, 1994]. EPANET allows you to simulate the quality of water in pipes and junctions, and also uses 4 models of water mixing to simulate its quality in tanks:

- Complete Mixing,
- Two-Compartment Mixing,
- FIFO Plug Flow,
- LIFO Plug Flow.

Another possibility in EPANET is to model flow chemical reactions and simulate wall reactions. The basis for calculating the mass flow reactions with n-th order kinetics is the demand for the instantaneous reaction rate (R in mass/volume/time).

$$R = K_b C^n \tag{1}$$

where: K_b – a bulk reaction rate coefficient; C – reactant concentration (mass/volume); n – a reaction order.

K_b has units of concentration raised to the (1-n) power divided by time (it is positive for growth reactions and negative for decay reactions). EPANET also allows the calculation of reactions where there is a concentration limit on the final increase or loss of a substance [Rossman, 1994].

$$R = K_b(C_L - C)C^{(n-1)}\ for\ n > 0, K_b > 0 \tag{2}$$

$$R = K_b(C - C_L)C^{(n-1)}\ for\ n > 0, K_b < 0 \tag{3}$$

where: C_L – is the limiting concentration.

Chemical simulation models consist of four stages:

1. First-Order Decay (when $C_L = 0$, $K_b < 0$, $n = 1$), for example: Chlorine simulations,
2. First-Order Saturation Growth (when $C_L > 0$, $K_b > 0$, $n = 1$), for example: Trihalomethanes simulations,
3. Zero-Order Kinetics (when $C_L = 0$, $K_b <> 0$, $n = 0$), for example: Water Age simulations,
4. No Reaction (when $C_L = 0$, $K_b = 0$), for example: Fluoride Tracer simulations.

EPANET water age simulation

Water age cannot be measured by physical tools, but water age can be simulated from mathematical modeling tools like EPANET [Blokker et al., 2016]. Water age is the time spent by a parcel of water in the network. New water entering the network from reservoirs enters with the age of zero. Each second of water in the network increases its age by one second (follows zero-order kinetics) [Rossman, 1994].

In the case of models powered by two sources, the ability to trace the origin of water in the network becomes an important element of the simulation. Water from different sources is mixed in different proportions in the network. This may have an impact on the age of the water when the residence time of the water portion from source A is longer than the residence time [of the water portion from source B [Haestad et al., 2004].

The material and methodology

The pressure reduction zone protects a part of the water supply network against excessive pressure. However, the reduction point is not at the highest point of the network, but almost at the lowest point of the network. The reason for these situations is very high pressure (approx. 1.2 MPa) prevailing in the main supplying the zone. The pressure is reduced depending on the current needs of the zone between 0.5–0.6 MPa. The difference in height between the highest and the lowest point of the network is 43 m. The average height in the zone is 397.4 m.

Distribution lines account for 68% of the network length and 96% of the water volume in the zone (Fig. 1). Tests and calculations were performed using the EPANET software. The preliminary work consisted in creating a model graph (data exported from the GIS system) and collecting information on the flushing processes of the designated pressure zone and data from the monitoring of the pressure reduction point.

Field measurements were performed using PrimeLog pressure data loggers mounted on above-ground hydrants. The pressure data loggers were characterized by a wide measurement range from 0 to 2 MPa with an accuracy of 0.1% FS [Primayer Ltd, 2013]. The data loggers recorded the pressure values in 10-minute intervals for 2 weeks. Then, static pressure, dynamic pressure, and water outflow from hydrants were measured using the HYDRO-TEST measuring set equipped with the HATEST electronic measuring device [Biatech Ltd., 2019]. The pressure zone model was calibrated from the collected pressure and flow data in the zone. The calibrated model was validated based on data from measurements of static and dynamic pressure on hydrants. The analysis of pressure distribution, flow velocity, and water age was carried out. The network washing and effectiveness simulations were carried out.

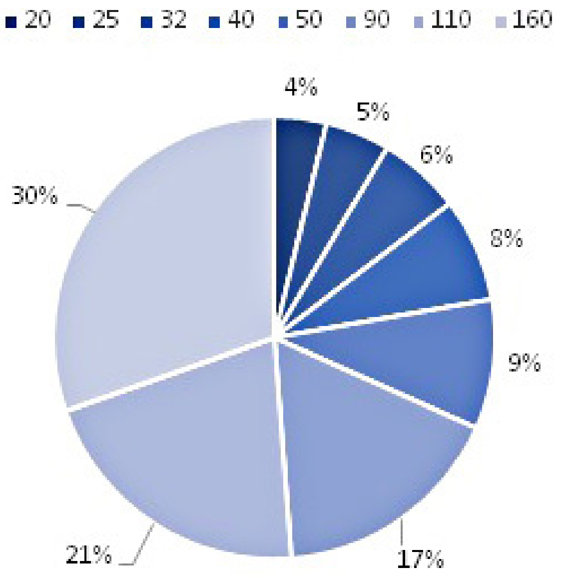

Figure 1. Share of pipes of a given diameter in the pressure zone

RESULTS

Baseline scenario - normal work

The baseline scenario for the calculations was to check the age of the water and the flow velocity in the pressure zone. There are five water age ranges:

- below 24 h,
- from 24 h to 48 h,
- from 48 h to 72 h,
- from 72 to 144 h,
- above 144 h.

There are 5 velocity ranges:

- below 0.01 $m \cdot s^{-1}$,
- from 0.01 $m \cdot s^{-1}$ to 0.1 $m \cdot s^{-1}$,
- from 0.1 $m \cdot s^{-1}$ to 0.5 $m \cdot s^{-1}$,
- from 0.5 $m \cdot s^{-1}$ to 1.5 $m \cdot s^{-1}$,
- above 1.5 $m \cdot s^{-1}$.

The main lines of the distribution network retain the age of the water for up to 72 hours. The visible outlets of a branched network are characterized by a water age of more than 72 hours, and the ends of the network are even more than 144 hours up to 240 hours (Fig. 2). Water flow velocity in most networks is below 0.01 $m \cdot s^{-1}$ (Fig. 3).

Variant H1

The H1 variant for flushing the network is characterized by the fact that the hydrant is located at the highest point of the network. The water outflow value obtained during field measurements is $Q = 21.96\ m^3 \cdot h^{-1}$. A typical flushing time provided by the water supply service was assumed to be $t = 1$ h. The distribution of water age in the pipes is shown in Figure 4. The velocity value in the pipes is presented in Figure 5.

Flushing the network refreshed the water in the main distribution lines. Major network departures have not gotten better. Single departures refreshed the age of the water. The simulation results clearly show that the water velocity in the main pipes has improved to a value in the range

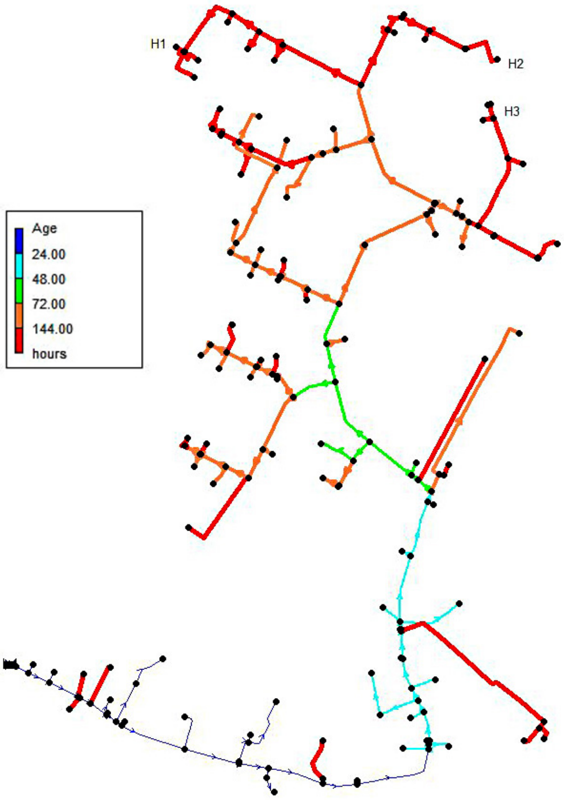

Figure 2. Age of water after 240 hours of simulation

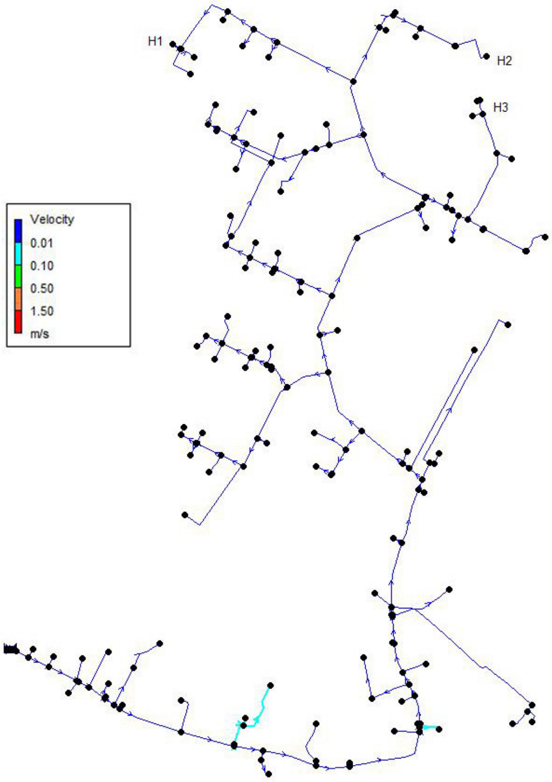

Figure 3. Water velocity in 240 hours of simulation

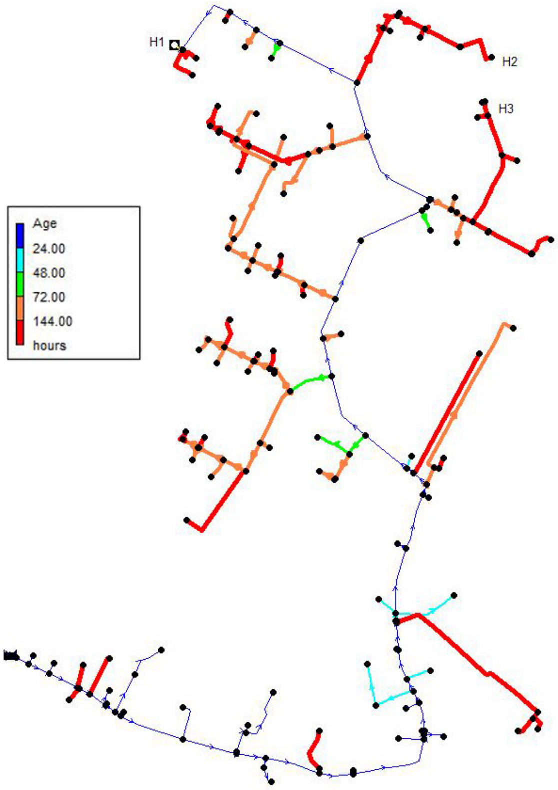

Figure 4. Age of the flushing at point H1

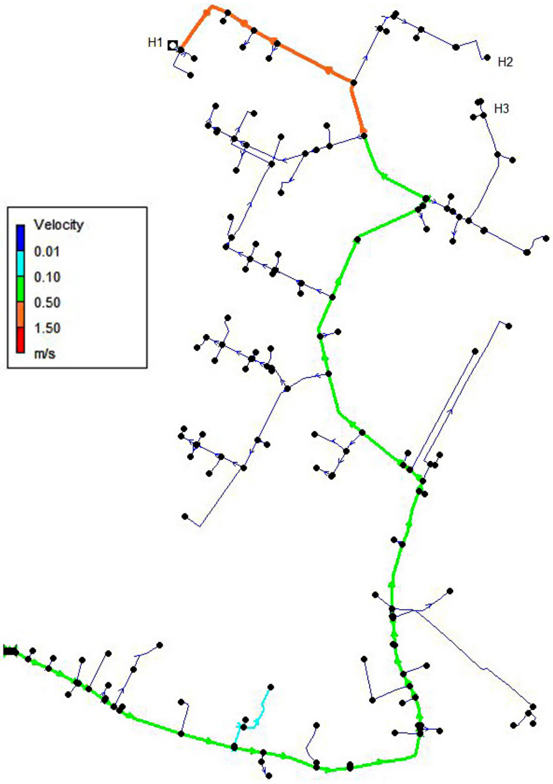

Figure 5. Water velocity during flushing at point H1

of 0.1–0.3 $m \cdot s^{-1}$. The last sections before the washing site are characterized by speeds in the range of 0.5–1.5 $m \cdot s^{-1.}$

Variant H2

The H2 flushing variant is characterized by the fact that the hydrant is located lower than point H1 and higher than H3. The lines supplying the H2 point mostly coincide with the supply of the H1 point. The water outflow value obtained during field measurements is Q = 35.32 $m^3 \cdot h^{-1}$ h. A typical flushing time provided by the water supply service was assumed to be t = 1 h. The distribution of water age in the pipes is shown in Figure 6. The velocity value in the pipes is presented in Figure 7.

Flushing the network refreshed the water in the main distribution lines. Major network departures have not gotten better. Single departures refreshed the age of the water. The simulation results clearly show that the water velocity in the main pipes has improved to a value in the range of 0.1–0.3 $m \cdot s^{-1}$. The last sections before the washing site are characterized by speeds in the range of 0.5–1.5 $m \cdot s^{-1}$.

Variant H3

The H3 variant of flushing the network is characterized by the fact that the hydrant is located lower than point H1 and higher than H2. The lines supplying the H3 point to a lesser extent coincide with the supply of the H1 and H2 points. The water outflow value obtained during field measurements is Q = 38.84 $m^3 \cdot h^{-1}$. A typical flushing time provided by the water supply service was assumed to be t = 1 h. The distribution of water age in the pipes is shown in Figure 8. The velocity value in the pipes is presented in Figure 9.

Flushing the network refreshed the water in the main distribution lines. Major network departures have not gotten better. Due to the location being further, then the H3 point, the northern part of the zone was not covered by the water change. Single departures refreshed the age of the water. The simulation results clearly show that the water velocity in the main pipes has improved to a value in the range of 0.5–1.5 $m \cdot s^{-1}$. The last sections before the washing site are characterized by speeds above 1.5 $m \cdot s^{-1}$.

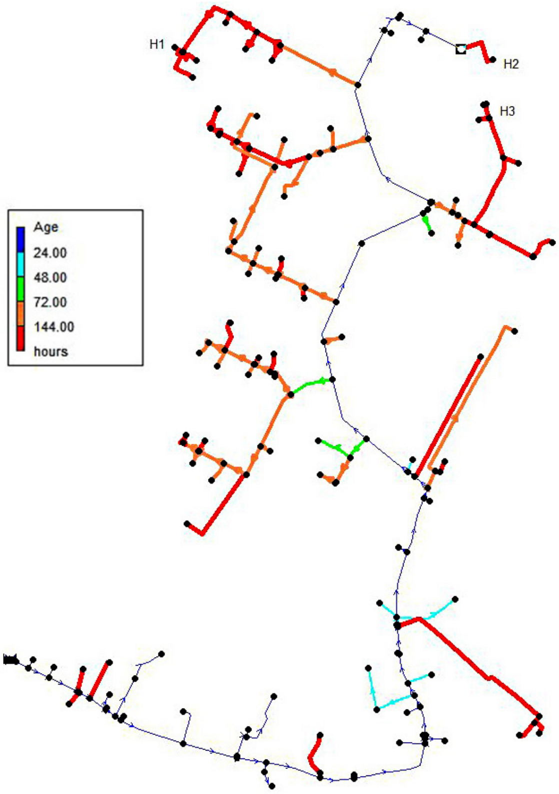

Figure 6. Age of the flushing at point H2

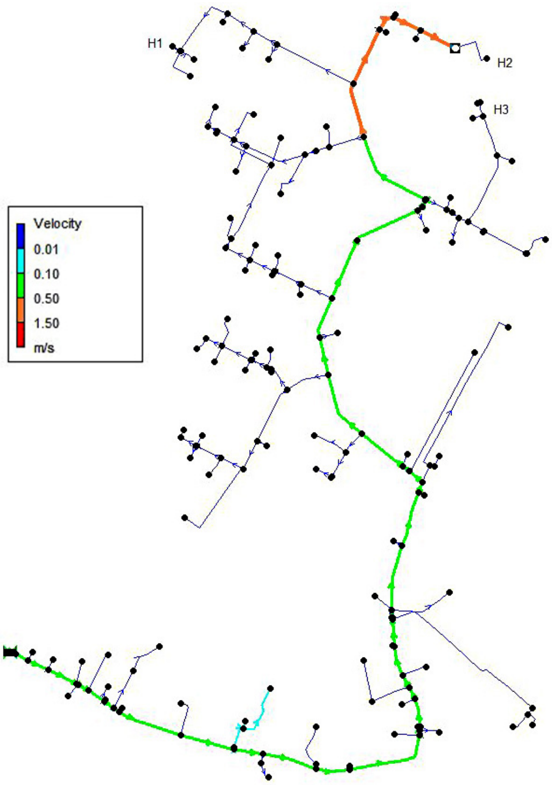

Figure 7. Water velocity during flushing at point H2

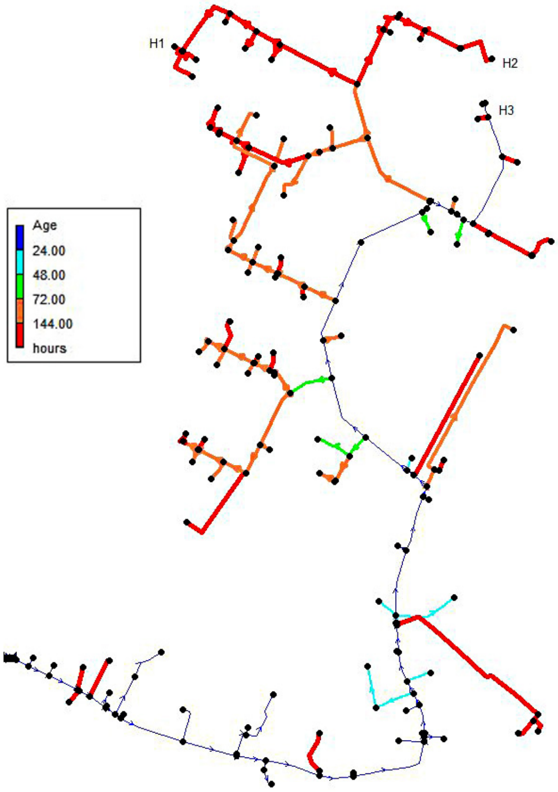

Figure 8. Age of the flushing at point H3

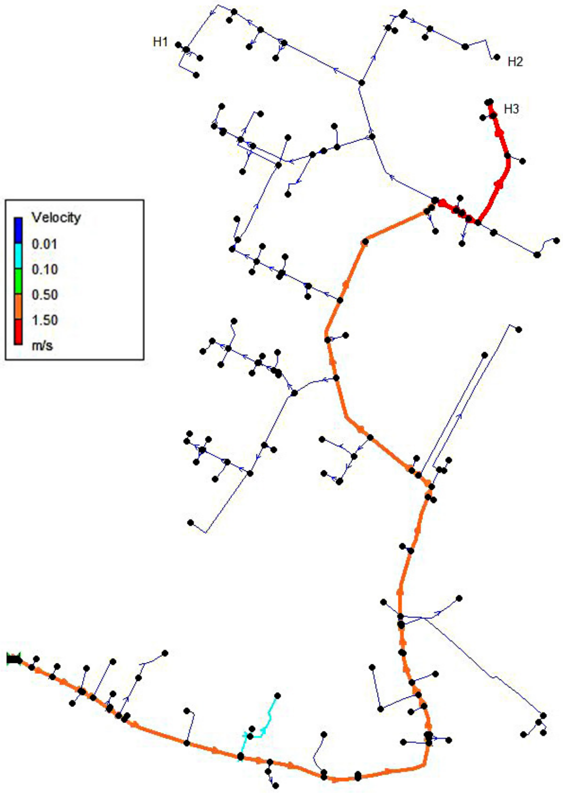

Figure 9. Water velocity during flushing at point H3

DISCUSSION

The median water age in the main distribution pipes DN 160 is below 37.5 hours, and it reaches the maximum of 112 hours in 240 hours of simulation. Median water in 110 mm pipes stays about 124 h. The age of water in 110 pipes ranges from over 59 to 238 h. Water in 90 mm pipes stays from over 107 h to 238 h. The median age of water in connections is 15 h for 20 mm pipes, 125 h for 25 mm pipes, 138 h for 32 mm pipes, 78 h for 40 mm pipes, and 120 h for 50 mm pipes. Water age after 10 days before flushing the network is presented in Figure 10.

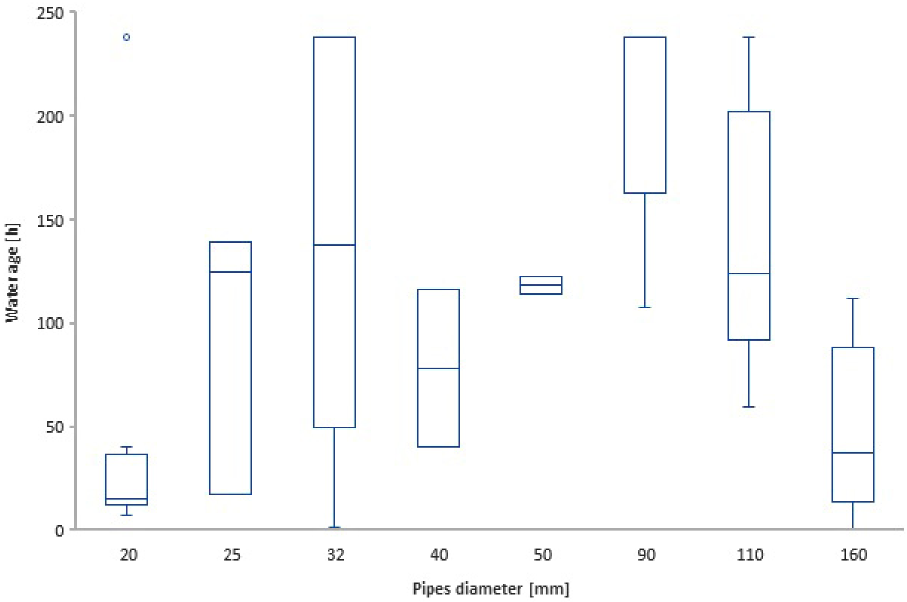

Figure 10. Water age after 10 days before flushing the network

Flushing the network by the H1 variant resulted in refreshing the water in the 160 mm pipes. Except for 2 episodes. The water in the 90 and 110 mm pipes was refreshed. The median age of the water decreased by 4 hours. A significant improvement was seen in the 90 mm tubing. The median age of water in 32 mm and 40 mm pipes decreased by 4–6 hours. The minimum age of water in 20 and 25 mm pipes decreased. The water age of variant H1, broken down by diameters, is presented in Figure 11.

Flushing the network by variant H2 resulted in refreshing the water in the 160 mm pipes. Except for 2 sections. The water in the 110 mm pipes was refreshed. The median water age decreased by 15 h. Variant H2 brought slight changes in water age in 90 mm pipes. the age of water in the 32 mm and 40 mm pipes median decreased by 2–4 h. The minimal age of water in the 20 and 25 mm pipes decreased (the results were identical to the H1 variant). The water age of variant H2, broken down by diameters, is presented in Figure 12. Flushing the network by the H3 variant resulted in refreshing the water in the 160 mm pipes. Except for 3 episodes. The H3 variant brought slight changes to the water age in the 110 mm pipes. The median age of the water decreased only slightly by 1 hour. The water was refreshed in a part of the pipes by 90 mm. The median and maximum age of the water in the 40 mm lines decreased by 20%. The age of the water in the pipes 20 decreased minimally (The results

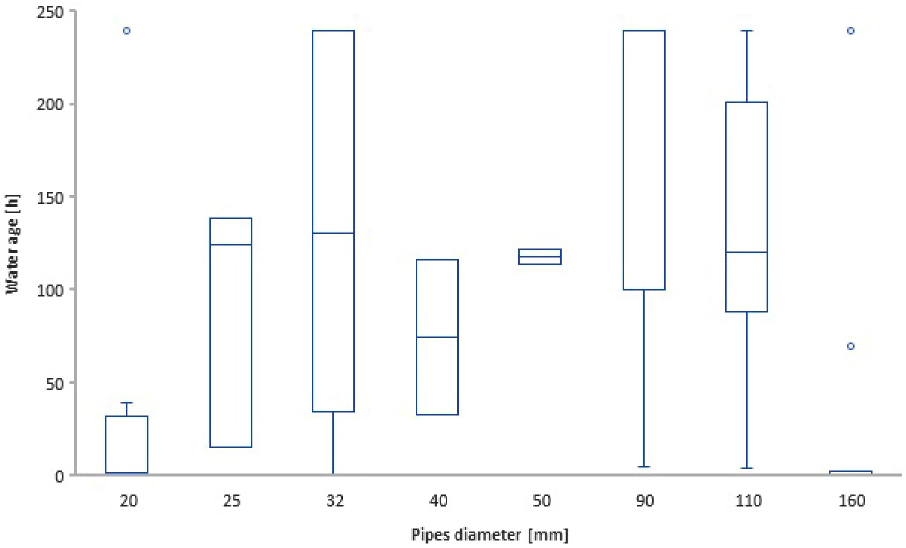

Figure 11. Age of water after flushing the network - Variant I

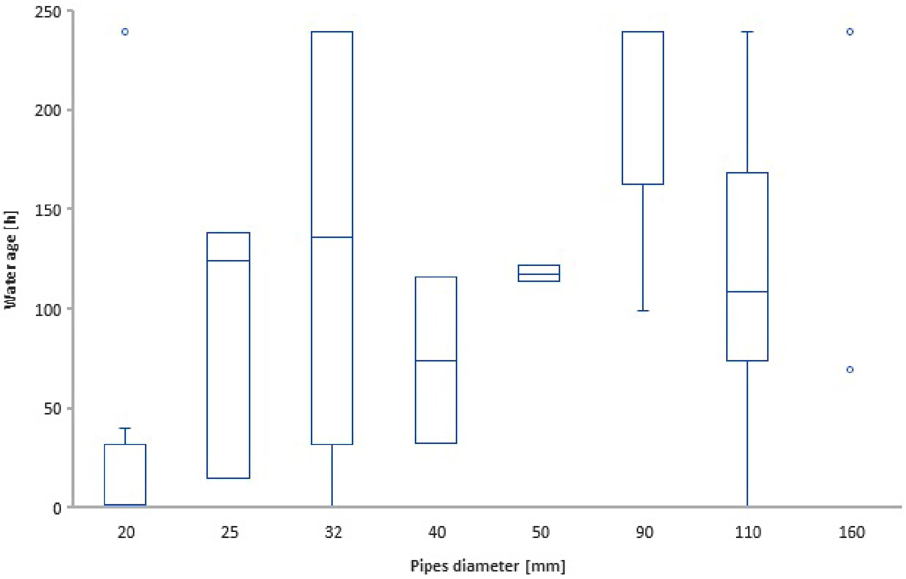

Figure 12. Age of water after flushing the network - Variant II

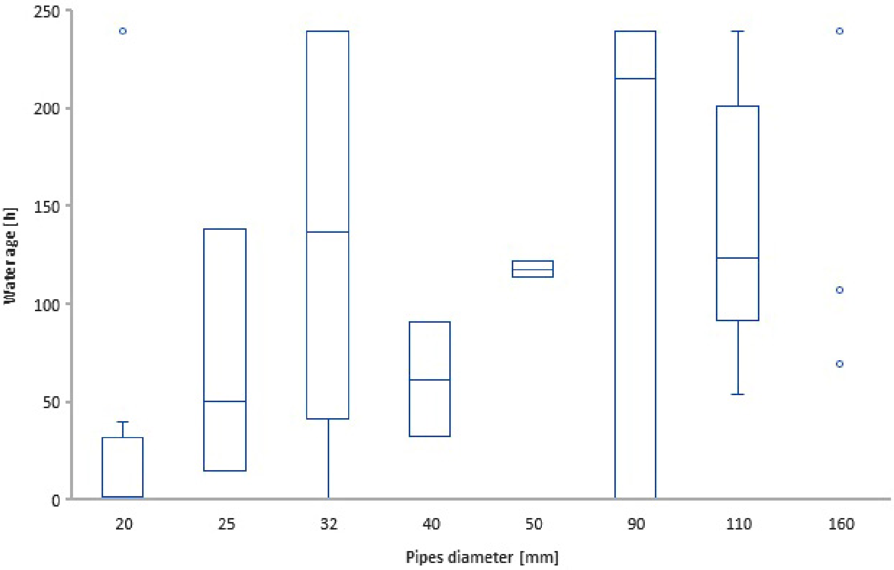

Figure 13. Age of water after flushing the network - Variant III

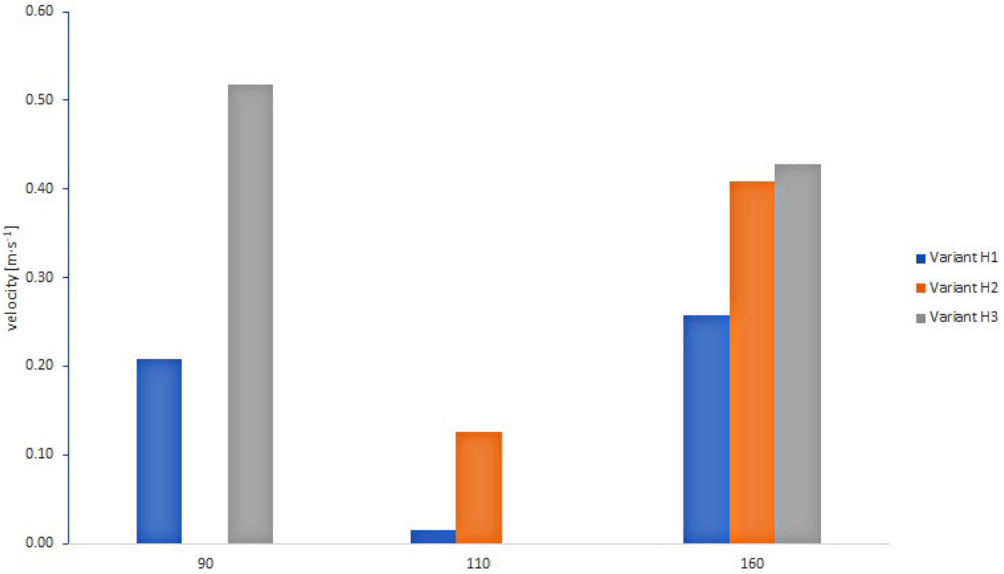

Figure 14. The average velocity of the water in the main lines during flushing on Variants H1–H3

were identical to the variant H1). In the 25 mm tubing, the median age of water decreased from 125 to 50 hours. The water age of variant H3, broken down by diameters, is presented in Figure 13.

When analyzing the median value of the water flow velocity in the 90 mm, 110 mm, and 160 mm pipes, it is clear that each flushing variant had a different effect on individual groups of pipes (Figure 14). The H1 variant increased the speed on the 90 mm and 160 mm wire groups. The H2 variant increased the speed in 110 mm and 160 mm pipes. The H3 variant increased the speed in 90 mm and 160 mm pipes. The highest median velocities were achieved in the H3 washing. This variant was characterized by the highest value of water outflow from the hydrant (10% more than in the H2 variant and 76% more than in H1). Variant H1, the median speed in individual groups did not exceed 0.3 $m \cdot s^{-1}$. Variant H2, only in the group of 160 mm pipes, did the median speed in 160 mm pipes increase above 0.3 $m \cdot s^{-1}$.

CONCLUSIONS

The research carried out consisted in combining computer simulation methods with field measurements. Information collected from employees of the water company was used. The tests were carried out on an atypical pressure zone – a reducing point located at the lowest point of the zone. The research confirmed the increasing age of the water in the pressure zone. All departures in the branched type network are particularly exposed to an increase in the age of the water. The existing points used by employees to rinse the zone allow for the quick refreshment of the age of the water in the zone. Rinses are mainly used to refresh the water. They do not allow the sludge to be picked up. It is a good phenomenon in terms of limiting the possibility of the inflow of pollutants to recipients (biofilm). The pressure values downstream of the PRV make it impossible to achieve higher efficiencies from the hydrants, however, they protect the entire zone against overpressure. The research was the effectiveness of the water exchange in the area for the main lines supplying the flushing hydrant was confirmed. Complete water change in main lines should be done for each main branch but for a shorter amount of time. Flushing the network through points H1, H2, and H3 at the current pressure settings in the PRV does not break the biofilm, but only refreshes the water. The highest water velocities were achieved in the H3 variant. The use of computer models combined with fieldwork gives good results in the form of simulation of the current states and possible solutions to engineering and operation problems.

Acknowledgments

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