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A Graph-Theory-Based PRV Placement Algorithm for Reducing Water Age in Water Distribution Systems

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Abstract: Water age is the time taken for water to travel through a distribution system and reach the consumer. Generally, there is a trade-off between water pressure and water age in a water distribution system—higher pressure results in higher flow velocity, which often means shorter traveling time for the water, while lower pressure leads to slower flow and thus higher water age. Low pressure is a desired objective in a distribution system, as it reduces the physical stress on its components and minimizes water losses in the event of a leak. Low water age is a desired objective as well, as increased age is regarded as having a low water quality. Therefore, the two objectives compete with one another. The problem of trying to minimize both water pressure and age is a common problem in water distribution systems' design and management. This paper introduces an algorithm for pressure reducing valves' (PRVs) placement for reducing water age in water distribution systems. The algorithm is based on graph-theory elements and uses EPANET 2.2 for simulation and analysis. The method is demonstrated on two small scale examples, and the results present relatively significant improvements in respect to water age.

Keywords: valve placement algorithm (VPA); pressure reducing valve (PRV); water age; optimization; water distribution system

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1. Introduction

'Water Age' is a term referring to the time water travels through a distribution system until it reaches the consumer. The age of the water is usually calculated in reference to its age at the source, which in most cases is considered to be zero. The water is pumped from the source into the distribution system, through which it flows either to consumers or storage facilities throughout the system. For a branched network, the water age at a certain node would be calculated simply by multiplying the distance the water has flowed by its velocity. For a looped network, the calculation becomes more complex, as different quantities of water with different ages mix at nodes throughout the network. In such cases, the water age at a certain node would be calculated as a weighted average of the ages and quantities of water flowing into the node.

Lower water age is an objective when designing or operating a water distribution system, as high water age could lead to various problems such as odd taste or odor, increased temperature, microbial growth, lower corrosion control or formation of disinfectant by-products [1].

Naturally, consumers who are adjacent to the water source will receive water with a relatively low age, as the water has to flow only for a short distance, as opposed to consumers who are located far from the source, to whom the water has to travel a long way. Therefore, a network containing multiple water sources which are located at different ends of the system is less likely to have problems related to water age. Storage facilities, such as reservoirs or tanks, significantly affect water age in the network—water entering a storage facility stays there until it is required to be supplied, all the while it does not mix with "younger" water, thus aging dramatically.

As mentioned earlier, the paths through which the water flows can affect its age. In a looped network, those paths are determined by the hydraulics of the system, depending on the nodal demands. If the paths were to be shortened, it would help improve the water age at the nodes located at the ends of those paths. Hydraulically, it is not possible to force water to flow in any desired path in a distribution system. That said, some paths could be changed, which could be achieved by intervening in the hydraulics of the system.

One way to create such an intervention is by installing pressure reducing valves (PRVs), which control the pressure where they are installed. Dictating the pressure at certain points throughout the system changes the formulation of the energy conservation equations and could lead to different flow paths for the water. PRVs are often used to reduce pressure in the system in cases where the pressure is too high. High pressure can have a negative effect on the components of the system, as well as lead to larger water loss when leakage occurs. When pressure is reduced, the water flow is reduced, which leads to an increase in water age. When the pressure is high, the forces acting on the water are larger, resulting in higher velocities and possibly shorter paths, which improves the water age. This creates a contest between the two desired objectives—low pressure and low water age—and improving one will impair the other.

The problem of water age reduction in a water distribution system is an optimization problem, which could be formulated in many ways. The water age could be added to the objective function so a minimization problem is formed; it could be treated as a constraint, so the water age in the system would not be allowed to surpass a certain undesired value; or a third option is to add it to both parts of the formulation and minimize it under certain constraints. In this paper, the water age is considered to be an objective which should be minimized, where the only constraints of the problem are the service pressure values specified for the nodes.

This paper proposes an algorithm for placing PRVs throughout a water distribution system in order to create shorter paths or higher flow velocities, which as a result will improve the water age in the system. It is based on an algorithm proposed by Price and Ostfeld (2022) [2], which deals with the problem of optimally placing PRVs in order to effectively reduce water pressure, modified in a way that would take into consideration the water age when determining the location for the PRV installation. The presented results will also allow to examine the mentioned trade-off between pressure and water age, by comparing the solutions obtained by the algorithm prioritizing water pressure (proposed by Price and Ostfeld [2]) to the one prioritizing water age, which is presented in this paper. It is worth noting that water age is a parameter whose behavior can represent many other water quality parameters that are assumed to be conservative, meaning the presented results could be implicated to water quality in general ([3]).

The paper will comprise a literature review, where different types of works conducted on the subject will be discussed; methodology details of the proposed algorithm, where the different steps of it will be explained; example applications, where the performance of the algorithm will be presented upon two looped networks; and finally, conclusions.

2. Literature Review

Several publications concerning optimal placements for PRVs throughout a water distribution system have been completed, with a number of different objectives. As mentioned, Price and Ostfeld (2022) [2] have presented a graph-theory-based algorithm for placing PRVs with the objective of reducing access pressure, on which the idea of this paper relies. Price et al. (2022) [4] then modified the method in order to further improve the design's ability to minimize water loss in the event of leakage, taking the lengths of the pipes into consideration. Both algorithms are of analytical and iterative nature and use PRVs to reduce pressure to minimize water losses. Pecci et al. (2022) [5] formed a nonconvex mixed integer nonlinear problem when trying to place valves and chlorine boosters throughout a water distribution system, which optimizes both pressure and chlorine concentration as a water quality parameter. Yang et al. (2022) [6] focused on interruptions in water distribution networks, such as maintenance or pipe bursts, and suggested optimal placement of valves that would overcome those interruptions. Hernandez and Ormsbee (2022) [7] looked at the same issue, proposing a graph-theory-based iterative heuristic to solve the problem while also keeping the number of valves used to a minimum. Ulosoy et al. (2022) [8] dealt with a bi-objective problem, trying to optimize the performance of the network in respect to both pressure and resilience. They have suggested a sequential hybrid method to compute the pareto front for those two competing objectives.

Several studies were dedicated to water age. Zhang et al. (2008) [9] looked at water age in distribution systems and suggested ways to realistically represent it. The study mostly focused on flow-through reservoirs, where the effect on water age can be significant. Torres et al. (2016) [10] pointed to a strong correlation between a water distribution system's performance and its topological characteristics, a significant one of them being water age. They have shown how water age increases and worsens for growing values of probabilities of nodal connectivity, which are related to the complexity of the network. Savić and Ferrari (2014) [11] presented the use of District Metering Areas (DMAs) when analyzing water age, as well as other parameters, in water distribution systems. This approach could lead to different decisions regarding PRV placements, or even completely different ways to tackle water-age-related issues. Also looking at DMAs, Zeidan et al. (2021) [12] have suggested a way to optimize water pressure, water age and pump operation by applying a heuristic on a network already divided into DMAs. Coupling pump operation and water pressure with water age obviously leads to a more complex problem, and the possible improvements in respect to water age are thus more limited, as opposed to optimizing water age alone. Kourbasis et al. (2020) [13] have presented a study optimizing both water age and pressure. The method does not rely on the use of PRVs, and the optimization process includes closing pipes throughout the network, calculating the maximal water age and minimal pressure, and finding the layout that leads to the best combination. Patelis et al. (2020) [14] examined the influence that pressure regulations in water distribution systems have over other aspects, such as water quality and water losses, by looking at the water distribution system of the town of Kos. The study highlighted the fact that, when pressure is reduced, water quality suffers the most—pointing to the trade-off between water age and water pressure. Brentan et al. (2021) [15] solved the problem of improving water age by optimal valve operation of already existing valves, as opposed to placing new valves. The method used in that study takes into consideration both water pressure and water age. It is suggested that optimizing the two objectives simultaneously helps in achieving significantly improved results for both pressure and water age.

The algorithm presented in this paper (which will be referred to as "Shmaya and Ostfeld's method") takes only the water age in the system as an objective and is applied to networks without any storage facilities or already existing PRVs. The water age is being improved only by adding new PRVs to the network, without performing clustering analysis or trying to simultaneously reduce access pressure. When trying to reduce water age, this method has not been proven to achieve significant pressure reduction, which will be presented and discussed as a part of the results section.

3. Methodology

This paper deals with the problem of reducing water age in water distribution systems by installing PRVs. As mentioned, this problem is a minimization problem with water age as an objective, where the decision variables are the links on which to place the PRVs and the only constraints are the specified service pressures at the nodes. The suggested algorithm is based on a method proposed by Price and Ostfeld (2022) [2] for PRV positioning, where the objective was reducing access pressure. The method was modified, so the algorithm will place the PRVs based on water age considerations and will consequently help reduce the water age in the network.

As a first step, a simulation is executed using EPANET version 2.2. For each time step t, the algorithm creates a directed graph based on the flow directions obtained by EPANET.

For each edge e, at each time step t, the algorithm creates a sub-graph consisting of the edge's downstream nodes and edges. This is accomplished by applying the Depth First Search (DFS) algorithm on the end node of the edge e—when applied on a directed graph, the DFS algorithm helps identifying all the nodes which are accessible from the end node of edge e, which in water distribution systems are considered to be the downstream nodes. SR_t^e is set to equal the sum of the downstream partial flows. The calculation of SR_t^e relies on each node's predecessors in the directed graph, as explained thoroughly by Price and Ostfeld (2022) [2]. MDA_t^e is set to equal the mean water age of the downstream nodes (Equation (1)):

$$MDA_t^e = \frac{\sum_{i=1}^{n} A_i}{n} \tag{1}$$

where e is the edge, t is the time step, i is a node which lies downstream to edge e, n is the number of the downstream nodes with a base demand greater than zero and A is the water age at node i. Only the nodes with a base demand greater than zero are taken into account, as those are the nodes of concern for water quality considerations. The parameter MNP_t^e is then set to equal the minimal pressure value at the downstream sub-nodes. After calculating all values for SR_t^e and MDA_t^e, the score of each link SC^e is calculated as the sum over t of the divisions between MDA_t^e and SR_t^e (Equation (2)):

$$SC^e = \sum_{t=1}^{T} \frac{MDA_t^e}{SR_t^e} \tag{2}$$

where T is the total number of time steps in the simulation. In a case where SR_t^e equals zero (a node without any downstream sub-nodes), the value of the division is taken as zero, and the algorithm proceeds to the next time step. This calculation is done in order to find the link which "delays" the water the most, that is, the link which contributes most negatively to the water age in the system. The edge with the highest score is chosen for the installation of the PRV. MEP is set to equal the minimal pressure at the end node of the chosen edge, and the setpoint TP for the PRV to be installed is calculated as the difference between MEP and the difference between the minimal value of the MNP vector corresponding to the chosen edge and the specified service pressure, SP. The PRV is then installed using two dummy nodes at each end, in order to prevent a connection between two PRVs. A detailed explanation of the algorithm's steps and parameter calculations can be found in Price and Ostfeld's paper [2]. The different symbols mentioned are explained in the notation at the end of this paper. The steps of the proposed algorithm are described in the flow chart below (Figure 1).

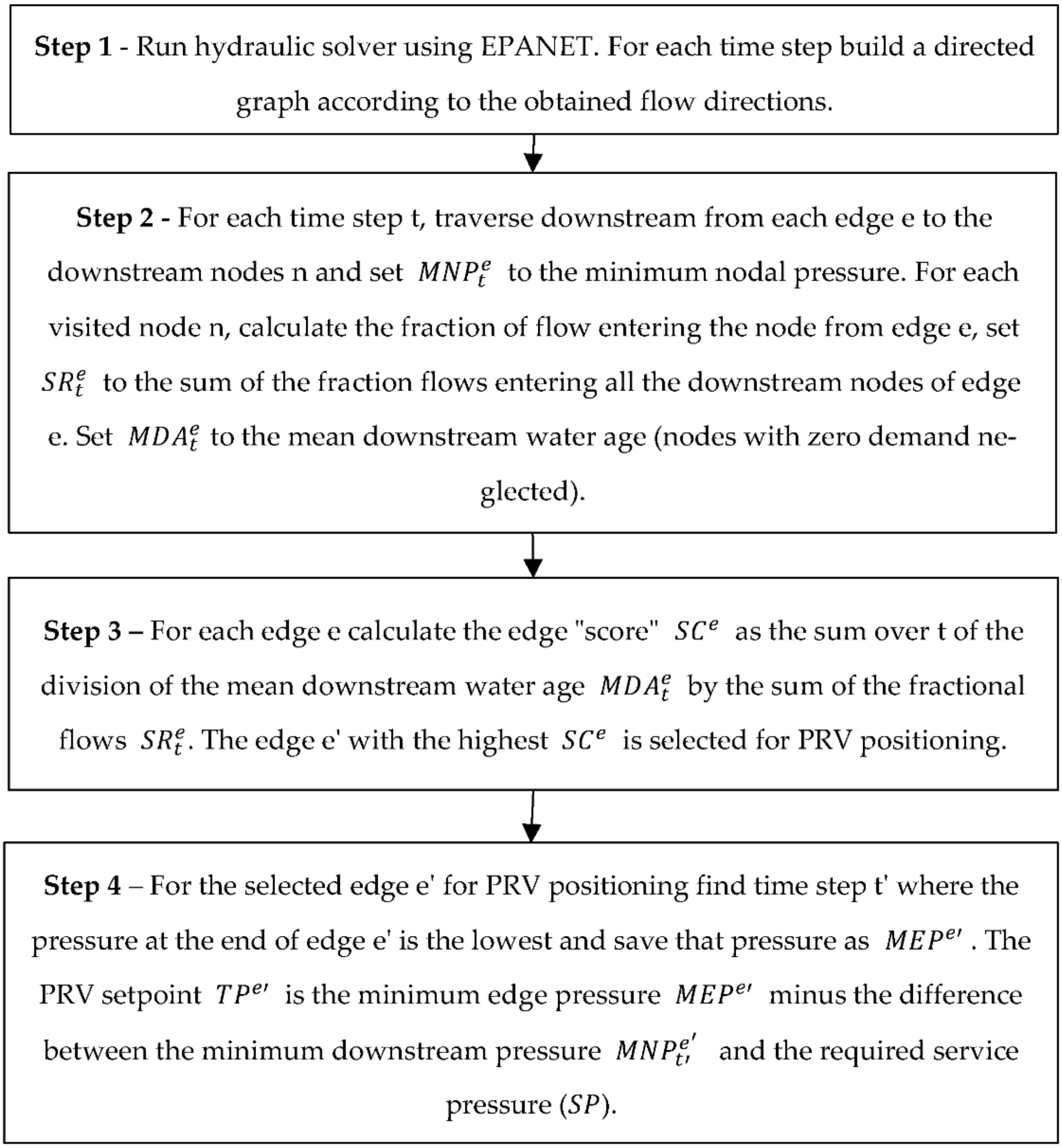
The steps detailed in the flow chart form one iteration, in the end of which the location of the PRV is determined. When step 4 is completed, the algorithm will return to step 1 only if more PRVs are wished to be installed in the network.

When trying to reduce access pressure, Price and Ostfeld [2] used the objective function shown in Equation (3).

$$min \sum_{t=1}^{T} \sum_{n=i}^{N} p_i^t \tag{3}$$

As the discussed algorithm prioritizes water age, the objective function was defined as minimizing the maximal water age out of all demand-bearing nodes in the system, as shown in Equation (4).

$$min\left(max\left\{A_i^t \middle| d_i > 0; i \in N; t \in T\right\}\right) \tag{4}$$



Step 1 - Run hydraulic solver using EPANET. For each time step build a directed graph according to the obtained flow directions.

Step 2 - For each time step t, traverse downstream from each edge e to the downstream nodes n and set MNP_t^e to the minimum nodal pressure. For each visited node n, calculate the fraction of flow entering the node from edge e, set SR_t^e to the sum of the fraction flows entering all the downstream nodes of edge e. Set MDA_t^e to the mean downstream water age (nodes with zero demand neglected).

Step 3 – For each edge e calculate the edge "score" SC^e as the sum over t of the division of the mean downstream water age MDA_t^e by the sum of the fractional flows SR_t^e. The edge e' with the highest SC^e is selected for PRV positioning.

Step 4 – For the selected edge e' for PRV positioning find time step t' where the pressure at the end of edge e' is the lowest and save that pressure as $MEP^{e'}$. The PRV setpoint $TP^{e'}$ is the minimum edge pressure $MEP^{e'}$ minus the difference between the minimum downstream pressure $MNP_{t'}^{e'}$ and the required service pressure (SP).

Figure 1. A flow chart describing the algorithm's methodology.

Below is a short list of the parameters mentioned above, with descriptions about their meaning and calculation.

SR_t^e—the sum of downstream partial flows of edge at time step t. Water exiting edge e keeps on flowing to many other nodes in the system, which receives water from other edges as well. The role of this parameter is to sum the proportionate share of flow entering each of the downstream nodes of edge e out of the entire amount of water entering those nodes.

MDA_t^e—the mean downstream water age of edge e at time step t. This parameter holds the average value of all water ages at the nodes downstream of edge e (with positive base demand).

MNP_t^e—the minimal downstream pressure of edge e at timestep t. As a sub-graph is created for edge e at a specific time step t, this parameter holds the value of the minimal pressure out of all the downstream nodes in the sub-graph.

MEP—the minimal end node pressure of the selected edge. After an edge is selected for PRV installation, this parameter holds the value of the minimal pressure at the end of the selected edge, out of all time steps.

TP—the target pressure, which is the setpoint for the PRV. First, the difference between MNP and the service pressure is calculated, and that value is subtracted from MEP to equal to the target pressure, TP.

SP—the specified service pressure of the network. For the original runs, it was determined to be 25 m, and in scenario 3 of the sensitivity analysis, it was changed to 15 m.

4. Example Applications

The suggested method was tested on two example applications—the first being a relatively simple network, while the other was a bit more complex. The results are presented along with a comparison to the results obtained by applying Price and Ostfeld's method [2] on those same examples.

A single load scenario would not enable the analysis of water age. Therefore, both examples include multiple load scenarios. The demand patterns which were used for both examples are presented in Figure 2.

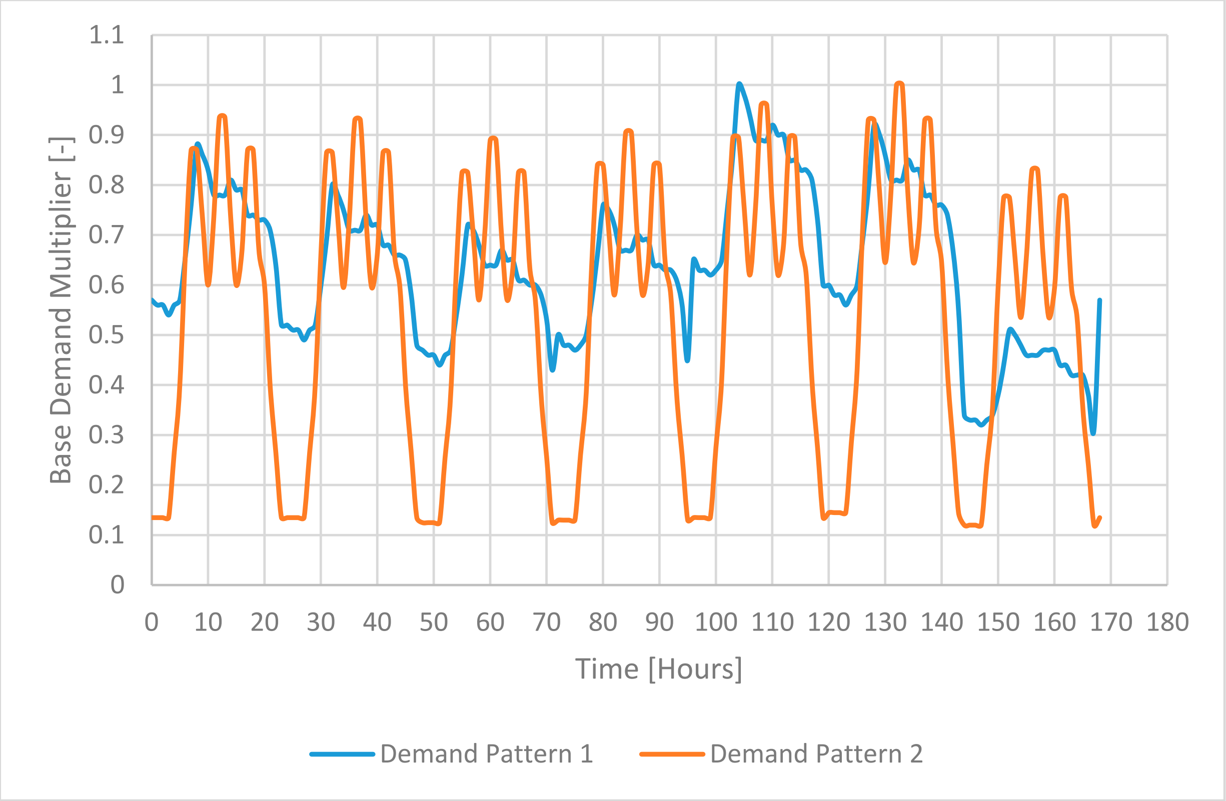


Figure 2. The demand patterns used for both example applications.

4.1. Example 1—Synthetic Network

The presented algorithm was first tested on a relatively simple looped network, described by Price and Ostfeld (2022) [2], where the network layout, properties and nodal information (elevation, base demand and demand pattern) can also be found. As Price and Ostfeld chose to stop after placing five PRVs, Figure 3 presents a comparison between the results for placing five PRVs on the synthetic network, using both Price and Ostfeld's method (Figure 3 left) and Shmaya and Ostfeld's method (Figure 3 right).

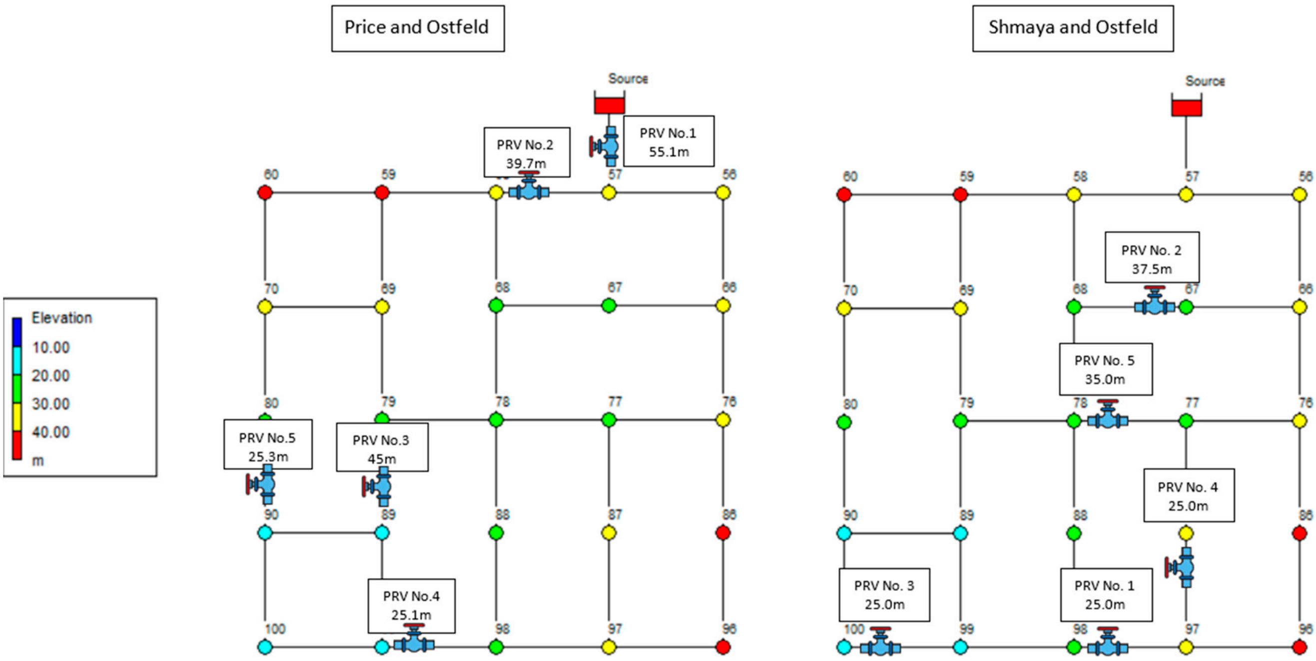


Figure 3. PRV locations and setpoints after applying Price and Ostfeld's method (**left**) and Shmaya and Ostfeld's method (**right**) on the synthetic network.

Both the locations and the setpoints of the PRVs are different. While Price and Ostfeld's algorithm appears to place the valves from an upstream point downward, that is not the case for the presented algorithm. When trying to reduce access pressure, an upstream pipe is more likely to be chosen for installation, as it better affects the downstream pressure. However, when dealing with water age, placing a PRV too far upstream will delay the arrival of water for many nodes in the system, resulting in increased water age.

Figure 4 top left, top right and bottom show the maximal water age, the mean water age and the sum of the pressures in the network, respectively, after the placement of each one of the seven PRVs placed by both algorithms—Price and Ostfeld's method (blue) and Shmaya and Ostfeld's method (orange). Although Price and Ostfeld decided to stop after the placement of five PRVs, the authors felt that the difference between the methods' impacts would be better emphasized by placing seven PRVs (the locations for the sixth and seventh PRVs were links 78–88 and 88–98 according to Price and Ostfeld, and on links 89–99 and 79–78 according to Shmaya and Ostfeld). As explained earlier, only the nodes consuming water (meaning, where demand was greater than zero) were considered for the calculation of the maximal water age and the mean water age in the distribution system.

The results shown in this figure reflect in a very clear way the trade-off between access pressure and water age in a water distribution system—as the sum of access pressure drops, water age increases. Applying Shmaya and Ostfeld's method on the network just barely reduces access pressure, as shown in Figure 4 bottom. Both the maximal and mean water age increase dramatically when applying Price and Ostfeld's method on the network. The maximal water age reaches its highest possible value after placing five PRVs—168 h, which is equal to the length of the entire simulation. This means that after a week of water consumption, some nodes in the network are consuming water which is a week old, even though there is a constant supply from the water source. After applying Shmaya and Ostfeld's method on the network, a clear improvement is obtained; the maximal water age decreases and eventually reaches a value approximately 8 h lower than it originally was without any PRVs installed, and almost five times lower than the result obtained by Price and Ostfeld. The mean water age decreases as well, by almost 1 h, and stands at a relatively low value of 14.5 h, compared to the relatively high 53.75 h that was reached by Price and Ostfeld.

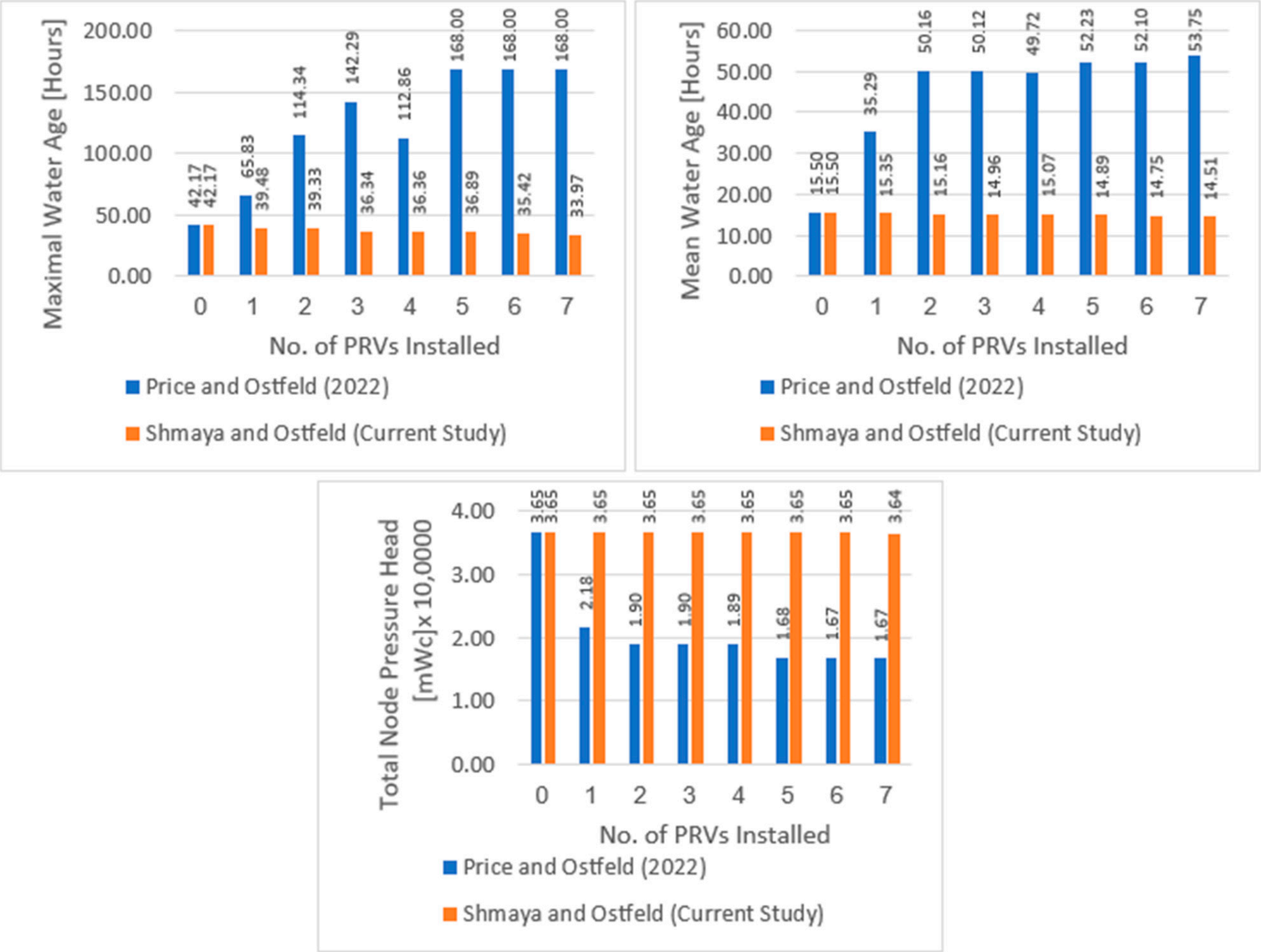


Figure 4. Maximal water age (**top left**), mean water age (**top right**) and total node pressure (**bottom**) after placing each one of the seven PRVs on the synthetic network using both methods.

Figure 5 left and right present the water age curves for nodes 97 and 88, respectively, after installing five PRVs in the network by applying Price and Ostfeld's method (blue) and Shmaya and Ostfeld's method (orange). The nodes are located at a relatively far distance away from the water source, where water age is more critical, and the impact of the method can be observed.

The water age clearly improves after applying Shmaya and Ostfeld's method, as it drops from the highest value of 52 h to less than 25 h at node 97, and from almost 100 h to less than 20 h at node 88.

In Figure 6, a sensitivity analysis that was executed on the model is presented. The analysis consisted of three scenarios, in every one of which a slight modification to the original scenario was made. In scenarios one and two, the modifications were in relation to the base demand at certain nodes, which were selected utterly arbitrarily and are highlighted in Figure 6 top left. In scenario three, the modification was in relation to the specified service pressure in the network, which was changed from 25 m to 15 m at all nodes in the network in order to test the sensitivity of the method's performance in respect to the service pressure. In scenario one, the base demands were changed as follows (all in cubic meters per hour): Node 67—from 4 to 2; Node 70—from 5 to 1; Node 77—from 5 to 1; Node 80—from 0 to 4; Node 89—from 0 to 2; and Node 98—from 0 to 4. In scenario two, the base demands were changed as follows (all in cubic meters per hour): Node 57—from 0 to 1; Node 60—from 1 to 0; Node 79—from 3 to 0; Node 86—from 1 to 4; Node 96—from 0 to 4; and Node 97—from 4 to 0.

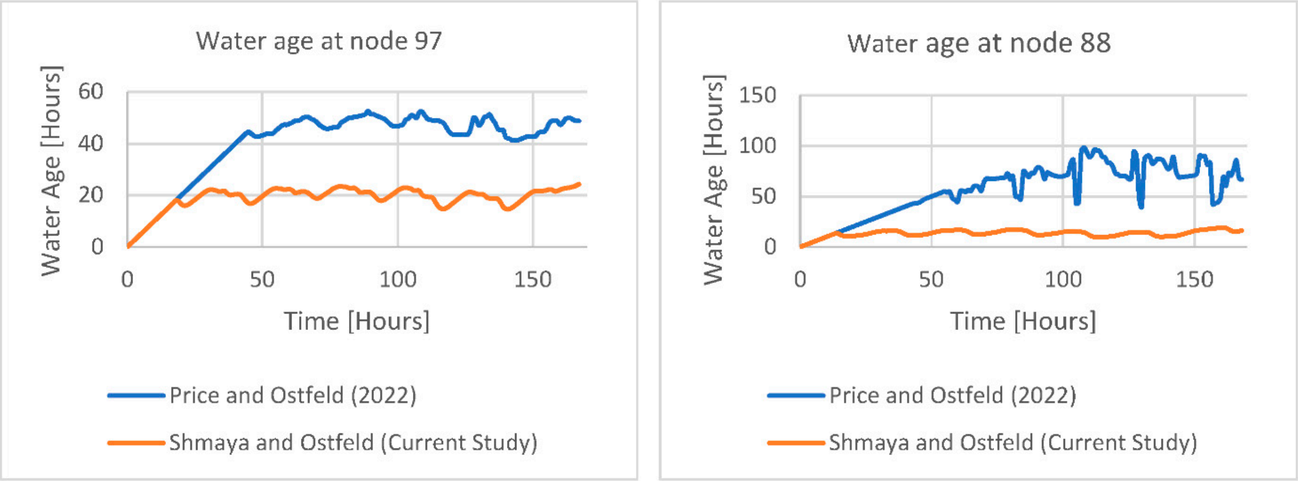


Figure 5. Water age at node 97 (**left**) and node 88 (**right**) throughout the simulation.

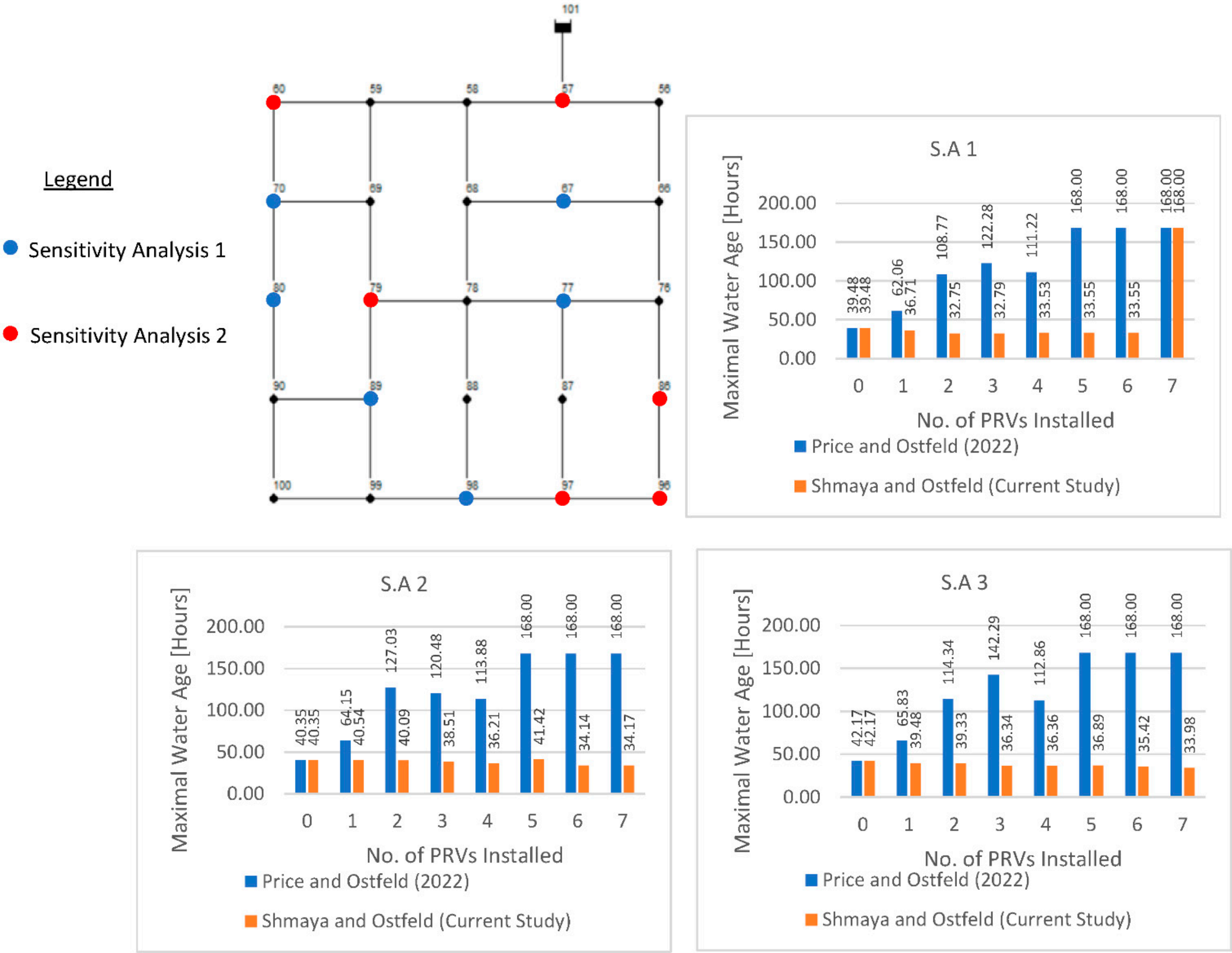


Figure 6. Sensitivity analysis results for the synthetic network. The modifications are shown in (**top left**). The results for scenario one are shown in (**top right**), for scenario two in (**bottom left**) and for scenario three in (**bottom right**).

An improvement in the maximal water age in the network is observed in all scenarios, when it drops from 39.48 h to 32.75 h after installing two PRVs in scenario one, from 40.35 h to 34.14 h after installing six PRVs in scenario two and from 42.17 h to 33.98 h after installing seven PRVs in scenario three. Adding PRVs by using Shmaya and Ostfeld's method does not necessarily help reduce the maximal water age in the system, as can be inferred from the column charts presented. This is demonstrated in Figure 6 top right, where installing a seventh PRV in the network damages the water age. The number of possible flow directions in the network is limited and depends on the demand, as well as on the physical properties of the network, meaning that in some cases it would be difficult to improve the water age. That said, in terms of water age, the results of applying Shmaya and Ostfeld's method are considered an improvement compared to those obtained after applying Price and Ostfeld's method for reducing access pressure.

4.2. Example 2—Fossolo Network

The method was then tested on a slightly more complex network known as the Fossolo network. This network is also a looped one and does not include any branches in it. Tables 1 and 2 include the properties of the links and the nodes in the Fossolo network, respectively. As mentioned, the demand patterns used for this network were the same as those used for the synthetic network, shown in Figure 2, meaning the length of the simulation was 168 h (or one week) as well.

Table 1. Fossolo network—link properties.

Link ID	Diameter (mm)	Length (m)	Start Node	End Node
'1'	244.80	1991.40	17	1
'2'	96.00	5620.20	2	17
'3'	96.00	1796.10	3	2
'4'	96.00	4690.80	4	3
'5'	156.00	4336.35	5	4
'6'	96.00	5044.95	6	5
'7'	96.00	2037.15	7	6
'8'	96.00	3018.90	24	7
'9'	96.00	1987.95	8	24
'10'	96.00	2169.90	28	8
'11'	122.40	2635.80	9	28
'12'	195.60	1682.55	36	9
'13'	308.40	3161.10	1	36
'14'	1227.60	1131.15	31	1
'15'	1104.00	2721.30	10	31
'16'	883.20	2204.40	11	10
'17'	540.00	2440.35	19	11
'18'	441.60	1494.60	12	19
'19'	244.80	794.70	4	12
'20'	244.80	2444.55	18	2
'21'	441.60	1259.40	10	18
'22'	613.20	747.30	32	10
'23'	540.00	1177.50	27	32
'24'	441.60	1489.05	16	27
'25'	368.40	1234.35	25	16
'26'	195.60	2212.35	8	25
'27'	244.80	2959.80	11	3
'28'	613.20	1249.50	26	11
'29'	540.00	1707.00	15	26
'30'	368.40	1212.30	22	15

Table 1. *Cont.*

Link ID	Diameter (mm)	Length (m)	Start Node	End Node
'31′	156.00	5114.55	7	22
'32′	96.00	1160.85	13	5
'33′	96.00	1685.55	14	13
'34′	244.80	560.10	20	14
'35′	308.40	1632.75	15	20
'36′	96.00	2742.30	16	15
'37′	96.00	2040.30	29	16
'38′	96.00	850.50	30	29
'39′	96.00	1861.20	9	30
'40′	96.00	3519.00	18	17
'41′	244.80	3057.45	13	12
'42′	96.00	3720.75	20	19
'43′	195.60	977.85	21	14
'44′	195.60	3151.35	6	21
'45′	244.80	2213.55	22	21
'46′	96.00	1557.00	23	22
'47′	195.60	3164.25	23	24
'48′	308.40	1126.20	25	23
'49′	96.00	2704.35	27	26
'50′	96.00	2235.75	29	28
'51′	195.60	3225.75	33	29
'52′	96.00	2166.60	33	32
'53′	308.40	521.10	34	33
'54′	441.60	898.95	34	31
'55′	195.60	2485.05	35	34
'56′	122.40	1799.55	35	30
'57′	195.60	1247.55	36	35
'58′	1375.20	15.00	1	37

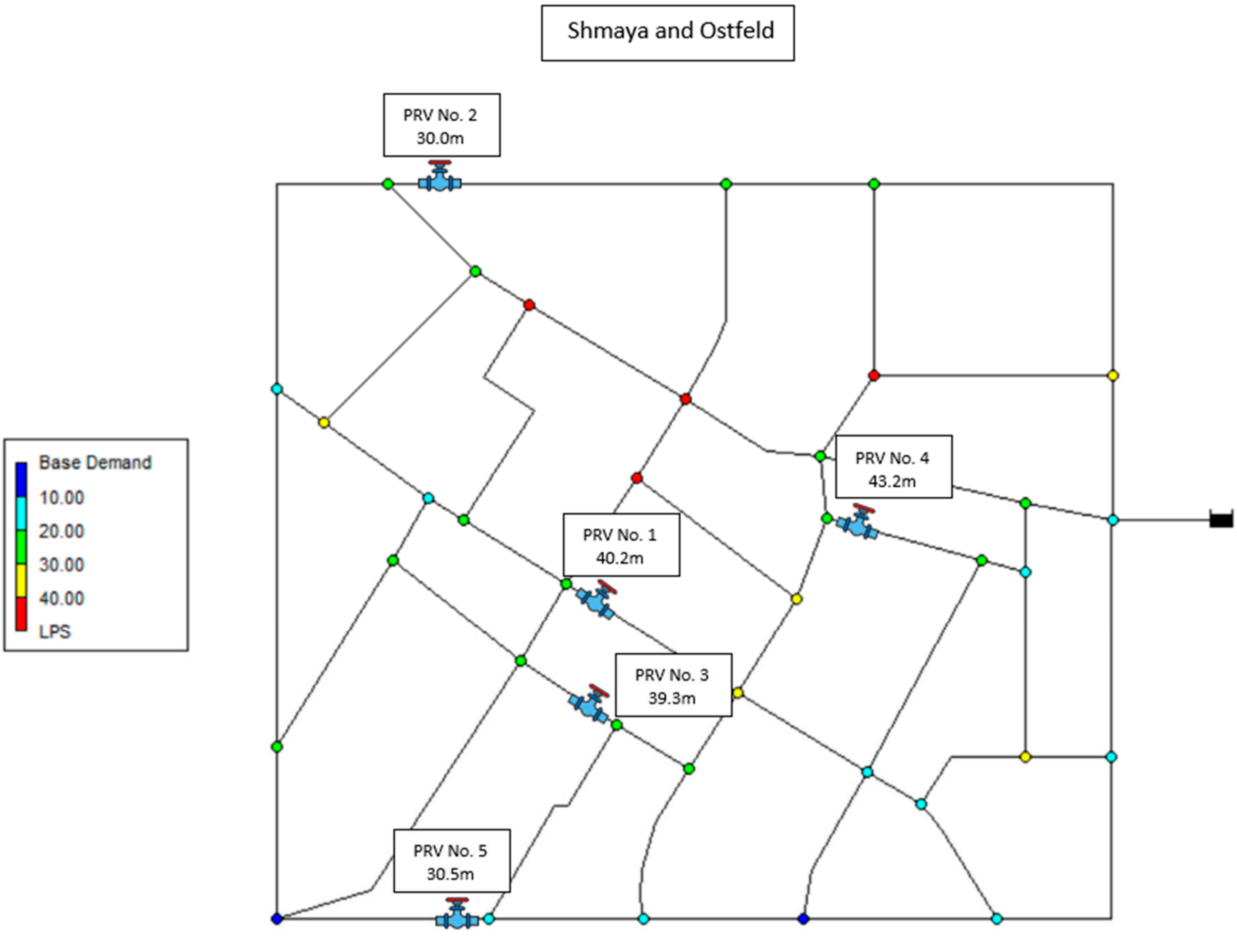
Table 2. Fossolo network—node properties.

Node ID	Elevation (m)	Base Demand (m^3/h)	Demand Pattern
'1′	65.15	47.63	1
'2′	64.40	101.09	2
'3′	63.35	99.14	1
'4′	62.50	78.73	2
'5′	61.24	61.24	2
'6′	65.40	76.79	2
'7′	67.90	25.27	1
'8′	66.50	56.38	2
'9′	66.00	52.49	1
'10′	64.17	107.89	2
'11′	63.70	170.10	1
'12′	62.64	88.45	2
'13′	61.90	112.75	1
'14′	62.60	52.49	2
'15′	63.50	106.92	1
'16′	64.30	117.61	2
'17′	65.50	123.44	1
'18′	64.10	196.34	2
'19′	62.90	182.74	1
'20′	62.83	90.40	2
'21′	62.80	93.31	1
'22′	63.90	94.28	2

Table 2. *Cont.*

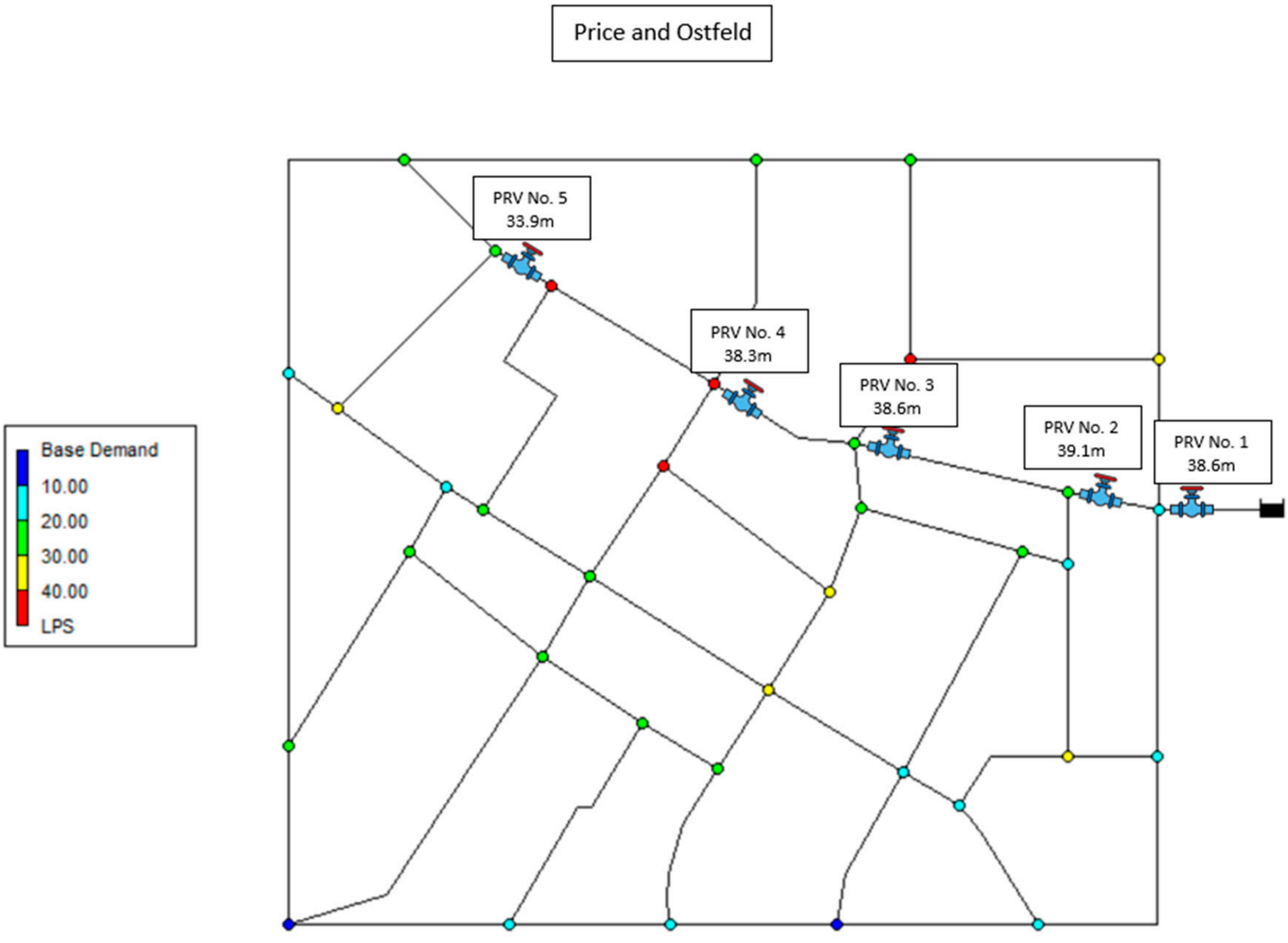
Node ID	Elevation (m)	Base Demand (m^3/h)	Demand Pattern
'23'	64.20	83.59	1
'24'	67.50	65.12	2
'25'	64.40	74.84	1
'26'	63.40	164.27	2
'27'	63.90	138.02	1
'28'	65.65	29.16	2
'29'	64.50	60.26	1
'30'	64.10	52.49	2
'31'	64.40	87.48	1
'32'	64.20	100.12	2
'33'	64.60	74.84	1
'34'	64.70	71.93	2
'35'	65.43	112.75	1
'36'	65.90	45.68	2
'37'	200.00	0.00	1

Figure 7A,B present the results of applying Shmaya and Ostfeld's method and Price and Ostfeld's method on the Fossolo network, respectively.



(**A**)

Figure 7. *Cont.*



(**B**)

Figure 7. (**A**) PRV locations obtained by applying Shmaya and Ostfeld's method on the Fossolo network. (**B**) PRV locations obtained by applying Price and Ostfeld's method on the Fossolo network.

There are clear differences between the chosen locations for the valves, as was seen in the previous example. The locations chosen by Price and Ostfeld's method almost form a continuous line, implying how influential the chosen links are, conveying most of the water. It is worth noting that these links are left untouched when applying Shmaya and Ostfeld's method—the fact that the links convey most of the water suggests that they are not delaying the water, and thus do not negatively affect the water age in the system, which is why they are not chosen for PRV installation.

In Figure 8, the results of the two methods are compared—the maximal water age in Figure 8 top left, the mean water age in Figure 8 top right and the sum of the pressures in Figure 8 bottom.

The maximal water age in the network drops from 19.1 h without any PRVs installed to 17.28 h after installing seven PRVs, an improvement of almost 2 h, as opposed to the result of applying Price and Ostfeld's method, where the maximal age increases to 25.15 h after installing the same number of PRVs. The mean water age also decreases, although very moderately, by approximately 6 min overall, while after applying Price and Ostfeld's method it increases by almost 2.5 h. Applying Price and Ostfeld's method reduces access pressure significantly, as seen in Figure 8 bottom, while Shmaya and Ostfeld's method does not have a noticeable effect on it.

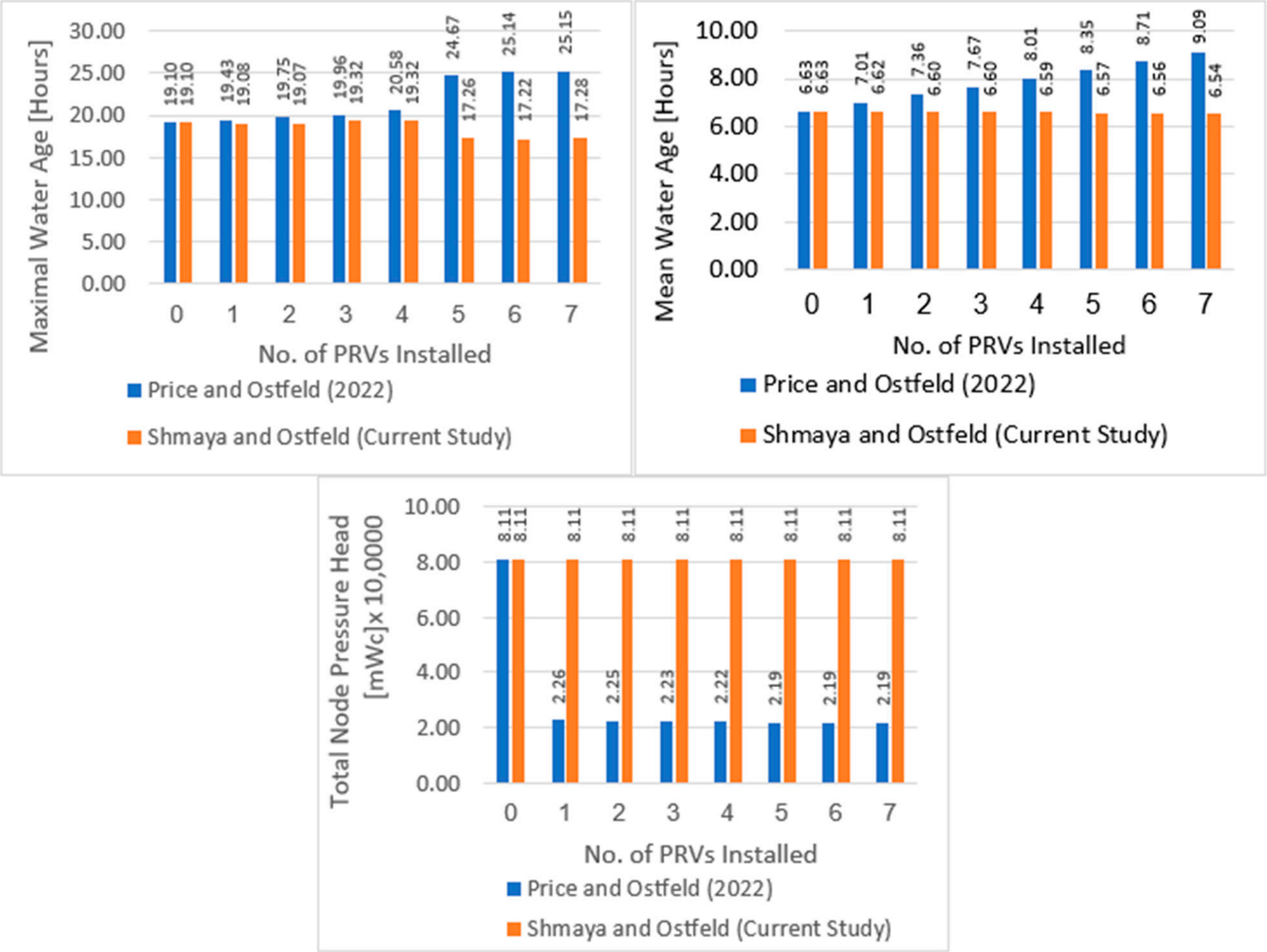


Figure 8. Maximal water age (**top left**), mean water age (**top right**) and total node pressure (**bottom**) after placing each one of the seven PRVs on the Fossolo network using both methods.

A sensitivity analysis of the model was conducted to examine its effectiveness on the Fossolo network, and the results are presented in Figure 9. The sensitivity analysis consisted of three scenarios, where scenarios one and two included eliminating base demands in arbitrarily selected nodes along the network, and scenario three included modifications in relation to the specified service pressure for all nodes of the network. The nodes whose base demands were eliminated in scenarios one and two are highlighted in Figure 9 top left. The specified service pressure was lowered in scenario three from 25 m to 15 m.

In scenario one, the maximal water age in the network seems to decrease in more than one hour—from 19.8 h to 18.37 h—after installing seven PRVs. The maximal water age reaches its lowest value after installing six PRVs, equaling 18.25 h. When applying Price and Ostfeld’s method, the water age increases by almost 6.5 h, and equals 26.24 after installing seven PRVs. In scenario two, the improvement is more subtle, although the maximal water age is still significantly lower than the one obtained after applying Price and Ostfeld’s method, where the difference is a bit higher than 6.5 h. Lowering the specified service pressure in scenario three leads to a similar result as in the original run, where the maximal water age is lowered by almost 2 h.

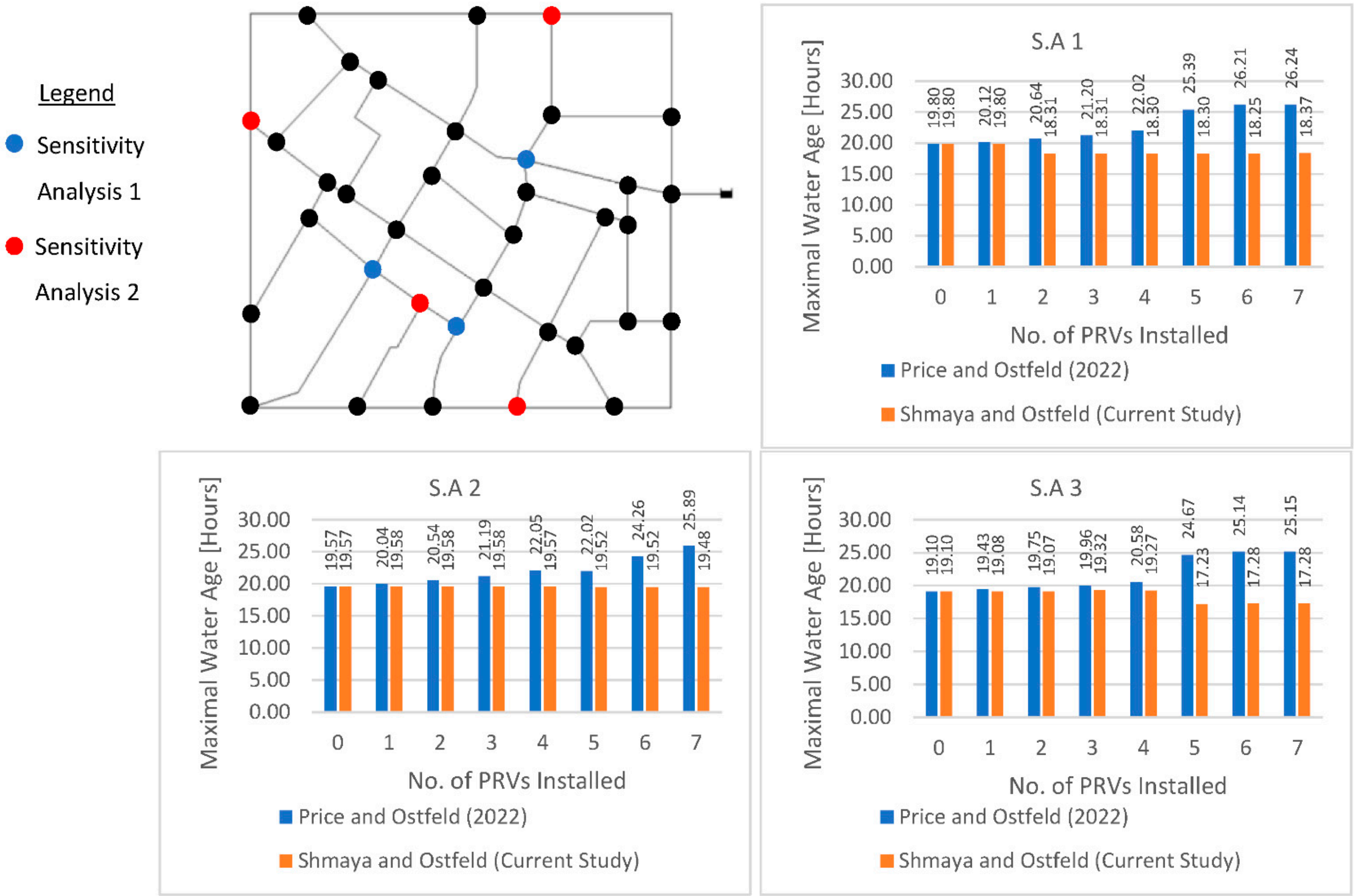


Figure 9. Sensitivity analysis results for the Fossolo network. The modifications are shown in (**top left**). The results for scenario one are shown in (**top right**), for scenario two in (**bottom left**) and for scenario three in (**bottom right**).

Figure 10 presents three curves of the maximal water age in the network at each time step throughout the simulation. At each time step, the node with the maximal water age was identified, and its age was indicated upon the graph. This was conducted three times—first for the network without any PRVs, then for the network containing five PRVs, which were placed according to Price and Ostfeld's method (blue), and lastly for the network containing five PRVs placed according to Shmaya and Ostfeld's method.

The maximal water age values can be seen near the 160 h mark, where the network without any PRVs obtains a maximal water age value of 19 h; the network with five PRVs placed according to Price and Ostfeld's method obtains a maximal water age value of almost 25 h; and the network with five PRVs placed according to Shmaya and Ostfeld's method obtains the lowest maximal water age value of 17 h. It can be observed that, throughout the simulation, at most times, the locations of the PRVs help keep the maximal water age below the original value, essentially allowing the water to flow through shorter paths or in higher velocities. The "price" of lowering access pressure is reflected in this figure by the blue curve, as it shows how water age increases as a result of reducing the access pressure.

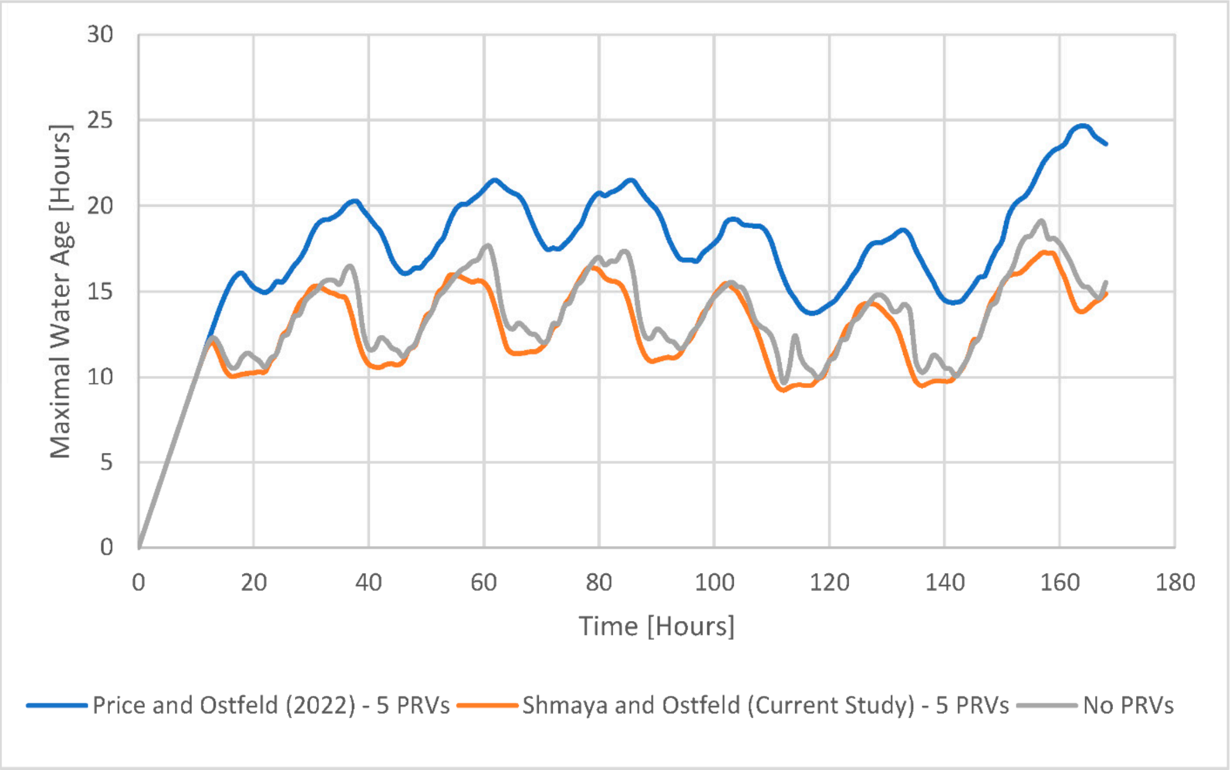


Figure 10. Maximal water age curves for the Fossolo network through the entire simulation, without any PRVs installed and after installing five PRVs using both methods.

5. Conclusions

This paper deals with the problem of high water age in water distribution systems and proposes an algorithm that could help reduce it by finding effective locations where pressure reducing valves should be installed. The algorithm is based on a method suggested by Price and Ostfeld to reduce access pressure in a water distribution system, with few modifications. The method iteratively adds a pre-defined number of PRVs to a given water distribution system after calculating a position for installation, based on the hydraulics of the system and the age of the water at each time step of the simulation.

The presented results show a 19% and 10% reduction in the maximal water age in the two networks that were examined, as well as a slight reduction in the average water age. Both the method presented in this paper and Price and Ostfeld's method were applied to the examined networks, and the better performance with respect to water age was obtained after applying the presented method. This allowed to explore the trade-off between water pressure and water age in water distribution systems as two competing objectives. For the examined cases themselves, the method's performance actually shows water age improvements without a significant increase in water pressure. A competitive nature is revealed when comparing the results to those obtained by Price and Ostfeld's method, where a much more dramatic water pressure reduction is observed. This means that the water pressure benefit obtained by installing just one PRV is drastically damaged when prioritizing water age.

The method was executed using a simulation of EPANET with demand-driven modelling (DDM). An execution using pressure-driven modeling (PDM) is not expected to create different results, as the method requires the nodal pressure to always remain above the specified service pressure (p_{max}), which would lead to constant demand and would not allow it to change its value.

However, the algorithm does pose a number of problems. The calculation used in the algorithm suggests that a pipe which affects small number of downstream sub-nodes will be more likely to be chosen for installation, as well as a pipe whose downstream sub-nodes have high values of water age. This would cause a problem when trying to apply the algorithm on a distribution network that contains branches, as the algorithm will most likely choose one of those branches for installation, which would not have any significant effect on the water age. Therefore, in order to use the algorithm, all branches must be aggregated and removed from the network before applying it. Regardless, more work should be conducted in order to make the algorithm more suitable for branched networks.

As a result of the nature of the calculation for the PRV location, the setpoint for the valve was calculated in the same way as presented by Price and Ostfeld, in order to try and avert the water as much as possible from flowing through the chosen pipe, without closing the pipe or increasing the water pressure. A more accurate calculation for the value for the required setpoint of the valve might help understand the nature of the relationship between water pressure and water age in a distribution system better, and perhaps achieve far better results.

As a result of considering only demand-bearing nodes for the evaluation of water age, areas of old unconsumed water can be created in the system. These areas constitute serious health risks, as that low-quality water could eventually mix with water flowing in the system and reach consumers. The algorithm does not take that into account, and a simulation of the obtained solution is required to ensure that such a condition does not occur.

The algorithm does not take into consideration the presence of storage facilities in the network, which are a main factor affecting water age. The method mainly focuses on the paths which the water takes to reach the consumer, and perhaps the presented work should be coupled with one focusing on optimal management of storage facilities in water distribution networks with water age as an objective, in order to create design methods which would help reduce the water age more significantly.

As was discussed earlier in this paper, the optimization problem of reducing water age can be formulated in several ways. A future study could improve the suggested method by adding a penalty for PRV locations which damage a previous obtained solution, essentially including water age as part of the problem constraints, and perhaps achieve better and more sensitive solutions.

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