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Comparison of Techniques for Maintaining Adequate Disinfectant Residuals in a Full-Scale Water Distribution Network

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Abstract: The present work provides a numerical comparison of different techniques that can be adopted to guarantee sufficient disinfectant residuals in a water distribution network (WDN) when chlorine or chloramine is used as disinfectant. First, while considering chlorine as a disinfectant, the implementation of booster stations in bulk areas and continuous outflows at dead-end nodes was considered. Afterward, the comparison between continuous and intermittent outflows was performed. The water volume being the same, water is provided through blowoffs for 24 h or for limited durations, respectively. Finally, the extent to which the results change was analyzed when chloramine is used instead of chlorine. The methodology is based on the use of the flow routing/water quality modeling software EPANET and its multispecies extension EPANET-MSX on a full-scale WDN. The results show that all the operational measures analyzed are effective to tackle the problem of low disinfectant residuals in WDN. Booster stations are effective to obtain a more uniform distribution of disinfectant throughout the WDN, while nodal blowoffs seem to be a necessary solution for the numerous and scattered dead-end nodes of WDN. The use of chloramine yielded a decrease in the number of blowoffs to open and in blowoff outflows.

Keywords: disinfectant residual; drinking water quality; management; modeling; water distribution network

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1. Introduction

1.1. Water Quality in Water Distribution Networks

Water utilities worldwide are required to comply with national water quality regulations (e.g., in Italy [1] as implementation of the European Council Directive 98/83/EC, in Australia [2], in Canada [3], in China [4], and in the U.S. [5]) to provide safe drinking water at consumers' taps. Maintaining a disinfectant residual within a water distribution network (WDN) is an important task to guarantee users' protection from microbial contamination. When disinfectant is provided at WDN sources, it will be hardly maintained throughout the system. In fact, disinfectant interacts with the natural organic matter (NOM) in the bulk water and/or with the biofilm on the surface of the pipes, resulting in a fast decay [6–8] (Figure 1).

Particularly, terminal sections of WDN, also called dead-end sections, are well known to be problematic zones in terms of water quality degradation [9]. In these sections, low flow conditions and high residence times lead to excessive decay of the disinfectant upstream from users. Consequently, in some terminal nodes, also called dead ends, disinfectant residuals decrease to values lower than the minimum as prescribed by the technical guidelines [1–5,10].

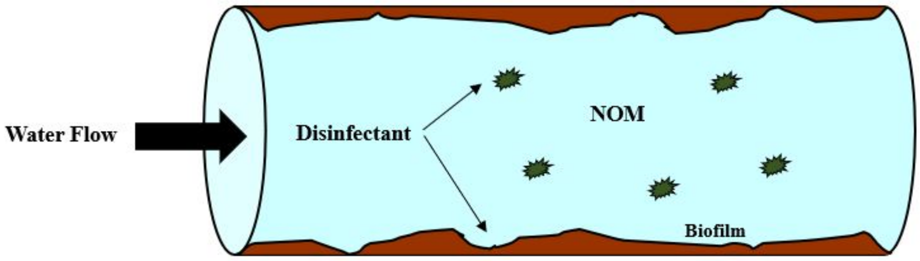

Figure 1. Interactions of the disinfectant inside the pipe.

1.2. Measures against Low Residuals

To tackle the problem of low disinfectant concentrations, there are several operational measures that can be adopted to meet the residual target, each with its own pros and cons. Walski [11] provided an overview of the range of options available to maintain disinfectant residuals. A possible solution may be to increase the disinfectant dose at source(s). However, this may lead to excessive disinfectant concentrations near the feeding points, resulting in taste and odor problems, as well as the formation of disinfectant byproducts (DBPs) (e.g., trihalomethanes (TTHMs) and haloacetic acids (HAAs)) considered harmful for public health [12,13].

Another solution may be to install booster disinfectant stations throughout the network. Booster disinfection reapplies disinfectant at strategic locations within the distribution system to compensate for the losses that occur as it decays over time [14]. However, this solution causes an increase in installation and operational costs for the water utility. In the reviewed scientific literature, many works were dedicated to the use of booster chlorine stations [14–19] and their combination with other measures, i.e., with the real-time optimal valve operation in [20]. Most of the mentioned studies formulated the problem of booster stations as an optimization using different optimization techniques and searching for solutions in terms of optimal injection scheduling, operation, and locations of booster stations. Ohar and Ostfeld [21] extended the problem of optimal design (overall placement and construction costs) and operation (chlorine dose) of booster stations to the reduction in the formation of TTHMs concentrations while delivering water with acceptable residual chlorine.

Although the placement of booster stations provides a more uniform distribution of disinfectant residuals within the system, it does not address the issue in dead-end sections of WDNs, for which other interventions, such as additional outflows or flushing, should be considered. Water flushing involves moving water at high velocity through the distribution system and discharging it through flushing devices, hydrants, or blowoff ports. The increase in flow velocity in proximity to dead-ends reduces the time available for the above-mentioned interactions thus leading to a lower disinfectant decay. Many U.S. utilities regularly schedule flushing programs (e.g., in the spring and the fall [22]), while others flush on an as-needed basis [23]. Flushing is especially common during warmer months since chlorine-based disinfectants are consumed in water more rapidly at higher temperatures [22]. The use of flushing strategies has been proposed by many researchers as a good management practice for improving water quality in WDNs [24–26]. A flushing program can achieve (a) the removal of deposits and contamination from water supply pipes [27,28]; (b) a first hydraulic response to contamination [29,30]; and (c) the maintenance of sufficient disinfectant residuals in WDN [31,32]. Focusing on disinfectant concentrations, a flushing activity may regain or maintain residuals by moving out stagnant water through hydrants or blowoffs and replacing it with fresher water.

Flushing activities can be operated in two ways, i.e., continuously through a manual flusher or at intermittent times by an automated one. Instead of intensive intermittent flushes, low outflows can be used from blowoffs. A blowoff is a flushing device that allows obtaining a continuous flow at a low rate at a dead-end node causing fewer undesired effects in terms of service pressure decrease, compared with the typical intense flushing.

It can be opened at a hydrant site close to the generic critical dead-end node, with the objective to eliminate water with low residuals.

Figure 2 shows a schematic representation of a blowoff. It can be placed in proximity to a dead-end node and connected to the closed pipe. The blowoff is manually opened by turning a valve operating nut in the proper direction with a valve wrench. When the valve is open, the blowoff is turned on and the stagnant water coming from the connected dead-end pipe is discharged by the blowoff into the environment (blowoff outflow). The outflow rate, which will be lower than the one obtained from typical fire hydrants, can be gradually increased by regulating the degree of opening of the valve operating nut.

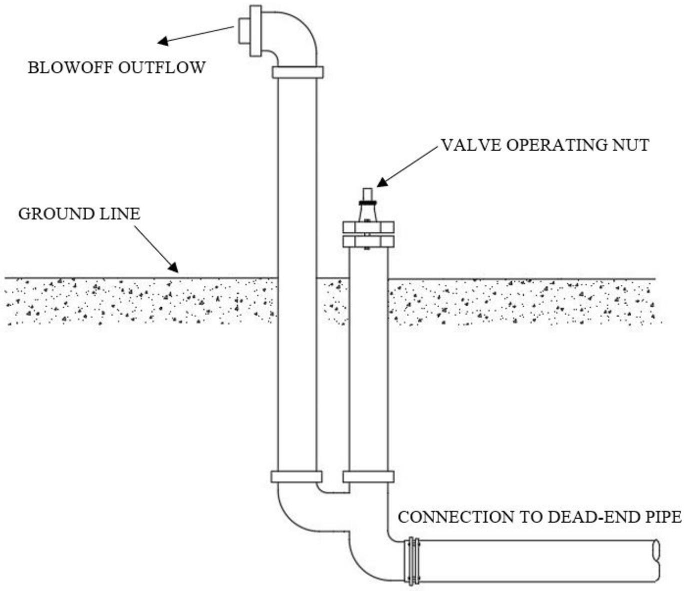

Figure 2. Schematic representation of a blowoff (not to scale).

Nodal outflows through blowoffs are designed to cause the smallest increase in pipe outflows for guaranteeing sufficient disinfectant residuals. This measure involves minimal capital and labor investment but can increase the amount of revenue water [11]. The use of continuous blowoffs to correct violations in dead-end nodes of WDN was investigated by [33]. They proved that the implementation of nodal blowoffs can fix the problem of low residuals at dead-end nodes in WDN with a percentage of leakage that only slightly increases compared with the no-blowoffs scenario. With the same water volume flushed, the effects of intermittent outflows should be investigated. In the case of intermittent outflows, water is provided for only limited durations with larger outflows. However, due to the larger outflow values, this solution may cause service pressure deficits in the WDN and undesired sediment mobilization if not done properly. Additionally, higher installation costs due to the automatization should be considered.

1.3. Chlorine-Based Disinfectants

Regarding the disinfectant typically used in treatment plants, chlorine products have been used since the 20th century to disinfect drinking water [34]. Unfortunately, this widely used free-chlorine treatment has disadvantages, including the high reactivity of chlorine with NOM and the production of DBPs, some of which are likely human carcinogens [34,35]. Hence, an option lies in permanently switching disinfectants to maintain a residual, typically from free chlorine to chloramine due to its slower decay. A study conducted by [36] showed that for initial concentrations of chlorine (as Cl_2) and of chloramine (as NH_2Cl), both set to 2.4 mg/L, chlorine falls below detectable limits (0.05 mg/L) much earlier (7 days) compared with chloramine (11 days).

The disinfection efficiency is dependent on several factors e.g., the disinfectant concentration, contact time, pH, and temperature [37]. Disinfectant concentration and contact time are integral to disinfection kinetics and the practical application of the CT value [38]. The CT value, equal to the disinfectant concentration (in mg/L or ppm) multiplied by the contact time (min), is commonly used to gauge the effectiveness of the disinfectant residual against different pathogens [39]. The lower the CT value, the more effective the disinfection agent. Of the two disinfectants, chloramines are the weaker, requiring significantly higher CTs to achieve levels of inactivation of pathogens comparable with free chlorine [40]. A review of CT values and corresponding inactivation rates for specific pathogens in the presence of free chlorine and chloramines is provided in [40]. Overall, it was demonstrated that only free chlorine was able to provide 99.99 percent (4-log) inactivation of viruses. To provide 99 percent (2-log) inactivation of most species, free chlorine and chloramine required a CT of <150 and 10,000 min·mg/L, respectively [40]. References on the effectiveness of chlorine-based disinfectants at pathogen inactivation can be found in [38–40].

Starting from the early 2000s, several water systems throughout North America have converted to chloramine for improving stability, taste, odor, and DBPs control [41,42]. Although chloramine is less reactive than free chlorine in producing regulated DBPs in combination with NOM, it still forms some DBPs, such as N-nitrosodimethylamine (NDMA) [43]. Chloramines, such as monochloramine, dichloramine, and trichloramine, are generated by the reaction of chlorine with ammonia [10]. The relative amounts of each of these species are dependent on pH, temperature, contact time, and the ratio of Cl_2 to NH_3-N [43]. In WDNs, monochloramine is the dominant and favorite species adopted because of its biocidal properties, relative stability, and relatively low taste and odor properties [43].

While prediction of chlorine performance can be made with widely available state-of-the-art chlorine decay modeling, the same cannot be said for chloramine performance. Starting from the first chloramine decay models proposed by [44,45], few authors [46–48] provided the evaluation of a multi-species chloramine model through the use of field-scale measurements and distribution system network modeling. None of the authors have explored the effect of operational techniques (i.e., booster stations or flushing) on the increase in chloramine residuals in WDNs. Of course, chloramines have their own issues such as the production of ammonia, which has the potential to promote nitrification reactions within the system. Nitrification can have adverse impacts, such as the reduction in chloramine residuals, alkalinity, pH, the promotion of bacterial regrowth [49], and the corrosion of infrastructural elements [50]. Intensive monitoring of the major water quality parameters (chlorine/chloramine residuals, DBP concentrations, etc.) within WDNs at a certain frequency and at specified locations is important to ensure that the water supply is in compliance with the required guidelines and standards.

1.4. Disinfection Practices and Regulations

The current approaches to disinfection are influenced by the wide diversity of water resources and supply infrastructures, as well as disinfection philosophy. For example, European countries vary considerably in their disinfection practices and use of disinfection. Unlike other European countries (e.g., Spain, Italy, Greece, and France), in the Netherlands and Germany, a disinfectant residual is not used. In these countries, water utilities rely instead on catchment protection, advanced treatment (via ozone or UV light), good WDN design, and operational and maintenance practices (i.e., monitoring, flushing, break repair, etc.), which prevent contaminants from entering the WDN [51].

The World Health Organization (WHO) publishes and regularly updates the *Guidelines for drinking-water quality*, which has become an authoritative basis for the setting of national regulations and standards for water safety in support of public health [10]. With regard to disinfectant residuals, the maximum values for free chlorine and monochloramine are set to 5 mg/L and 3 mg/L, respectively [10]. These levels are greatly in excess of the residuals of chlorine and monochloramine found in drinking water supplies, which typically range from 1–2 mg/L [10,52]. At the point of delivery, a minimum residual concentration of 0.2 mg/L of free chlorine should be maintained throughout the distribution system, while it is normal practice to supply water with a chloramine residual of 0.1–0.15 mg/L to act as a preservative during distribution [10]. In the absence of field measurements or as a complement, simulation models such as EPANET [53] support water utility operators in understanding the problem and taking operational decisions for low residuals based on local conditions.

1.5. Aim of the Study

As mentioned above, there have been various works dedicated to modeling of the disinfectants chlorine/chloramine and use of booster stations and flushing hydrants/blowoffs in WDNs; however, to the best of our knowledge, little attention has been dedicated to the analysis and comparison of the effects of the various solutions, implemented alone or in a combined way, on a large-scale WDN.

For example, Propato and Uber [5] developed a simulation framework to assess the vulnerability of a WDN to microbiological contamination. Their study showed that the risk of consumer exposure is affected by the residual maintenance strategy employed. A chloramine residual, instead of free chlorine, may weaken the final barrier against pathogen intrusions. On the other hand, the addition of a chlorine booster station may improve consumer protection without requiring excessive disinfectant doses.

In the light of the above considerations, the present work addresses the existing research gap in analyzing and comparing different operational measures aimed at ensuring safeguard requirements for water quality in a real large-scale WDN.

2. Materials and Methods

2.1. Methodology Adopted

In this work, four solutions are compared to increase disinfectant residuals in a full-scale WDN. As shown in the following Table 1, five scenarios of the network model are analyzed.

Table 1. Number of violating nodes for each scenario analyzed.

Scenario	Disinfectant	N. of Booster Station	Flushing Blowoffs	N. of Violating Nodes
0	Chlorine	0	0	41
1	Chlorine	3	18-continuous	0
2	Chlorine	3	18-intermittent	0
3	Chloramine	0	0	18
4	Chloramine	0	12-continuous	0

Note: violating nodes = nodes with a disinfectant residual below the minimum requirement (e.g., in this study C_{min} = 0.2 mg/L).

Scenario 0 represents the network's behavior to the injection of chlorine as a disinfectant at the sources. To correct the disinfectant violations encountered in scenario 0, scenario 1 considers the installation of booster stations and continuously dripping blowoffs. Scenario 2 differs from scenario 1 due to the adoption of intermittent outflows in lieu of continuous outflow. In scenario 3, chloramine is adopted as a disinfectant and the network's response is modeled. Finally, scenario 4 considers the placement of continuous dripping blowoffs as a measure to meet the residual target in the chloraminated network.

These potential solutions can be developed by making use of models that simulate WDN behavior in terms of both flow routing and water quality (disinfectant decay). The software EPANET ver. 2.2 [53] and its multi-species extension EPANET-MSX [54] is used to simulate the chlorine and chloramine decay, respectively. It was linked to the Matlab R2021a [55] environment to extract and analyze the water quality results at all WDN nodes. The procedure for each scenario analyzed is described in the following subsections.

2.1.1. Scenario 0—Chlorine

In this scenario, the network's response to the injection of chlorine at the WDN sources is modeled. In the model adopted, the chlorine decay simulation is first order (Table A1 in the Appendix A). For all the links, the bulk decay constant (k_b) is assumed to be 0.5 d^{-1} from the scientific literature [56–59] and the wall decay constant (k_w) is set to 0 because it is supposed that network pipes are made of plastic material (smooth surface of pipes' internal wall).

First, a constant value of chlorine concentration C_{cl}, as an example, a concentration C_{cl} = 2.0 mg/L, is injected into the WDN sources. Then, the flow routing/water quality simulation of the WDN is run to model the hydraulic and water quality behavior of the WDN and to create a list of nodes with a deficit of disinfectant residuals. The resulting nodes are sorted in descending order of maximum deficit. Modeling chlorine, this residual can be evaluated taking the minimum value $C_{cl,min}$ = 0.2 mg/L as a benchmark. It must be highlighted that the zero-demand nodes are not considered in the list of violating nodes because they are meaningless for this kind of analysis. In fact, disinfectant deficits are dangerous only in the case of water consumption at the generic node.

2.1.2. Scenario 1—Chlorine, Booster Stations, and Continuous Nodal Blowoffs

The water quality outputs (chlorine residuals) obtained in scenario 0 are used for the implementation of booster stations and nodal blowoffs as operational measures. Simulations are used to evaluate the placement first of booster stations and then of dripping blowoffs.

Booster stations reapply disinfectant at intermediate locations of the WDN to obtain a more uniform distribution of disinfectant while keeping residuals within specific limits. It is important that a booster station delivers disinfected water to as many nodes as possible. Theoretically, a booster station can be located at any node of a WDN. Therefore, the potential number of booster stations is equal to the number of nodes in WDN. However, in large networks, the exploration of each node of the WDN as a potential location for a booster station would make the computation difficult and very demanding from the computational viewpoint. In this study, suitable locations for the installation of a booster station are chosen by simulation attempts, relying on network hydraulics and selecting bulk areas experiencing low or intermittent residual coverage. Booster stations are modeled as set point injections, delivering a constant mass dosage rate of chlorine C_{cl} = 2.0 mg/L. A criterion used for selecting a booster location is the reachability (number of nodes that can receive disinfected water from the booster node). The reachability of a node is determined by simulating a constant chlorine concentration C_{cl} = 2 mg/L for the generic node i and by determining the resulting number of nodes with chlorine residuals greater or equal to the minimum value $C_{cl,min}$. In this study, the minimum value of reachability is set to 5, meaning that the placement of a booster station is required to increase the chlorine residuals of 5 nodes above the target $C_{cl,min}$ in the water quality monitoring window considered.

Beyond the bulk areas affected by low disinfectant residuals, there can still be critical nodes scattered in the WDN and located at various dead ends. This happens due to the occurrence of low flow velocities and high residence times that cause an excessive disinfectant decay upstream from users. Unless as many boosters are installed as the number of critical nodes, the problem cannot be solved by sticking to the booster stations solution alone. Therefore, for these nodes the implementation of continuous outflows through nodal additional outflows may be effective. This consists of a slight increase in the nodal outflow at the generic critical node all day long, through the opening of a dripping blowoff at the hydrant site. In fact, this results in an almost constant outflow at the critical dead-end node to be added to the outflow to users and to leakage outflow.

The continuous low flow scenario was proposed by the authors in the previous work [33] by making use of emitters in the software EPANET. In EPANET, the flow through an open hydrant, simulated as an emitter, with pressure-driven demand q is given by Equation (1):

$$q = e\ P^n \tag{1}$$

where q is the flow through the hydrant ($m^3\ s^{-1}$), e is the emitter coefficient ($m^{3-n}\ s^{-1}$), P is the pressure head upstream of the hydrant (m), and n is the emitter exponent (typically set at 0.5). Using the emitters, the flushing outflow rate in the considered node depends on the value of the pressure head in each time step.

With similar effects, the additional outflow can be obtained by introducing a new demand category at the generic node of the WDN. For the generic node i in the list of critical nodes, a new demand category with multiplicative daily temporal pattern constantly equal to 1 is added in the software to represent the nodal outflow through blowoff. Then, the lowest blowoff demand that fixes the nodal disinfectant residual is searched for by trials, corresponding to a certain daily blowoff volume V_i (L). Since this blowoff demand is applied for 24 h in a day, it is indicated as $q_{i,24.}$ (L s^{-1}). Its relationship with V_i is expressed by Equation (2):

$$V_i = 24{\cdot}3600\, q_{i,24} \tag{2}$$

2.1.3. Scenario 2—Chlorine, Booster Stations, and Intermittent Nodal Blowoffs

Keeping the operational measures identified in the previous scenario, a comparison between continuous and intermittent blowoffs is carried out. The water volume being the same, water is provided through blowoffs for all day long or for only limited durations, respectively.

At the generic node i, intermittent outflow sub scenarios can be created for the same daily value of V_i in Equation (2). As an example, let us assume a sub scenario with k h of a blowoff operation and $(24 - k)$ h of no blowoff operation in the day. The water discharge of the blowoff can be calculated through the following formula, Equation (3):

$$q_{i,k} = \frac{24}{k}\, q_{i,24} \tag{3}$$

As a particular case of an intermittent flow sub scenario, Equation (3) returns the continuous flow scenario for k = 24, i.e., for the blowoff duration of 24 h in the day. The demand coefficient pattern for a sub scenario with k hours of blowoff operation is made up of k values equal to 1 and $(24 - k)$ values equal to 0. In this context, we assume that outflows are regularly spaced in time in the day. Therefore, if j is the hour in the day when the first outflow takes place, the following hours of blowoff will be $j + (24/k)$, $j + 2(24/k)$, $j + 3(24/k)$, and so forth, up to the end of the day. Let us assume that we want to split a water volume V_i = 86,400 L into k = 3 h of blowoff. Starting from Equations (2) and (3), we obtain $q_{i,24}$ = 1 L/s and $q_{i,3}$ = 8 L/s, respectively. If we assume that the first outflow takes place at hour j = 1, the following ones will be at hours 9 and 17. Therefore, for the generic intermittent flow sub scenario with k hours of outflow, the hour j of the first blowoff becomes a decisional variable of the problem, which can take on all integer values between 1 h and $(24/k)$ h. As an example, in the case of the sub scenario with k = 3 h of outflow, it ranges from 1 h to 8 h because 8 h is the last hour that enables having 3 one-hour-long blowoffs regularly spaced in the day, i.e., at times 8 h, 16 h, and 24 h. In the calculations, j is optimized in such a way as to maximize the effectiveness of the intermittent outflow for fixing the disinfectant residual deficit at the node. This is accomplished by minimizing the total duration $v_{k,j}$ (min) of residual deficit violations at the node, given by Equation (4):

$$f_j = \min\left(v_{k,j}\right) \tag{4}$$

The methodology is applied by considering 8 different sub scenarios of outflows' operation time: a sub scenario of continuous flow and 7 sub scenarios of intermittent flows, with k values equal to 1, 2, 3, 4, 6, 8, and 12, respectively.

2.1.4. Scenario 3—Chloramine

This scenario investigates the effects of switching the disinfectant from chlorine to chloramine. Hence, the network's response to the chloramine injection is modeled. The chloramine reaction model used in this work was developed previously by [44,45] and takes account of the chloramine decay due to auto decomposition alone and due to the chloramine decay because of auto decomposition in the presence of NOM. The reaction model converted into an EPANET-MSX file consists in 14 bulk species and no surface species (Table A2 in the Appendix A). In the absence of field measurements and in order to make a comparison with the chlorine model described previously, the initial condition for the monochloramine dose is set to 2 mg/L at each source. The values of parameters $CaCO_3$ (alkalinity) and pH for all nodes are set respectively to 200 mg/L and 7.75. The sources are assigned a TOC concentration of 0.5 mg/L (in drinking water, values for TOC are typically <1 mg/L [60]) consisting of 1% slow reacting sites and 42% fast-reacting sites in the NOM structure. The values adopted are consistent with typical values founded in WDN sources and with experiments carried out in the scientific literature. Using the chloramine decay model described, the network is run in EPANET-MSX, and nodes with a minimum chloramine concentration $C_{ch,min}$ = 0.2 mg/L are searched for.

2.1.5. Scenario 4—Chloramine and Continuous Nodal Blowoffs

Based on the results concerning the chloramine residuals, additional techniques (boosters or dripping blowoffs) are implemented in this last scenario. The procedure carried out in scenario 2 is repeated for the chloraminated network.

2.1.6. Estimation of Total Volume of Water and Total Mass of Disinfectant

For each scenario considered, the average total volume of water delivered *Vol* (m^3) and the average total mass dose of disinfectant supplied *W* (kg) in the simulation analysis are estimated. The average total volume *Vol* (m^3) of water input into the WDN per the total duration of the simulation is given by Equation (5):

$$Vol = \sum_{i=1}^{n_s} \sum_{j=1}^{N_{\Delta t}} Q_{i,j} \Delta t, \tag{5}$$

where $Q_{i,j}$ (m^3 s^{-1}) is the flow rate supplied by the i-th of the n_s source nodes at the j-th of the $N_{\Delta t}$ number of time steps Δt considered for the simulation (i.e., 3600 s). As a result of mass conservation, the variable *Vol* equals all nodal outflows (leakage from WDN pipes + user outflow + additional outflow due to nodal blowoffs considered for fixing disinfectant residuals).

The average total mass *W* (kg) of disinfectant fed into the network per the total duration of the simulation is given by Equation (6):

$$W = \sum_{i=1}^{n_s} \sum_{j=1}^{N_{\Delta t}} C_{d,i} Q_{i,j} \, \Delta t, \tag{6}$$

where $C_{d,i}$ is the concentration of disinfectant imposed on the i-th supply (sources and booster stations) (kg/m^3).

2.2. Case Study

The case study considered in this work is the network model from the Battle of the Water Sensor Networks 2006 (BWSN Network 2) [61].

This large network is made up of 12,523 nodes, 2 reservoirs, a source (well), 2 tanks, 14,822 pipes, 4 pumps, and 5 valves (layout in Figure 3). Figure 3 is intended to be a schematic representation of the network model used as a benchmark in this study. This figure aims to show the network size and where the sources are located to clearly define what the disinfectant path is before reaching the final users of the network. All the pipes are assumed to feature a Hazen–William roughness coefficient of 140, a diameter ranging up to 1219 mm, and a length from to 1 to 4019 m. Nodes are assumed to have an elevation between 0.00 and 40.67 m above sea level (ASL) and a base demand ranging from 0 to 15.55 L/s. Among the network nodes, 1971 nodes are zero-demand nodes and are then excluded from the analysis of violations. Tanks use a completely mixed modeling technique. There are simple control statements that affect the operations of pumps and valves surrounding each tank. The network is subject to five variable demand patterns. WDN emitters corresponding to leakage are tuned in such a way as to obtain a percentage of leakage around 15%, which is a reasonable value for modern and well-maintained WDNs.

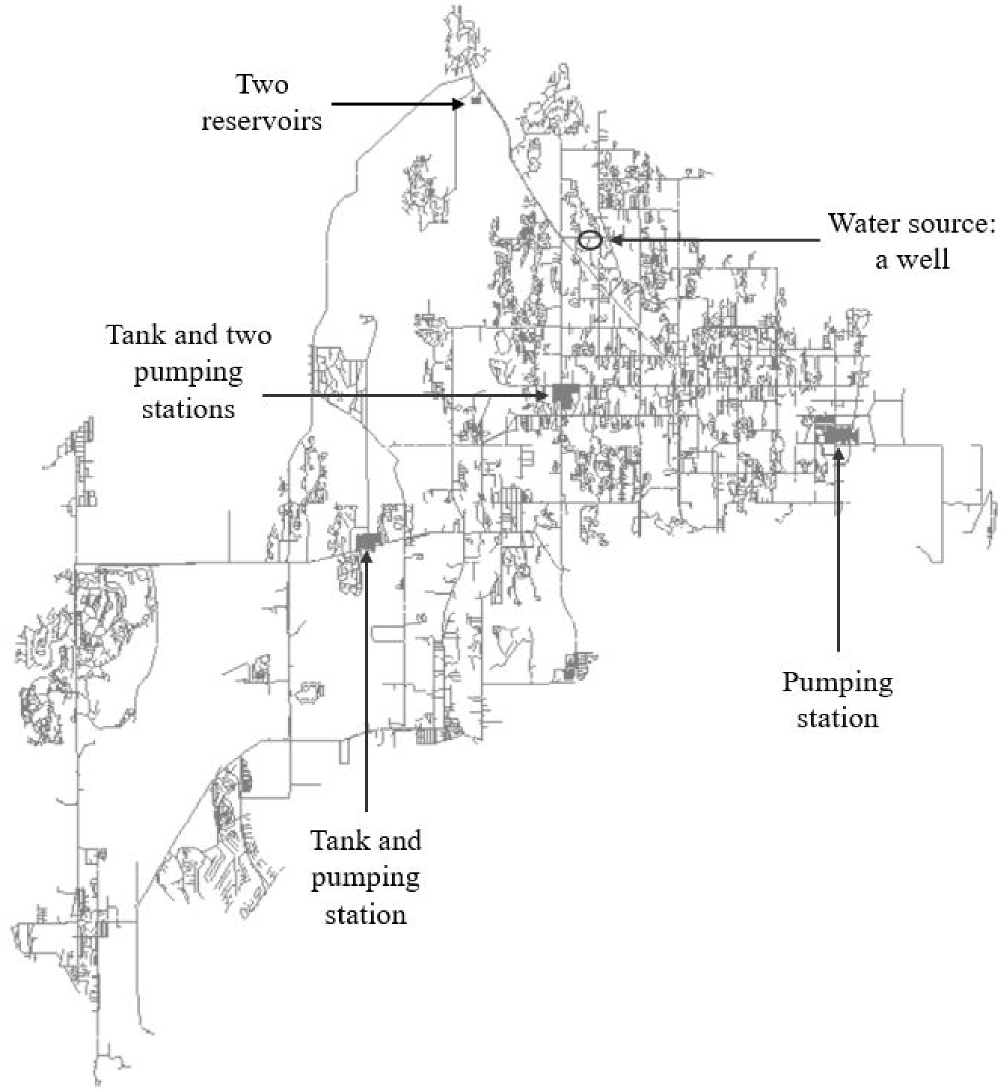

Figure 3. Case study layout (not to scale) based on [61].

For water quality simulations, chlorine and chloramine are chosen as disinfectants for scenarios 0, 1, and 2 and for scenarios 3 and 4, respectively. Both disinfectants are supplied at the sources and booster stations with a constant concentration of 2 mg/L. The initial chlorine/chloramine concentration is set to 0 at all WDN nodes. A simulation duration of 240 h (10 days) is used for the analysis to make sure that the disinfectant injected into the sources has enough time to reach the terminal nodes of the network and to reach well-established cyclical operating conditions in the last day of simulation. The hydraulic and water quality time steps used in calculations are 1 h and 5 min, respectively. The constraints used in all scenario models require that residual concentrations of both chlorine and chloramine be maintained between a minimum C_{min} = 0.2 mg/L and a maximum C_{max} = 2.0 mg/L over the last 48 h monitoring time window. Therefore, this time window is considered to evaluate disinfectant violations.

3. Results

Generally, water quality simulations indicated that, for both disinfectants injected into the three sources, residual requirements were not satisfied in all WDN nodes without the implementation of boosters and additional outflows at critical nodes. Specifically, 41 violating nodes were identified in the network in scenario 0, with a chlorine concentration below $C_{cl,min}$ = 0.2 mg/L (Table 1). Water quality simulations showed that violations occurred in both bulk areas and in terminal sections of the network affecting many dead-end nodes.

The results obtained for scenario 1 show that the placement of three booster stations and the opening of 18 nodal additional continuous outflows can increase overall chlorine concentrations in WDN (Table 2, Figure 4).

Table 2. Blowoff emitters *e* and average outflows *q* of flushing blowoffs in scenarios 1 and 4.

Node	e (L/s/m$^{1/2}$)	q (L/s)	e (L/s/m$^{1/2}$)	q (L/s)
ID	**Scenario 1**	**Scenario 1**	**Scenario 4**	**Scenario 4**
941	0.0052	0.033	0.003	0.019
1800	0.026	0.192	0.023	0.170
2330	0.0081	0.056	0.0025	0.018
2340	0.013	0.117	0.0046	0.054
3220	0.0024	0.071	-	-
3491	0.016	0.154	0.0064	0.078
3510	0.015	0.127	0.0069	0.062
3844	0.016	0.124	0.014	0.109
3618	0.0068	0.081	-	-
3857	0.0033	0.027	-	-
4181	0.005	0.046	0.0025	0.028
4910	0.0038	0.032	-	
5056	0.038	0.238	0.033	0.208
8057	0.028	0.228	0.013	0.121
8480	0.042	0.352	0.018	0.175
8476	0.0032	0.149	-	-
8954	0.0028	0.029	-	-
10046	0.041	0.381	0.014	0.169

Note: Scenario 1: disinfectant chlorine—3 booster stations and 18 flushing blowoffs. Scenario 4: disinfectant chloramine—no booster stations—12 flushing blowoffs.

The analysis of the nodes in terms of low chlorine residuals and high reachability pointed out that nodes 1853, 3854, and 12,346 may be suitable locations for a booster station. Since these booster stations serve three bulk areas of the network, they helped in increasing the chlorine concentrations of the neighboring nodes. The reachability (number of nodes that receive disinfected water from the booster node) is equal to six for both boosters 3854 and 12,346 and five for booster 1853. The problem of low residuals can be solved by placing booster stations at nodes 1853 and 12,346 without any additional operational measure in the surrounding areas. Conversely, though increasing chlorine residuals in the area served, the booster at node 3854 required placement of additional nodal outflows to be used at three critical dead-end nodes not reachable by the booster. Beyond the three bulk areas, there were still critical dead-end nodes scattered in the WDN. For these nodes, 18 continuous blowoffs (including the three ones placed in the bulk area served by booster 3854) were opened all day long to fix chlorine residuals. The blowoff emitter coefficients were tuned in such a way to obtain the lowest blowoff outflows that correct chlorine deficits. The emitter coefficients and the nodal average outflows (including outflows to fix chlorine residuals and leakage outflows) for critical dead-end nodes in WDN for scenario 1 are reported in Table 2.

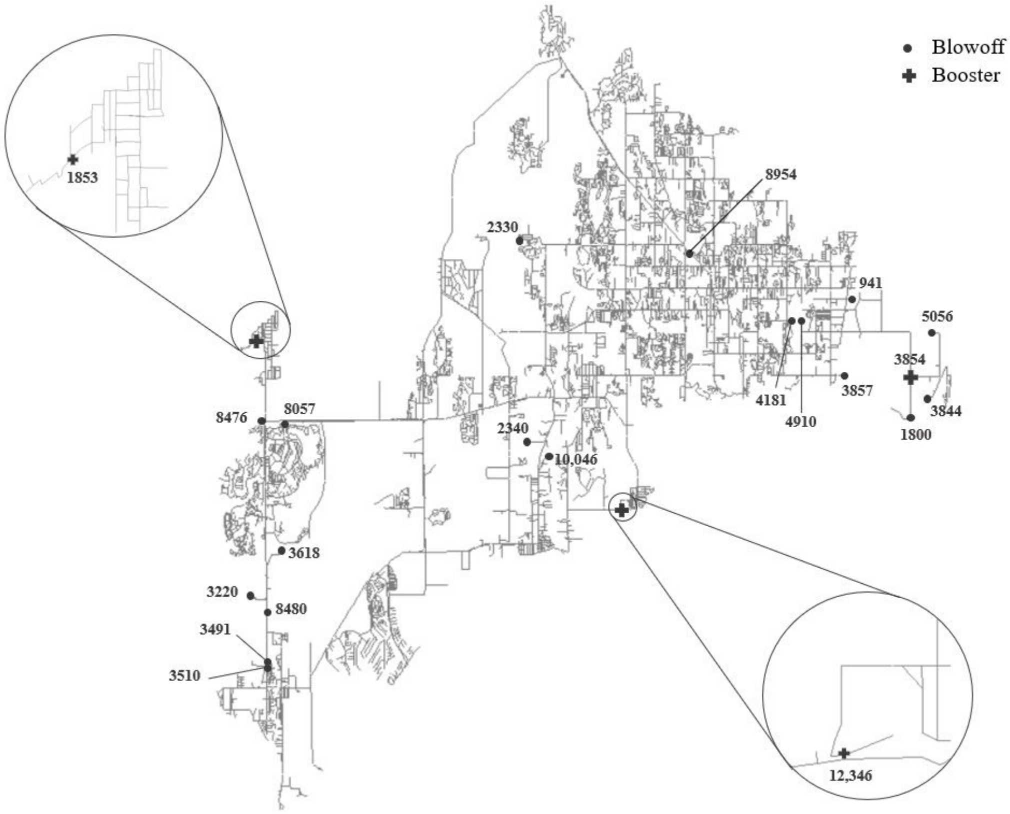

Figure 4. Booster stations and flushing blowoff placement in the network for scenarios 1 and 2.

The comparison between continuous flow and intermittent flow was carried out for all nodal blowoffs placed in the WDN. Intermittent blowoffs were considered only in the chlorinated network due to the higher computation times required for the chloraminated network. It must be remarked that intermittent flows, like continuous flows, never cause service pressure deficits in the WDN, except in case the intermittent blowoff at node 8480 is opened 1 h per day. In fact, the average outflow of 1 h flushing for node 8480 is almost 7 L/s, an excessive value compared with the outflows obtained for the other intermittent blowoffs. Hence, it was deemed that, in all the sub scenarios of 1 h flushing considered, all intermittent blowoffs were opened at 1 h per day while considering continuous flow (24 h) only for node 8480. As a representative situation, the comparison between continuous and intermittent outflows is reported just for nodes 1800 and 3510, both located in peripheral areas of WDN. For each intermittent supply sub scenario, the one minimizing f_j was chosen.

As for node 1800, the minimum continuous outflow that fixed the chlorine residual above 0.2 mg/L was that with $q_{1800,24}$ = 0.17 L/s, corresponding to a daily volume V_{1800} = 612 L. For this value of blowoff volume V_{1800}, intermittent outflow sub scenarios were generated using the procedure described in Section 2.1.3 for scenario 2. The graphs in Figure 5 show the patterns of flow rate supplied by blowoff and chlorine concentration at node 1800 for both continuous and intermittent supply sub scenarios for the j that minimized the total duration of residual chlorine deficit violations at the node. These patterns refer to the last day of the 10-day long flow routing/water quality simulation.

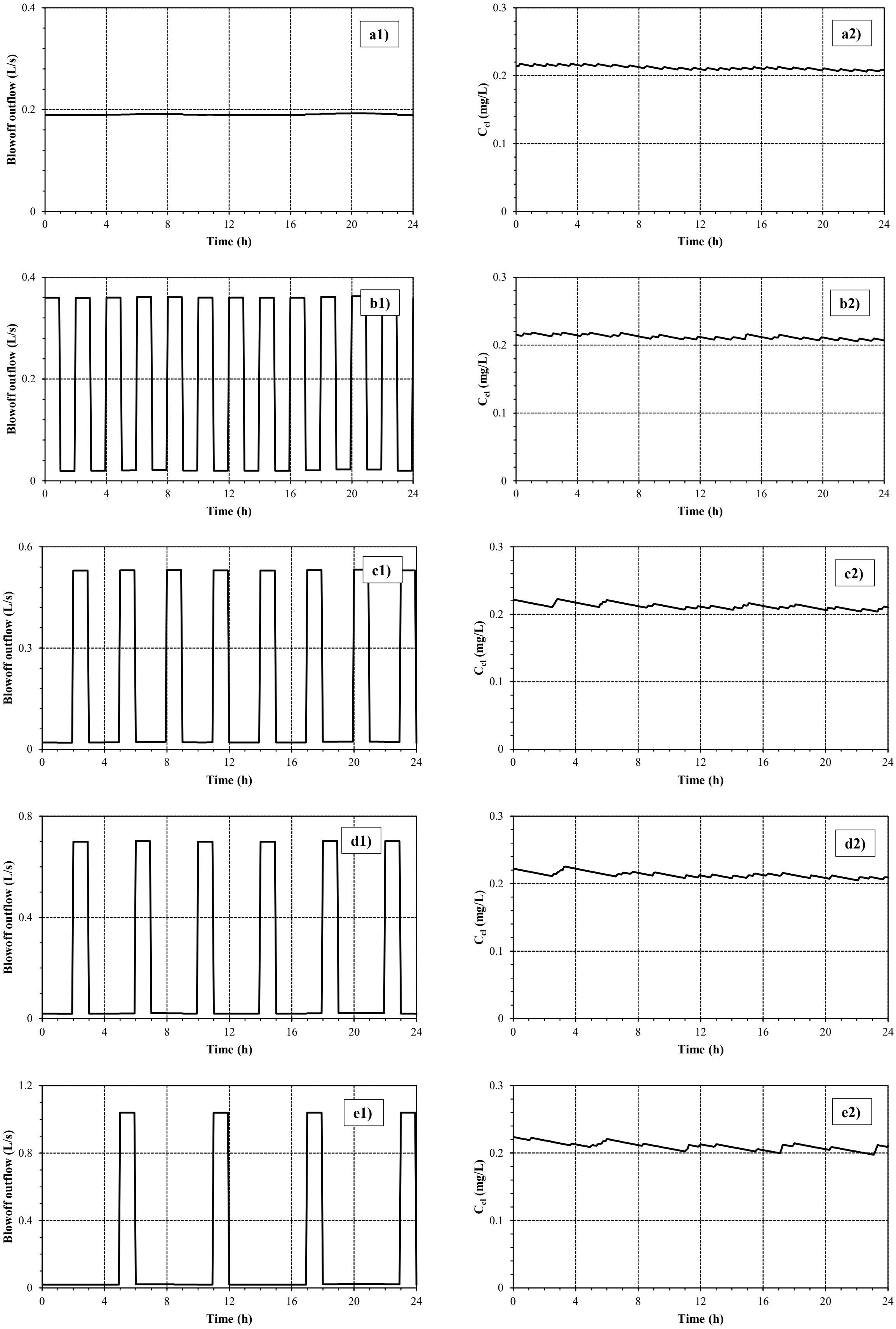

Figure 5. *Cont.*

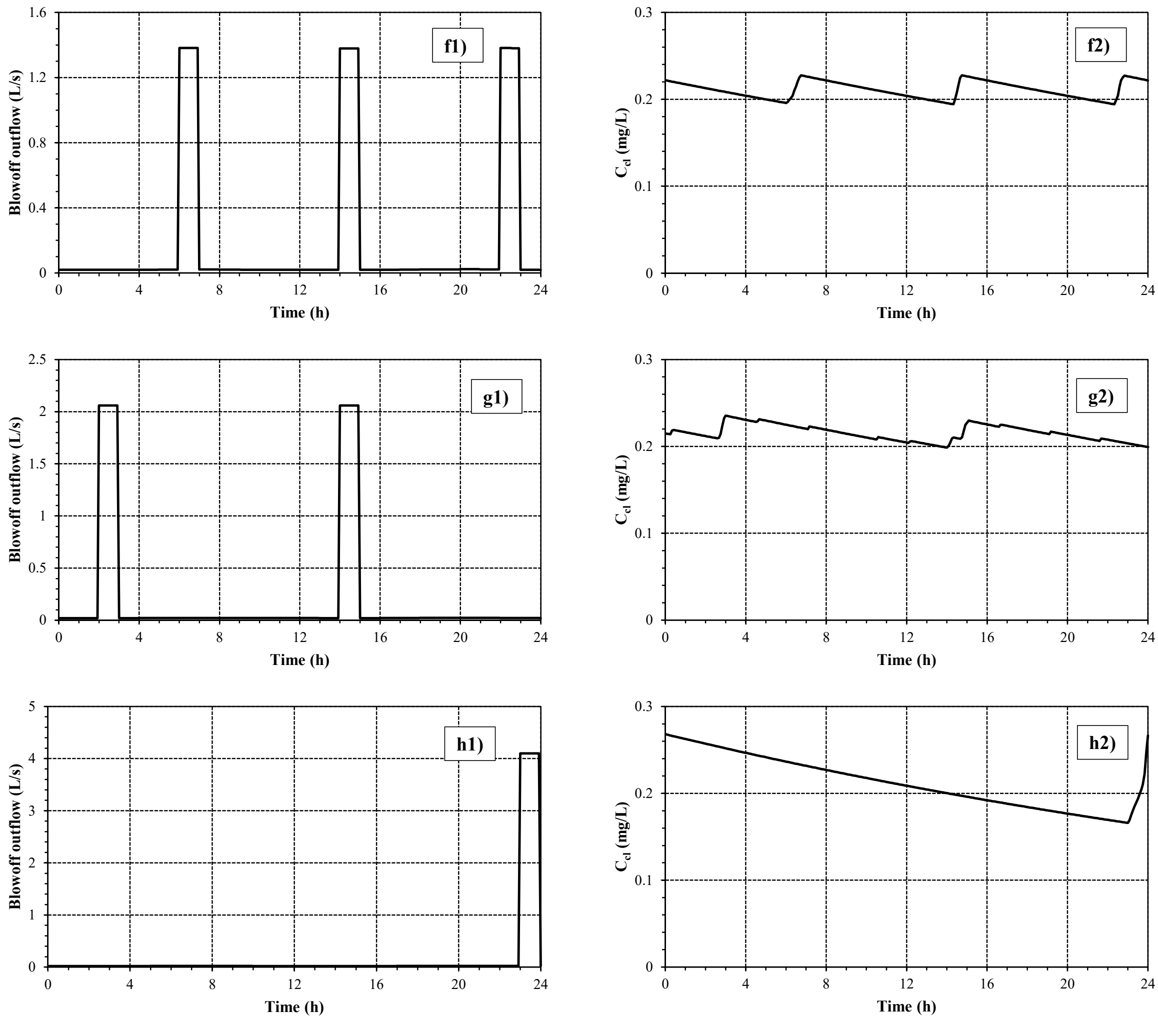

Figure 5. Blowoff outflow (1) and chlorine concentration (2) patterns at node 1800 in the last day of simulation in outflow sub scenarios 2 with k = 24 h (**a1**,**a2**), 12 h (**b1**,**b2**), 8 h (**c1**,**c2**), 6 h (**d1**,**d2**), 4 h (**e1**,**e2**), 3 h (**f1**,**f2**), 2 h (**g1**,**g2**), and 1 h (**h1**,**h2**) per day.

Table 3 reports the main features of the blowoff sub scenarios in terms of number k of hours of flow, blowoff flow $q_{1800,k}$, first hour j of outflow in the day, and duration $v_{k,j}$ of chlorine residual violations in the day.

Table 3. Summary of outflow scenarios for the node 1800.

Sub Scenario	k Hours of Blowoff in the Day	Blowoff Flow $q_{1800,k}$ (L/s)	First Hour j of Outflow in the Day (h)	Duration $v_{k,j}$ of Violations (min)
2a	24	0.17	1 (from 0 h to 1 h)	0
2b	12	0.34	1 (from 0 h to 1 h)	0
2c	8	0.51	3 (from 2 h to 3 h)	0
2d	6	0.68	3 (from 2 h to 3 h)	0
2e	4	1.02	6 (from 5 h to 6 h)	0
2f	3	1.36	7 (from 6 h to 7 h)	150
2g	2	2.04	3 (from 2 h to 3 h)	0
2h	1	4.08	24 (from 23 h to 24 h)	515

As for node 3510, the minimum continuous outflow that fixed the chlorine residual above 0.2 mg/L was that with $q_{3510,24}$ = 0.1 L/s, corresponding to a daily volume

V_{3510}=360 L. For this value of blowoff volume V_{3510}, intermittent outflow sub scenarios were generated using the procedure described in Section 2.1.3 for scenario 2. The graphs in Figure 6 show the patterns of flow rate supplied by blowoff and chlorine concentration at node 3510 for both continuous and intermittent supply sub scenarios for the j that minimized the total duration of residual chlorine deficit violations at the node. These patterns refer to the last day of the 10-day long flow routing/water quality simulation.

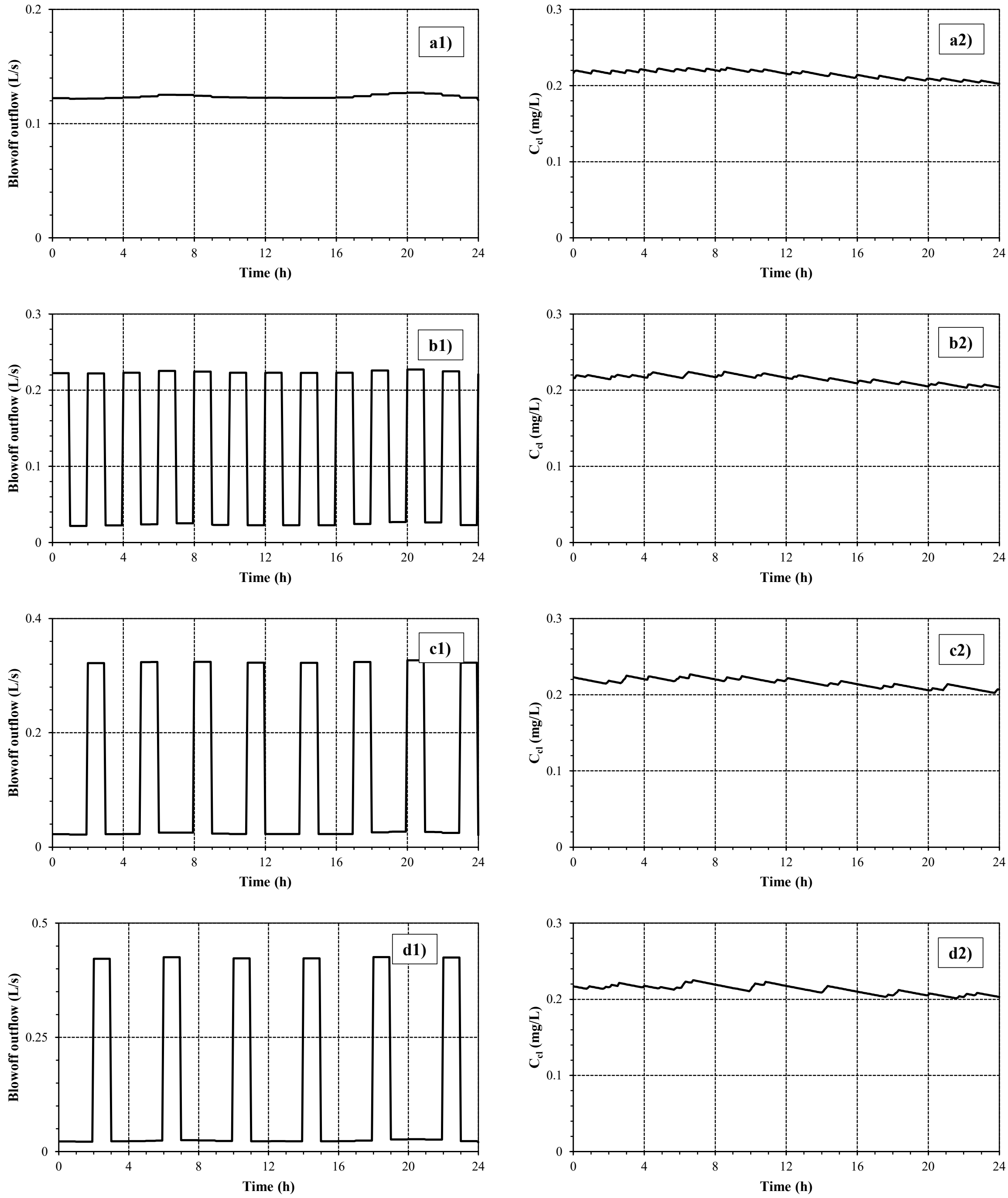

Figure 6. *Cont.*

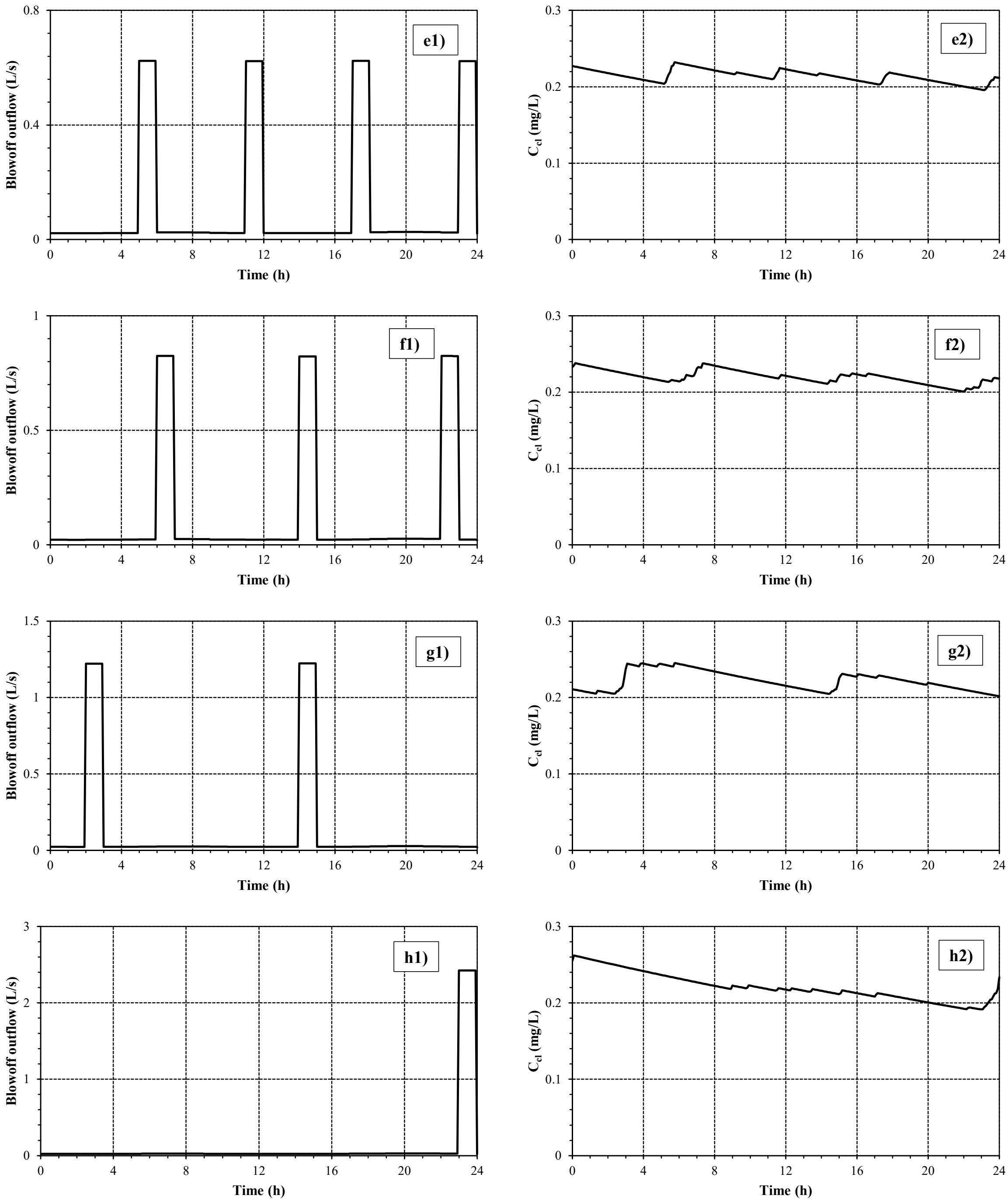

Figure 6. Blowoff outflow (1) and chlorine concentration (2) patterns at node 3510 in the last day of simulation in outflow sub scenarios 2 with k = 24 h (**a1**,**a2**), 12 h (**b1**,**b2**), 8 h (**c1**,**c2**), 6 h (**d1**,**d2**), 4 h (**e1**,**e2**), 3 h (**f1**,**f2**), 2 h (**g1**,**g2**), and 1 h (**h1**,**h2**) per day.

Table 4 reports the main features of the blowoff sub scenarios in terms of number k of hours of flow, blowoff flow $q_{3510,k}$, first hour j of outflow in the day, and duration $v_{k,j}$ of chlorine residual violations in the day.

The results presented in Figures 5a and 6a confirm the validity of the continuous outflow scenario. Referring to intermittent flow sub scenarios of the node 1800, nodal blowoff can fix the minimum constraint of 0.2 mg/L in all the cases except for cases (f) and (h). In case (f), the chlorine residual becomes slightly lower than the target close to 5th and 6th h ($c_{cl,min}$ = 0.196 mg/L), 13th and 14th h ($c_{cl,min}$ = 0.194 mg/L), and from 21st to 22nd h ($c_{cl,min}$ = 0.194 mg/L). The worst case is the last one, case (h), in which there is a progressive decrease in chlorine concentration, starting from 14th h to 23rd h ($c_{cl,min}$ = 0.166 mg/L). Instead, the use of intermittent blowoff close to node 3510 seems to have benefits on the chlorine residual in all the cases except for cases (f) and (h). Besides the times when the minimum constraint is slightly violated as in the case (f) close to the 22nd and 23rd h ($c_{cl,min}$ = 0.195 mg/L), there is a violation in the case (h) from the 21st to 23rd h ($c_{cl,min}$ = 0.191 mg/L).

Table 4. Summary of outflow scenarios for the node 3510.

Sub Scenario	*k* Hours of Blowoff in the Day	Blowoff Flow $q_{3510,k}$ (L/s)	First Hour *j* of Outflow in the Day (h)	Duration $v_{k,j}$ of Violations (min)
2a	24	0.1	1 (from 0 h to 1 h)	0
2b	12	0.2	1 (from 0 h to 1 h)	0
2c	8	0.3	3 (from 2 h to 3 h)	0
2d	6	0.4	3 (from 2 h to 3 h)	0
2e	4	0.6	6 (from 5 h to 6 h)	40
2f	3	0.8	7 (from 6 h to 7 h)	0
2g	2	1.2	3 (from 2 h to 3 h)	0
2h	1	2.4	24 (from 23 h to 24 h)	155

Globally, results proved that intermittent outflows are effective at solving the problem of low disinfectant concentrations for all WDN blowoffs, if a percentage of violation of 10–15% for a few hours per day is considered acceptable.

Finally, the choice of using chloramine as an alternative to chlorine was investigated. As expected, chloramine tended to have a slower decay than chlorine. Specifically, 18 violating nodes were identified in the network in scenario 3, with a chloramine concentration below $C_{ch,min}$ = 0.2 mg/L (Table 1). These violations occurred only at critical dead-end nodes of the network. Therefore, in scenario 4 no booster stations were placed in bulk areas and fewer flushing blowoffs were installed than those of scenario 1 (Table 1, Figure 7).

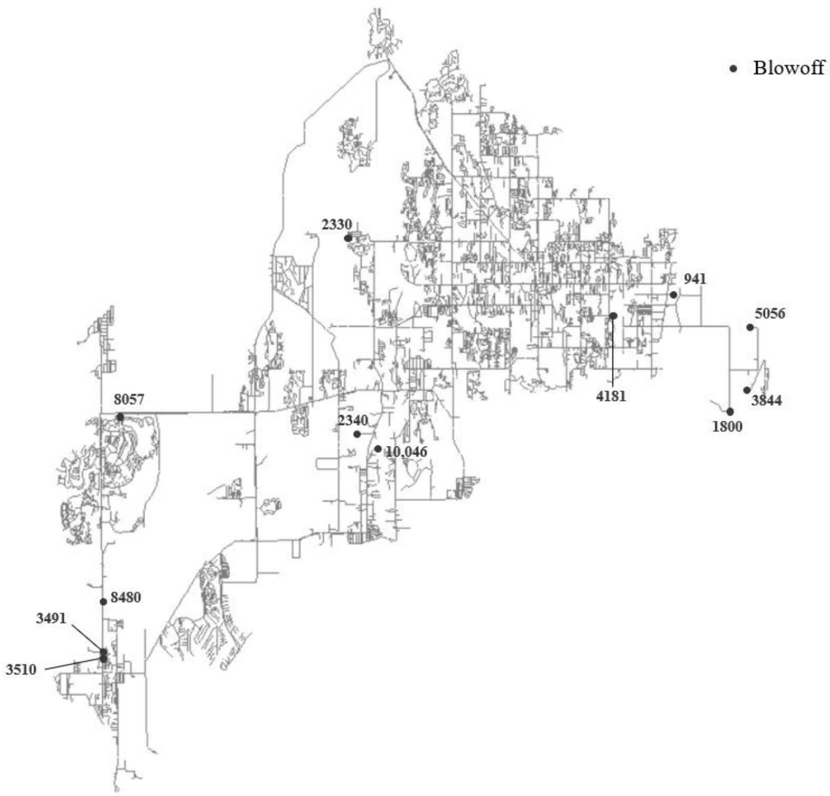

Figure 7. Flushing blowoff placement in the network for scenario 4.

The blowoff emitter coefficients were tuned to obtain the lowest blowoff outflows that correct chloramine deficits. Therefore, the injection of chloramine at WDN sources led to a decrease in the number of blowoffs to open and in the blowoff outflows. The emitter coefficients and the average nodal outflows (including outflows to fix chloramine residuals and leakage outflows) for critical dead-end nodes in WDN for scenario 4 are reported in Table 2. For all scenarios considered, the average total volume of water delivered *Vol* and average total mass dose of disinfectant *W* supplied in the 10 days of simulation analysis for each scenario were estimated and are reported in Table 5.

Table 5. Daily average total volume of water delivered *Vol* and daily mass dose of disinfectant *W* supplied in the 10 days of simulation analysis for each scenario.

Scenario	W (kg)	Vol (m^3)
0	3171	1,585,416
1	3174	1,586,871
4	3172	1,586,177

Note: Scenario 0: disinfectant chlorine—no booster stations and no flushing blowoffs. Scenario 1: disinfectant chlorine—3 booster stations—18 flushing blowoffs. Scenario 4: disinfectant chloramine—no booster stations—12 flushing blowoffs.

As it is shown, the average total volume *Vol* (including supply, leakage, and additional outflow by blowoffs considered for fixing disinfectant residuals) only slightly increases in scenarios 1 and 4 compared with the no-blowoffs scenario (scenario 0). The fewer flushing blowoffs needed in the chloramine model (scenario 4) led to a decreased volume of water supplied compared with the chlorine model (scenario 1).

Generally, the slight opening of nodal blowoffs for improving water quality at dead-end nodes worsened water losses only slightly in the WDN. Referring to the average total mass dose *W* (including disinfectant mass dose injected in sources and booster stations), the maximum value was obtained for scenario 1, in which three booster stations were placed to meet the residual target in bulk areas. However, this value was only slightly larger than the values obtained for scenarios 0 and 4, for which no booster station was necessary.

4. Discussion

The problem of low residuals cannot be solved by simply increasing disinfectant dose at the sources. In this context, other EPANET and EPANET-MSX simulations showed that, even when disinfectant concentration C_d at sources grows, it is infeasible to eliminate all violating nodes (Figure 8).

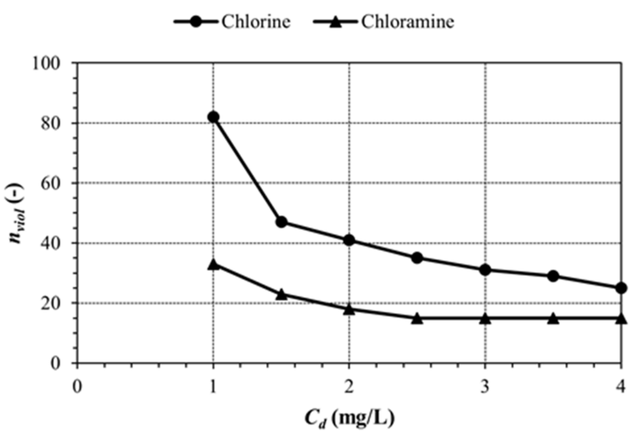

Figure 8. Number of violating nodes for each disinfectant dose C_d at sources in the chlorine and chloramine model.

In fact, even in the case of C_d = 4 mg/L (a high value compared with typical disinfectant concentrations found in WDNs), 25 and 15 violating nodes persist for chlorine and chloramine, respectively. Results confirm the slower decay rate of chloramine than chlorine for each dose at sources. The chloramine curve tends to stabilize at C_d = 2.5 mg/L after which, while increasing the dose at sources, 15 violating nodes are always detected. The choice of using a disinfectant concentration of C_d = 2 mg/L at sources may be a good compromise between keeping the disinfectant residuals in the target and avoiding the production of harmful DBPs that are known to be caused by excessive doses of disinfectant within WDN.

In light of the results reported in this work, the implementation of continuous or intermittent additional outflows at critical dead ends can contribute to the solution of this problem, in combination with the installation of disinfectant booster stations. Though flushing is a practice that can increase nonrevenue water, incentives can be proposed to users to encourage them to use more water, for instance, for irrigation purposes. The solution of nodal blowoffs can be implemented in real WDNs by installing a small tap for water immediately upstream from the hydrant. If the outflow proposed by simulations at the generic node is too small to be obtained by the tap, this device should be adjusted at the smallest feasible setting. Some automated flushing technology may have a disinfectant residual sensor built into the flushing device. However, this technology will be quite expensive and will require substantial maintenance.

It is clear there is no best solution for improving disinfectant residuals in WDN. Each of the alternatives shown has its own pros and cons. Booster stations are effective to obtain a more uniform distribution of disinfectant and can be placed in suffering bulk areas, though requiring a significant capital investment for the water utility. Continuous nodal blowoffs, instead, seem to be a necessary solution for the numerous and scattered suffering dead-end nodes in WDNs. They can be obtained by manually regulating blowoffs at critical nodes, e.g., close to the hydrant site; therefore, causing no costs for the automatization. Furthermore, they cause no service pressure deficits in the WDN. Cons include that the very low water discharges associated with their operation can be hardly obtained in the field. Therefore, larger water discharges than those predicted through the modeling, and larger water losses as a result, should be obtained in the field. In the case of intermittent blowoffs, the total outflow volume being the same, larger water discharge values, more easily obtainable in the field, were obtained. However, as cons, this solution may have higher installation costs due to the automatization and could cause local service pressure deficits in WDN due to the larger outflows. With higher velocities, this solution may also stir up sediment if not carried out properly. The use of chloramine as a possible alternative to chlorine led to an overall increase in residuals within the WDN and consequently to a decrease in the number of operational measures to be implemented.

The choice of a solution depends on multiple factors such as local conditions (i.e., decay rate), the water utility's choice for incurring additional capital, labor, etc. Hydraulic/water quality models, such as EPANET, can be very effective in comparing operational alternatives to solve the problem of low residuals in the system under study. However, the use of software modeling should be combined with field sampling in order to obtain a more complete picture of the system and to reflect local conditions (i.e., decay rate), as well as to consider factors neglected in the EPANET modeling, such as the chemical diffusion/dispersion effects. Indeed, these effects may play a role in alleviating the problem of disinfectant residual violations that may arise due to low flow conditions in proximity to dead ends.

The proposed approaches can be extended to other real WDNs. However, the characteristics (e.g., the number and location) of the operational measures implemented in this work are strictly related to the network model considered, which is a meaningful example of a real large-size WDN. This study demonstrates that chlorine booster stations and continuous or intermittent nodal blowoffs are valid solutions to improve the residuals when chlorine or chloramine is used as a disinfectant at the sources. However, the results obtained are influenced by the assumptions underlying the study. Other factors should be investigated, such as the variability in decay rates and in flow demands. In real systems, disinfectant decay rates are not constant but vary due to seasonal variations in network conditions. For example, an increase in the water temperature or in the organic content in the treated water causes the growth of disinfectant consumption. Similarly, flow demands are not constant but vary due to users' habits as well as seasonal patterns. The variability in these parameters can affect the water quality results and hence the solutions to be implemented. It should be expected that a decrease in flow demands in the WDN and a growth of the disinfectant decay cause an increase in the number of booster stations and blowoffs to be located, and vice versa.

The last comment concerns the potential nitrification problem that may occur in a WDN when chloramine is used as a disinfectant. Nitrification reactions, due to the production of ammonia, can have the adverse impact of reducing chloramine residuals, promoting bacterial regrowth. Furthermore, it can be accompanied by a decrease in pH, thus promoting the corrosion of the infrastructure. The chloramine decay model implemented in EPANET-MSX takes into account the formation of ammonia (NH_3). A health-based guideline has not been derived, as reported in the *Guidelines for drinking-water quality* [10] since ammonia is not of direct importance for health in the concentrations to be expected in drinking water. However, referring to the European [62] and Italian [1] regulations, concentrations lower than a guideline value of 0.5 mg/L should be guaranteed. Results obtained show that 39 out of 10,551 nodes have ammonia concentrations above the target 0.5 mg/L in the monitoring time window (last 2 days of simulation) with values up to 0.59 mg/L. However, this percentage of violation (18%) occurs only for very few nodes in the WDN.

5. Conclusions

The present work provided a comparison between different techniques to increase disinfectant residuals in a WDN. First, the implementation of booster stations in bulk areas and continuous nodal blowoffs at critical dead-end nodes was carried out in a full-scale chlorinated WDN. Afterward, the comparison between continuous and intermittent outflows through nodal blowoffs was performed at critical dead-end nodes. The work ended with the investigation of switching chlorine with chloramine. The methodology used is based on the use of flow routing/water quality software EPANET and its multi-species extension EPANET-MSX. Results showed that all the techniques analyzed, each with their own pros and cons, are effective to tackle the problem of low disinfectant residuals in WDN. The main findings of this work can be summarized as follows:

- Booster stations are effective to obtain more uniform coverage of disinfectant and can be placed in suffering bulk areas, while nodal blowoffs seem to be a necessary solution for the numerous and scattered suffering dead-end nodes in WDN;
- Intermittent blowoffs have a similar performance to the continuous blowoffs if a percentage of violation of 10–15% for a few hours per day is considered acceptable;
- The use of chloramine as a possible alternative to chlorine led to an overall increase in residuals throughout the WDN and, consequently, to a decrease in the number of blowoffs to open and in blowoff outflows.

The problem of low residuals may occur in centralized systems as well as in systems divided into district metered areas (DMAs). The case study analyzed in this work is an example of a centralized system. Therefore, future works will analyze and address the problem of low residuals in DMAs.

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Appendix A

Table A1. Chlorine first-order decay model based on Vasconcelos et al. (1997) [6] implemented in EPANET considering only the effect of the bulk reaction.

Reaction Equation	Rate Coefficient
$[HOCl]_t = [HOCl]_0 \cdot e^{-k_1 \cdot t}$	$k_1 = 0.5\ d^{-1}$ [a]

Note: [a] Bulk decay coefficient values range from 0.1–1 d^{-1}. In this work, a typical value $k_1 = 0.5\ d^{-1}$ from the scientific literature.

Table A2. Chloramine auto decomposition based on Vikesland et al. (2001) [44] and Duirk et al. (2005) [45] models and implemented in EPANET-MSX.

N.	Reaction Stoichiometry	Rate Coefficient/Equilibrium Constant [a]
1	$HOCl + NH_3 \rightarrow NH_2Cl + H_2O$	$k_1 = 1.5 \times 10^{10}\ M^{-1}\ h^{-1}$
2	$NH_2Cl + H_2O \rightarrow HOCl + NH_3$	$k_2 = 7.6 \times 10^{-2}\ h^{-1}$
3	$HOCl + NH_2Cl \rightarrow NHCl_2 + H_2O$	$k_3 = 1.0 \times 10^{6}\ M^{-1}\ h^{-1}$
4	$NHCl_2 + H_2O \rightarrow HOCl + NH_2Cl$	$k_4 = 2.3 \times 10^{-3}\ h^{-1}$
5	$NH_2Cl + NH_2Cl \rightarrow NHCl_2 + NH_3$	$k_5 = 2.5 \times 10^{7}\ [H^+] + 4.0 \times 10^{4}\ [H_2CO_3] + 800\ [HCO_3^-]\ M^{-2}\ h^{-1}$
6	$NHCl_2 + NH_3 \rightarrow NH_2Cl + NH_2Cl$	$k_6 = 2.2 \times 10^{8}\ M^{-2}\ h^{-1}$
7	$NHCl_2 + H_2O \rightarrow I$	$k_7 = 4.0 \times 10^{5}\ M^{-1}\ h^{-1}$
8	$I + NHCl_2 \rightarrow HOCl +$ products	$k_8 = 1.0 \times 10^{8}\ M^{-1}\ h^{-1}$
9	$I + NH_2Cl \rightarrow$ products	$k_9 = 3.0 \times 10^{7}\ M^{-1}\ h^{-1}$
10	$NH_2Cl + NHCL_2 \rightarrow$ products	$k_{10} = 55.0\ M^{-1}\ h^{-1}$
11	$NH_2Cl + S_1$ [b] $\times$ TOC $\rightarrow$ products	$k_{11} = 3.0 \times 10^{4}\ M^{-1}\ h^{-1}$ $S_1 = 0.01$
12	$HOCl + S_2$ [c] $\times$ TOC $\rightarrow$ products	$k_{12} = 6.5 \times 10^{5}\ M^{-1}\ h^{-1}$ $S_2 = 0.42$
13	$HOCl \leftrightarrow H^+ + OCl^-$	$pKa_1 = 7.5$
14	$NH_4^+ \leftrightarrow NH_3 + H^+$	$pKa_2 = 9.3$
15	$H_2CO_3 \leftrightarrow HCO_3^- + H^+$	$pKa_3 = 6.3$
16	$HCO_3^- \leftrightarrow CO_3^{2-} + H^+$	$pKa_4 = 10.3$

Notes: [a] All rate coefficients and equilibrium constants are for 25 °C. [b] S_1 is the fast reactive fraction of TOC. [c] S_2 is the slow reactive fraction of TOC.

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