sciendo

ANNALS OF WEST UNIVERSITY OF TIMISOARA PHYSICS
Vol. LXV, 2023

DOI: 10.2478/awutp-2023-0007

CHLORINE DECAY SIMULATION IN REAL WATER DISTRIBUTION SYSTEM USING EPANET PROGRAM

Mekki Malika[1], Bouabdesselam Hassiba[1], Laib Radouane[2], Beloufa Nabil[3,4], Bekheira Samir[5] and Mohamed Trari[6]

[1]LTE Laboratory. National Polytechnic School Oran, ENPO-MA, BP 1523, El M'Naouer, 31000, Oran, Algeria
[2]University of Relizane, Ahmed Zabana, BP 48000, Bourmadia, Relizane, Algeria
[3]Hydrometeorological Institut for Formation and Research IHFR, Oran, Algeria
[4]Laboratory of Micro and Nanophysics (LaMiN), National Polytechnic School Oran, ENPO-MA, BP 1523, El M'Naouer, 31000, Oran, Algeria
[5]Laboratory of Materials (LabMat), National Polytechnic School Oran, ENPO-MA, BP 1523, El M'Naouer, 31000, Oran, Algeria
[6]Laboratory of Storage and Valorization of Renewable Energies (LSVER), Faculty of Chemistry, U.S.T.H.B., BP 32 El-Alia, 16111 Algiers, Algeria

Article Info

Received:29.06.2023
Accepted: 21.08.2023

Keywords:
Chlorine Decay; Simulation; Water Distribution Network; Water Quality; EPANET 2.0.

Abstract

Deterioration of treated drinking water intended for consumption during distribution may be due to physical, chemical or microbiological changes that occur in the water. In addition, the type of pipe material and disintegration of a disinfectant agent can affect the quality of the water supplied. Therefore, the research approach is to simulate the decay residual Cl_2 through potable water distribution networks produced by a desalination plant of Oran city in western Algeria. EPANET 2.0 software was used for estimating and predicting Cl_2 concentration at different water network points. The value of bulk flow decay coefficient (Kb) is set to -1,99 day^{-1} for a 50-year-old steel pipe, value for the wall decay coefficient (Kw) was determined using a trial-and-error procedure and assumed to be -1,2 day^{-1}.

An efficient model with an extended simulations period of 72 h can plot spatial and temporal variations of residual Cl_2 concentrations at all links and nodes. Cl_2 is injected at the El Mactaa desalination plant, with a concentration of 0.6 mg/l permanently. As well, it was observed that 51.33% of the Cl_2 loss is due to pipe wall reaction, while 42.34 and 6.33% represent the bulk and tank reactions respectively. The results show that the range of residual Cl_2 (0.11-0,45 mg/l) and most of the measured values are less than are below the minimum authorized threshold (0.2 – 0.5 mg/l) WHO standard. Therefore, it is recommended to rehabilitate the old water transfer pipes and re-chlorination stations were necessary to add into network. Statistical analysis shows that the calculated results correspond well to the observed data. EPANET can follow the Cl_2 concentration in the drinking water network produced by El Mactaa desalination plant. It is a research tool to improve our understanding of water movement in the distribution system.

1. Introduction

The main reasons for water quality deteriorations in old distribution systems is the release of corrosion products from the pipe surfaces, caused by aggressive aqueous environments of desalination waters treatment plants. Several factors can contribute to the deterioration of water quality during distribution, including interactions between the distributed water and pipe material or interactions within bulk water [1]. In addition, the decomposition of a disinfectant agent, such as chlorine, can degrade the microbial conditions of a distribution system, leading to a possible health risk to the consumers [2].

Chlorine is one of the most effective disinfectants in water treatment. It is used in the form of free chlorine or mono chloramines to disinfect the drinking water distribution systems and to monitor bio films growth [3, 4, 5]. Therefore, it is essential to maintain adequate chlorine residual throughout the whole distribution system in order to preserve the chemical and microbial quality of distributed water [6, 7].

However, as a strong oxidizer, chlorine with a potential of 1.36 V_{SHE}, reacts rapidly with organic and inorganic compounds and thus decomposes inside the distribution system through reactions both in the bulk phase and at the pipe wall [2, 6, 7, 8, 9, 10]. In addition, Cl_2 can be consumed by the corrosion process of the pipe material [2, 6]. as well as the bio film attached to the pipe wall. The degradation induced by bio films varies enormously, but the interactions between biofilms and disinfectants are still poorly understood [3, 8]. The performance of the organic material intrusion is dependent on the bulk coefficient, lower bulk coefficient leading to faster reaction rates, and thus lower organic material concentrations in the network [11]. During water treatment process, Cl_2 is usually being supplied as compressed gas, solution of sodium hypochlorite or solid calcium hypochlorite. All used forms of Cl_2 are generally chemically equivalent due to quick equilibrium between dissolved chlorine and products of dissociation of hypochlorite (ClO^-).

In relation to the form of Cl_2 application, the following reactions occur in water [12].

$$\text{Gaseous chlorine: } Cl_2 + H_2O \rightarrow H^+ + Cl^- + HOCl \quad (1)$$

$$\text{Sodium hypochlorite: } NaOCl + H_2O \rightarrow H_2O + Na^+ + ClO^- \quad (2)$$

$$\text{Calcium hypochlorite: } Ca(OCl)_2 + 2H_2O \rightarrow Ca^+ + 2OH^- + 2HOCl \quad (3)$$

HOCl dissociates to give hydrogen ions (H^+) and hypochlorite ions:

$$HOCl + H_2O \rightarrow H_3O^+ + OCl^- \quad (4)$$

$$HOCl + 2Fe^{2+} \rightarrow 2Fe^{3+} + Cl^- + OH^- \quad (5)$$

Equation (5) describes the reactions of HClO with inorganic substances, leading to the immediate use of residual chlorine.

In water with a high Cl^- concentration, the Cl^- reacts with Fe^{3+} and Fe^{2+} to form metal chlorides. $FeCl_3$ results from the reaction of $FeCl_2$ with chlorine in water. The production of $FeCl_3$ is determined by two main reactions [13-15].

$$Cl_2 + H_2O \rightarrow HClO + H^+ + Cl^- \quad (6)$$

$$FeCl_2 + HClO \rightarrow FeCl_3 + H2O \quad (7)$$

Thus, its constant disintegration in time is observed, independently to availability of other factors affecting its usage [9, 16]. All the decomposition processes occurring in water body and in the boundary layer are referred to as the chlorine demand by water.

Bulk fluid reactions occur within the fluid volume and are a dependent of constituent concentrations, reaction rate and order, and concentrations of the synthesis products. The sign of the reaction coefficient signifies that a formation reaction (positive) or a disintegrating reaction (negative) is occurring. The parameter used to express the rate of the reaction occurring within the bulk fluid is called the bulk reaction coefficient (Kb) which can be determined through the bottle test [17].

The rate of disinfectant decomposition at the pipe wall depends on the swift transport of the disinfectant to the pipe wall and the speed of the reaction once it is there. Clark et al. (1993) stated that the wall decay coefficient (Kw) could de higher than (Kb). Hua et al. (1999) reviewed three test pipes and found that Kw is only 10% of Kb [18]. Rossman et al. (2001) has shown that Kw value on the order of 3 day^{-1} was tolerated for cast and ductile iron pipes [19]. A study by Doshi et al. (2003) [20] estimated that with older unlined metal pipes, chlorine wall demand increases considerably with flow rate.

This study involves simulating the complex process of chlorine decay using EPANET software. The hydraulic calibration of the EPANET model is followed by a long-term water quality calibration in order to determine the pipe wall decay coefficient. This tool can be used

to specify the value and location of the critical chlorine residual concentration in the water distribution system, as also the rate of chlorine concentration required to meet the minimum requirements set by the WHO [21].

2. Materials and methods

2. 1. EPANET Program

EPANET 2.0 software, developed by the US-EPA Environmental Protection Agency, allows users to simulate a network in real time, based on hydraulic data and water quality parameters [22]. This software has been utilized by several researchers since the 1990s to estimate the amount of chlorine that remains in the water distribution system after chlorination. The EPANET software is developed based on the basic principles of energy conservation and continuity equations, where continuity equations show that the algebraic sum of the flow rate in a pipe meeting at a node along with any external flow is zero [23].

The EPANET 2.0 program offers many facilities for modeling water quality [24]:

- supervises throughput in a node relative to other nodes;
- modeling the transfer and evolution of a reactive material, illustrating the rise or fall in concentration over time;
- enables the reactions to be reduced or increased up to a concentration limit set by the standards;
- allows the concentration to be changed over time at any location in a network.

2. 2. Case study description

The study was carried out in a sector of the drinking water transport network that supplies the city of Oran, in western Algeria (Figure 1). The El Mactaa desalination plant mainly supplies this network. Reverse osmosis treated water flows by gravity to the three interconnected ST1 mixing tanks where each has isolation valves for cleaning and maintenance.

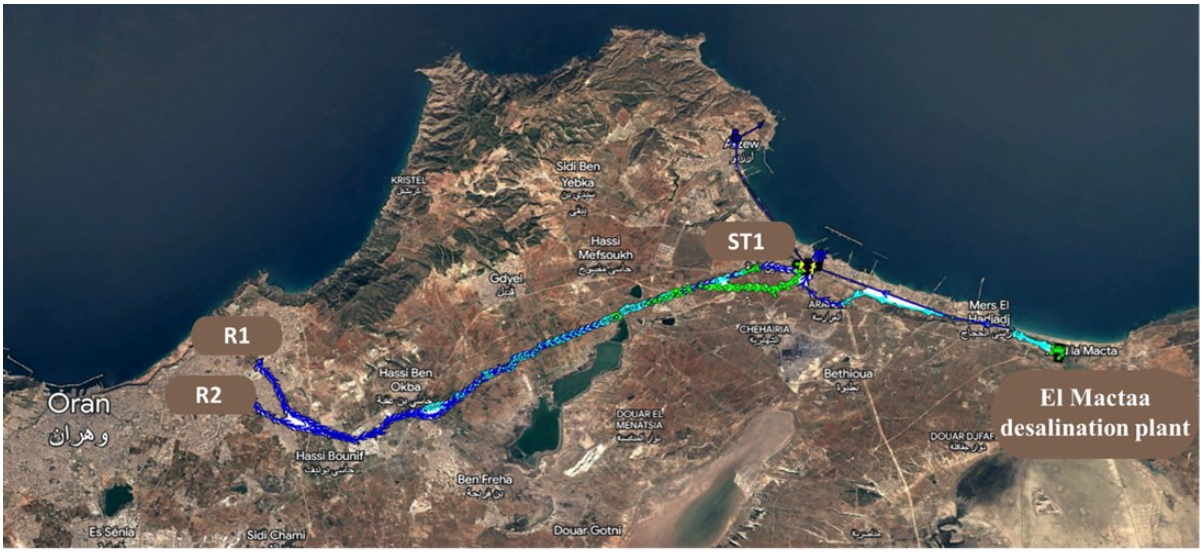


Figure 1. Case study's EPANET model

Water from ST1 is pumped to the reservoir from the water supply area R1 and R2. The flow is controlled by the water levels in the reservoirs and therefore depends on the demand at the delivery points.

The system comprises a main section consisting of two water transfer pipes of 14 and 12 km in length with diameters ranging from 4,000 to 2,000 mm. The dominant materials of the transfer pipes are mainly steel, with an average age of 50 years. Two other supply lines of 31 and 29 km in length and diameters ranging from 100 to 400 mm (average age 25 years) exist.

Desalinated water treated by reverse osmosis membranes was characterized by a high Cl^- content (500 mg/l). Reverse osmosis permeate is more corrosive when transported in steel pipes and is susceptible to corrosion if the choice of materials is inappropriate.

The average Cl_2 content is 0.6 mg/l at the outlet of the desalination plant and 0.19 mg/l at the inlet of the ST1 reservoir, whose water appears yellowish brown with an iron concentration (0.797 mg/l) exceeding the authorized standard (0.3 mg/l) with a low level of residual Cl_2.

2. 3. Chlorine Decay Kinetics

Water quality models that simulate Cl_2 degradation are very useful for managing residual chlorine. They are regularly applied for dosing optimization, location of chlorination

facilities and detect critical points where Cl_2 may decay to ineffective levels. Despite many efforts have been made in the last decades [25, 26], chlorine residual modeling remains complex. It is based on the accuracy of hydraulic models to describe the models of flow rates and flow velocities [27, 28], and on the consistency of Cl_2 decay kinetic [29]. The n^{th} order bulk decay kinetic model with respect to Cl_2 is described by the following equation:

$$\frac{dC}{dt} = -Kb \times C^n$$

Where C is the Cl_2 concentration, Kb the overall decomposition rate coefficient and ***n*** the order of the reaction with respect to Cl_2. First-order global decay is a special case of ***n***-order kinetics, widely used in the simulation of Cl_2 degradation in water supply systems [25].

2. 4. Chlorine content measurement

The most widely test is the DPD (diethyl paraphenylenediamine) pointer test [30]. The test was performed out using a disk (LOVEBOND) with a DPD detector, the cell was then placed in the disk (LOVEBOND) and the color of the test samples was compared with the color shades present on the turntable on the set.

2. 5. Determination of decay coefficients

2. 5. 1. Bulk decay coefficient Kb

EPANET models reactions in the body of water with ***n***-order kinetics, which means that the instantaneous reaction rate R (in units ofmass/volume/time) depends on the concentration according to the formula:

$$R = Kb \times C^n$$

with the bulk decay of chlorine using first-order kinetics and at the limiting chlorine concentration CL the expression becomes:

$$R = Kb(CL - C)C^{(n-1)}; \qquad CL = 0, Kb < 0, n = 1$$

Where R is the bulk rate of reaction, mass/volume/time, C the Cl_2 concentration, mass/volume and *n* the order of reaction [31].

In this study, Kb was determined assuming first-order. It is experimentally obtained by following the evolution volume coefficient of Cl_2 in a test bottle containing a water source changes over time.

Laboratory tests were carried out using the method described below (Figure 2):

1. Water sample was taken from the distribution network.
2. The water sample was then divided into 13 different sub-samples of 10 ml each and placed in closed non-reactive glass vials. They were then tested to assess the remaining Cl_2 concentration with DPD
3. The first sub-sample was tested immediately after it was taken (t0) followed by the other 12 sub-samples with an interval of 1 hour between each (t1, t2, t3...t13, see Figure 2).

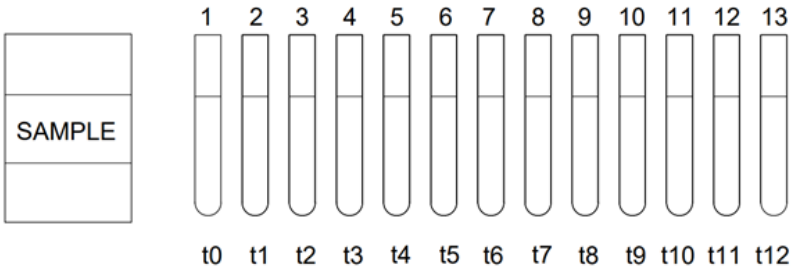


Figure 2. Testing procedure

The data of log (concentration of residual chlorine at any time CL/ initial concentration Co) versus time is illustrated in Figure 3. The bulk decay coefficient Kb = -0.083 h^{-1} which has the highest determination coefficient (R^2 =0.9106) and corresponds to -1.99 $day^{-1.}$ The negative sign refers to reduction of chlorine residuals with time.

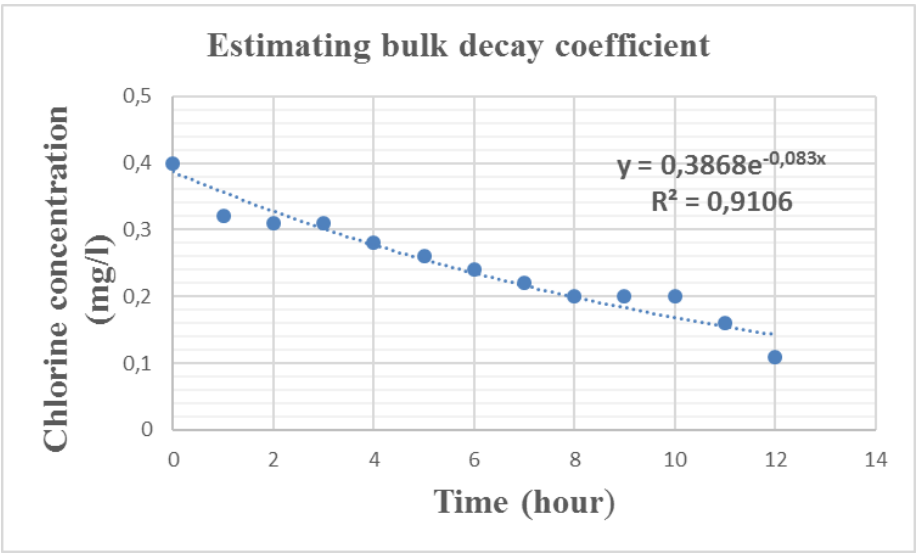


Figure 3. Chlorine decay at bulk fluid and respective first order adjustment

2. 5. 2. Wall decay coefficient Kw

The rate of water quality reactions relating at or near the pipe wall, can be considered dependent on the concentration in the bulk flow and is expressed by:

$$R = (A / V)\, Kw \times C^n$$

where Kw is the wall reaction rate coefficient and A/V the surface area per unit volume within a pipe (equal to 4 divided by the pipe diameter) [32].

The pipe wall decay coefficient was evaluated using trial and error method by assuming different wall decay rate constants and running the EPANET water quality model and determining the residual Cl_2 concentrations at various points in the water transfer network. The first order reaction model has been applied for modeling the wall decay of Cl_2.

The calibration has been performed by calculating the Square Error (MSE) between the observed and simulated Cl_2 concentrations as illustrated below [33]:

$$MinimizMSE = \frac{1}{n} \sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2$$

During calibration, residual Cl_2 measurements at various sampling points in the transfer system were used to compare the result of the field measurement with that of the model output. The sum of squares of the error between the model output and the residual Cl_2 in the field was plotted against the assumed wall degradation rate constant used in the modeling [12].

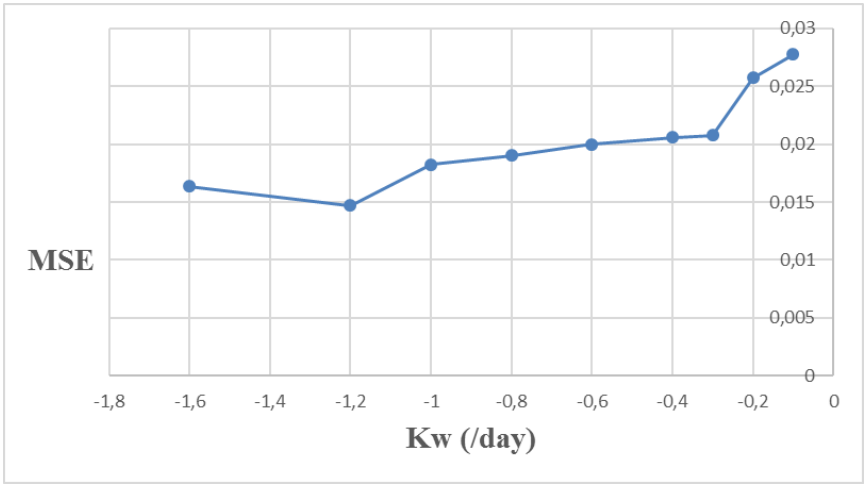


Figure 4. Plot of sum of error squares of chlorine residual plotted against wall decay coefficient used in the EPANET model

The graph showing that minimum total squared error occurs for a wall decay rate constant of 0.015 per day (Figure 4). The wall decay rate constant was used for further modeling. Finally, the value of Kw was assumed to be -1.2 (day^{-1}).

2. 6. Using EPANET

The water network map drawn with AutoCAD software was imported into the EPANET platform and the data required for the analysis was transferred digitally from the map. The network comprised two pumps located at the source of the desalination plant, three mixing tanks and a network of pipes consisting of 1247 480 knot pipes and two service tanks. The diameters, lengths and elevations of the pipelines entered in our model were acquired from the location map.

The complementary input values for water were the bulk decay coefficient and the wall decay coefficient determined in the above paragraph for the 50-year-old pipes. For 25-year-old steel pipes, Cl_2 degradation coefficients, in the bulk and in the wall, were taken from previous works and from some existing models in the literature. A value of the overall decomposition coefficient of (-1 day^{-1}) was selected while the wall decomposition coefficient was set to zero.

The roughness coefficients (Hazen-Williams) of the steel network varied between 108 and 118 depending on the diameter of the pipes. They were adjusted to fit a network made up of 50-year-old steel pipes and one that had been in service for 25 years. Concentrations of 0.6 mg/l were introduced into the desalination plant and the ST1 mixing tank.

According to the WHO, the Cl_2 concentration in a distribution network should remain between 0.2 and 0.5 mg/l [34]. Thus, two sets of simulations were carried for the two networks. The first one was carried out to set the lowest initial Cl_2 concentrations needed to maintain the required minimum concentration throughout the distribution system. The second simulation was made to find the necessary locations for re-chlorination with a rehabilitation of the old corroded pipes by modifying the roughness coefficient in order to maintain the Cl_2 concentration within the recommended limits. For Cl_2 levels, the simulation lasted 72 h for the network to reach equilibrium.

3. Results and discussions

3. 1. Chlorine decay simulation results

Simulations of Cl_2 degradation presented in EPANET can be seen for each node and link. The colors represent the different Cl_2 concentrations over the time series.

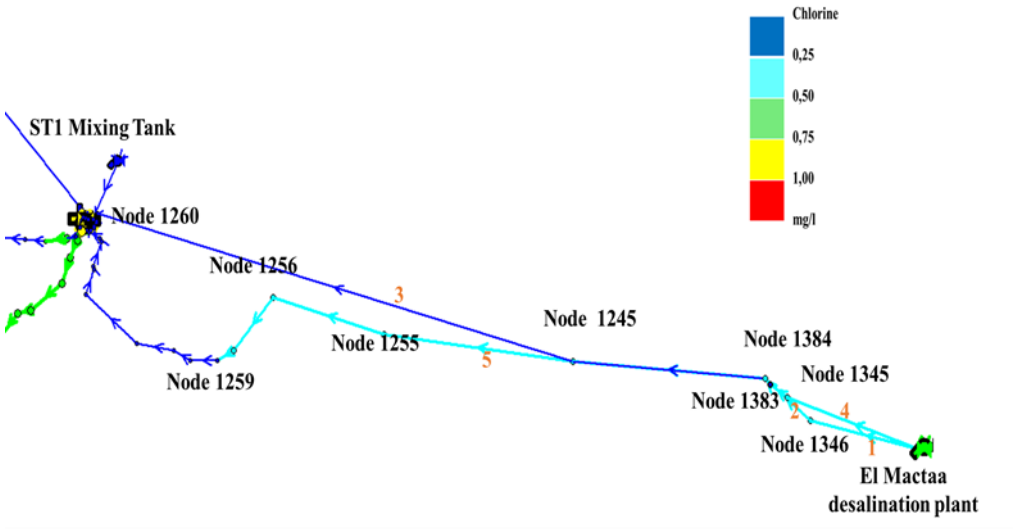


Figure 5. Transfer pipe from the source to de STI station

Figure 5 shows a degradation of Cl_2 concentrations in the two water transfer lines from the supply station to the mixing tank ST1. The Cl_2 residuals for nodes 1345, 1346, and 1383 are between 0.3 and 0.6, which are close to the power source. However, a significant decrease in Cl_2 is recorded from node 1384 to node 1260 (0.19 - 0.05 mg/l), values below the required minimum standard of 0.2 mg/l which confirms the deterioration of these pipes.

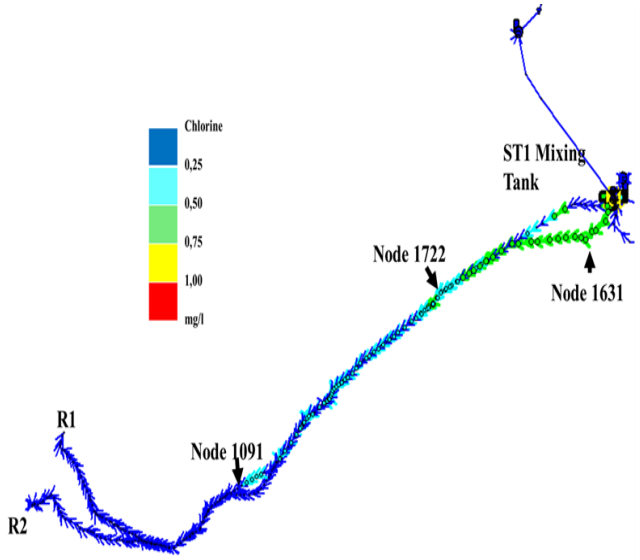


Figure 6. Transfer pipe from the ST1 mixing station to the R1 and R2 distribution tanks

Figure 6 shows that the Cl_2 concentrations between the ST1 station and the R1 and R2 reservoirs indicated by the nodes (1722 and 1091) are less than 0.5 mg/l. However, for points R1 and R2, which are close to the population, the Cl_2 concentrations are lower (< 0.2 mg/l), which are well below the standard prescribed by the World Health Organization 2022).

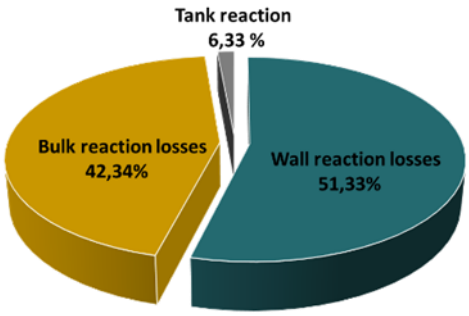


Figure 7. Cl_2 losses

It appears from Figure 7 that most of the Cl_2 decay is due to the reaction with the walls, which absorbs 51.33% of the total chlorine decay in the network, 42.34% in the bulk flow and 6.33% in the reservoir. This result may refer to the deterioration of pipes by corrosion, a factor that has the greatest effect on water quality.

It can be predicted that a hose replacement program will be more effective in reducing the overall chlorine loss in this system. The high level of decomposition in the pipes could be more serious for a longer stay in the tanks. These losses imply that the pipes are old and corroded, in particular the pipe connecting the El Mactaa desalination plant to the ST1 reservoir.

3. 2. Time series graph for age of water

Figure 8 shows the results of free Cl_2 residuals calculated in the main nodes of the two water transfer pipes from the source to the ST1 station for 72 h. As can be seen, the concentrations are less than 0.2 mg /l for nodes 1256, 1259 and 1260, which are downstream from the source.

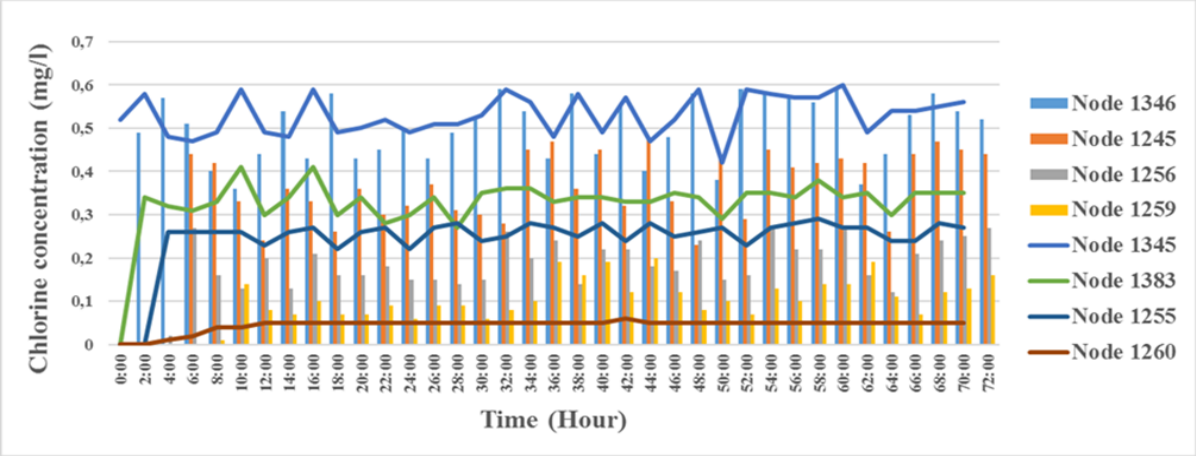


Figure 8. Cl_2 concentration of nodes in the water transfer pipes for El Maacta to ST1

This was highly expected due to the predominance of low flow velocities (0.19 m/s, Fig 9). The latter is low and allows sufficient time for global reactions to occur. It should be noted that the zones with low Cl_2 concentrations (< 0.2 mg/l) are due to the aging of the pipes, the diameter of which is no longer that of the initial installation. Over time, a community of micro-organisms develops on the walls (bio film) and the size of the corrosion nodules becomes larger and larger. This results in the slowing down of the flow at the level of the walls and the moderately high residence in the pipes of the 14 km long network.

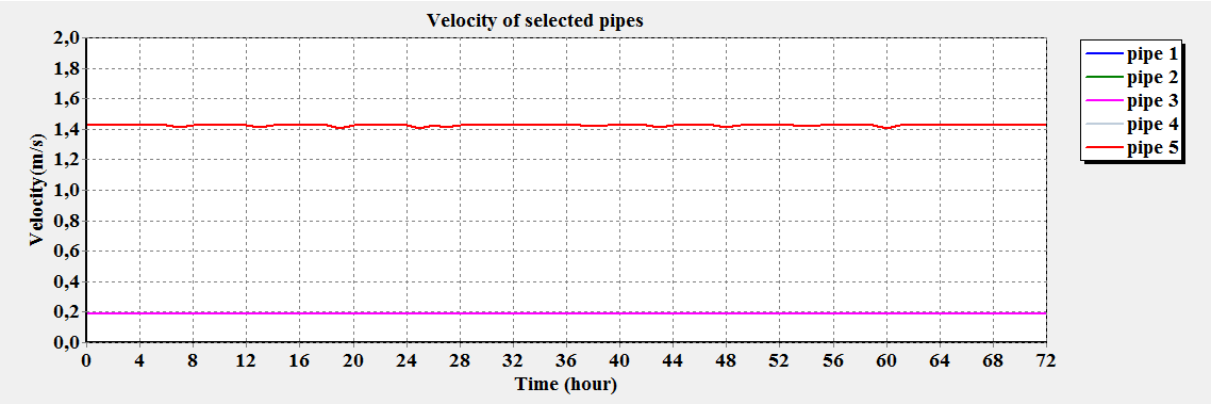


Figure 9. Flow velocity in selected pipes at 72 h of modeling

Fig 10 shows the residual Cl_2 concentrations in the lower part of the network, 32 km long, which carries water from the ST1 mixing station to the R1 and R2 distribution reservoirs. It can be seen that the remaining Cl_2 concentration degrades along the network as the residence time of the water increases (spatio-temporal influence). The water arrives at the tanks with a residual Cl_2 concentration (0.05 - 0.16 mg/l) after 36 h.

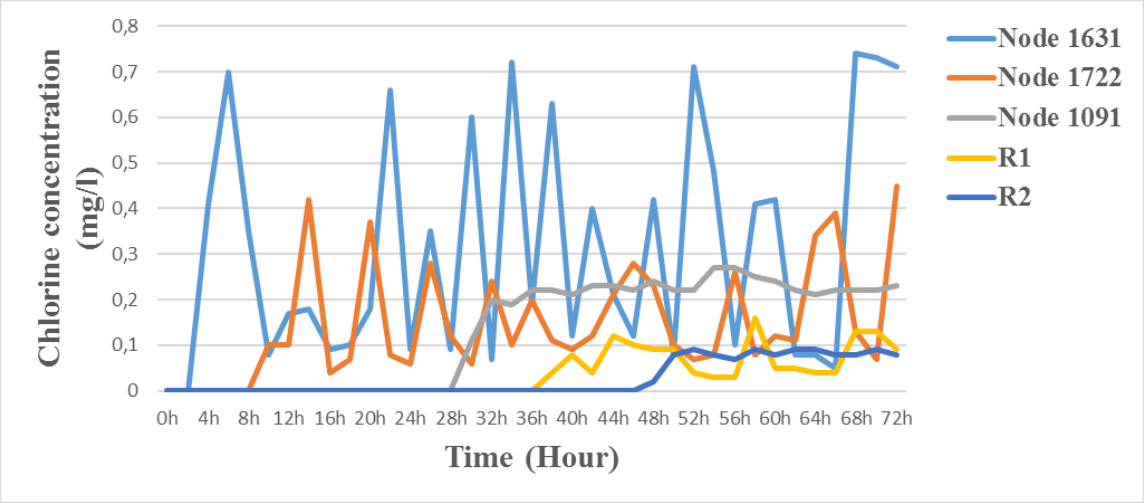


Figure 10. Cl_2 concentration of nodes in the water transfer pipes for ST1 to distribution tanks

3. 3. Performance of the numerical model

Fig11 shows the model performance where the Cl_2 concentration simulation was evaluated using the statistical analysis of observed data and simulated results; the determination coefficient of the simulated values was 0.8932. Such value, the reduction profile in free residual Cl_2 concentrations was almost reproduced, thus confirming that the developed model is valid to give results within an acceptable accuracy.

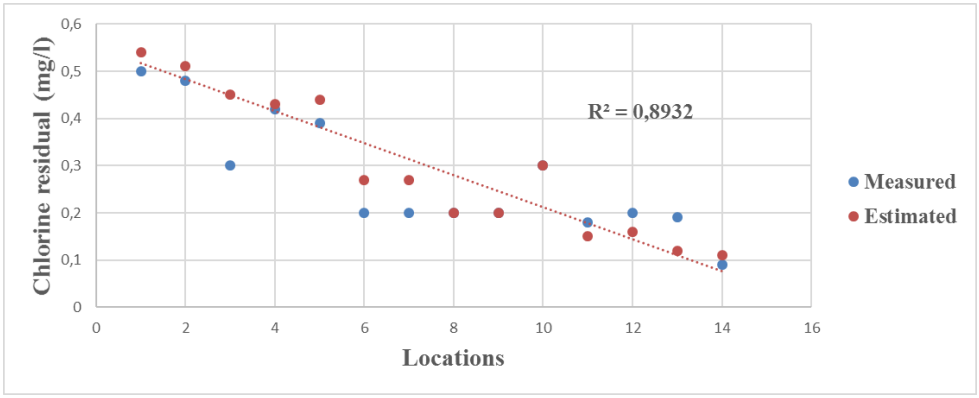


Figure 11. Comparison between measured and estimated values of Cl_2

3. 4. Re-chlorination

With EPANET, it is now possible to add Cl_2 at specific network nodes in order to maintain a sufficient concentration throughout the network. This was made possible by using make-up chlorination. This technique allows the Cl_2 concentration in the water leaving a node at a set level, which in this case was 0.8 mg/l in order to keep the Cl_2 level between the recommended levels (Fig 12).

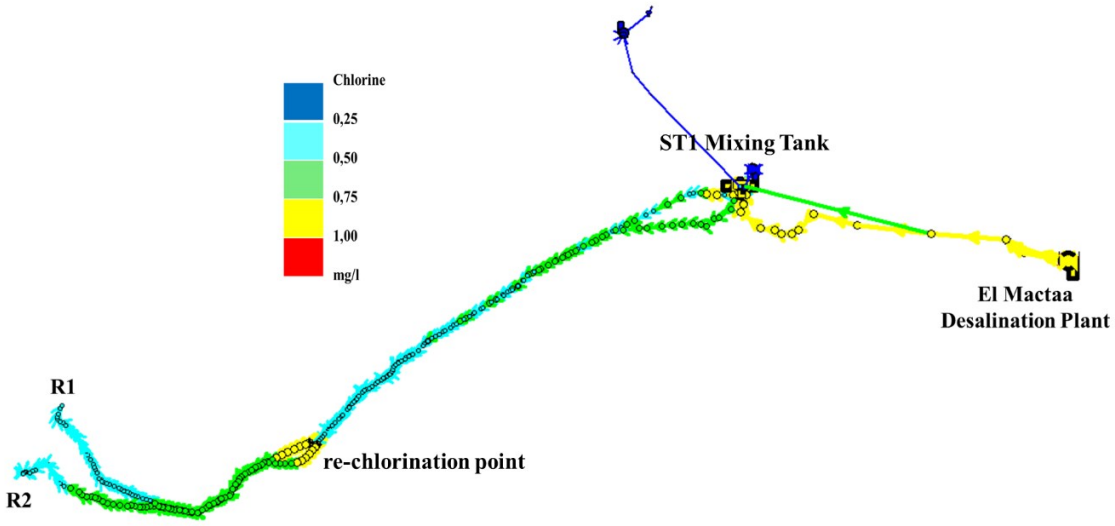


Figure 12. Re-chlorination nodes in the water transfer system representation in EPANET

Re-chlorination was necessary in the nodes closest to the distribution reservoirs R1 and R2, due to the fact that the path of the water in the pipes is very long (31 km). When the distance increases, the residual Cl_2 concentration in the water decreases. Therefore, to maintain the Cl_2 concentration, the additional points for chlorine must be added at a certain distance when its concentration has become lower than required (0.2 - 0.5 mg/l).

So to add the extra points, we need to know the exact distance before we can place the extra points, to make sure we placed at the right points. Moreover, there was a need for re-chlorination mainly in the remote nodes of the network. However, it should be noted that the furthest nodes in the network are not dead ends, but rather nodes with demand from where water is distributed further to consumers. This is why the re-chlorination in these nodes is a justifiable concentration in the network. We can thus improve the quality of the user's water supply and protect public health by controlling waterborne diseases.

From the Cl_2 concentration, contours were drawn after 72 h of simulation (Fig 13). They showed that after adjusting the re-chlorination site, renewed the pipes by modifying the roughness of the upper part of the network, which was in a critical state where the chlorine concentration is very low.

The Cl_2 concentration remains between 0.2 and 1 mg/l over the entire network water transfer, unlike the situation without re-chlorination where between 0.1 and 0.5 mg/l.

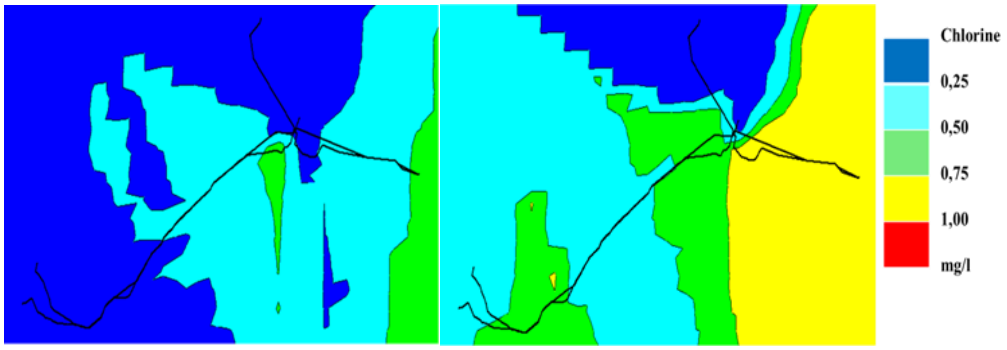


Figure 13. Left: Cl_2concentration in the network before re-chlorination.
Right: Cl_2concentration in the network after re-chlorination

4. Conclusions

Modeling of residuals chlorine in water distribution systems is an important exercise in the management and monitoring of Cl_2 concentrations at the source and the resulting residuals within water distribution systems. From the analysis of outcome data, the following conclusions can be drawn:

The complex process of Cl_2 decay in the water distribution system was successfully modelled using the EPANET software. The results gathered from extended period of simulations (72 h) include the spatial and temporal variations of the flow and residue Cl_2 concentrations at all links and nodes.

The study showed a decrease of residual Cl_2 concentrations throughout the main network from the supply source. In addition, the results revealed that nearly 51.3% of the average residual Cl_2 concentration reaction rates occurred in the pipe walls. Flow velocities below the minimum values required in 50-year-old pipes confirm the unfavorable state of this part of the network. This requires the rehabilitation of the pipes with materials suitable for the quality of the desalinated water of the plant supply. The RO permeate is more corrosive due to its high content of dissolved salts (TDS), in particular Cl^- ions (500 mg/l).

The water transmitted to the R1 and R2 distribution reservoirs has very low concentration values of around 0.11 mg/l, Prolonged ageing of the water leads to a deterioration of the water exchange in the system, thus limiting the transport of chlorine to remote parts of the network.

Re-chlorination is required at nodes in the most remote parts of the network by injecting a concentration of 0.8 mg/l of chlorine, in order to maintain the chlorine concentration within the recommended limits in the distribution network to the consumer.

It can still be confirmed that EPANET 2.0 software has a significant dependability in a water quality simulation of a water distribution systems. And most importantly, the computed results fit well together with the observed data.

References

[1] G.J. Kirmeyer, M. Friedman, K.D. Martel, P.F. Noran, D. Smith, *Journal of AWWA*., 93 (2001) 7.

[2] R.M. Cark, MC. Haught, *J. Water Resour. Plan. Manage*., 131 (2005) 3.

[3] V. Jegatheesan, G. Kastl, I. Fisher, M. Angles, *J. Chandy Water Sci Tech*., 41 (2000) 4–5.

[4] R.W. Meier, BD. Barkdoll, *Journal of Water Resources Planning and Management*., 126 (2000) 4.

[5] P. Vikesland, *Water Research*., 35 (2001) 7

[6] J.J. Vasconcelos, L.A. Rossman, W.M. Grayman, P.F. Boulos, R.M. Clark, *Journal of AWWA*., 89(1997)7.

[7] G.R. Munavalli, MSM. Kumar, Journal *of Water Resources Planning and Management*., 129 (2003) 6.

[8] L. Kiéne, W. Lu, Y. Lévi, *Water Sci Tech*., 38 (1998) 6.

[9] J. C. Powell, NB. Hallam, J.R. West, C.F. Forster, J. Simms*, Water Res*., 34 (2000) 1.

[10] R.M. Clark, M. Sivaganesan, *Journal of Water Resources Planning and Management*, 128 (2002) 2.

[11] S. Tamminen, H. Ramos, D. Covas, *Water Resour. Manage.*, 22 (2008) 1579.

[12] D.C. Gang, T.E. Clevenger, S.K. Banerji, *Journal of Environmental Informatics*., 1 (2003) 1.

[13] Y. Lu , B. Cheng , J.W. Wang , Z.P. Wang , W.S. Li, *Mat. Eng*., 43(2014)1.

[14] M.P. Ryan, DE. Williams, R.J. Chater, B.M. Hutton, D.S. McPhail, *Nature*., 415(2002) 6873.

[15] M. Son, N. Akao, N. Hara, K. Sugimoto, *J. Electrochem*., 415 (2001) 6873.

[16] H. Kim, S. Kim, J. Koo, *Procedia Eng*., 119 (2015) 1.

[17] M.A. Kahil, *International Journal of Scientific & Engineering Research*, 7 (2016)11.

[18] F. Hua, J.R. West, R.A. Barker, C.F. Forster, *Water Research*., 33 (1999) 12.

[19] L.A. Rossman, R. Brown, P. Singer, J. Nuckols, *Water Research*., 35 (2001) 14.

[20] P.E. Doshi, W.M. Grayman, D. Guastella, *Journal of the American Water Works Association*., 83 (2003) 7.

[21] World Health Organization, 2022. 4th ed. Geneva.

[22] C.M. Virlan, D. Toma, F. Stătescu, N. Marcoie, C.C. Prăjanu, *Environmental Engineering and Management Journal*., 20 (2021) 4.

[23] N.S. Muhammad, S.M. Shin, J. Abdullah, *International journal of integrated engineering*, 13 (2021) 3.

[24] E. Dineț, PhD Thesis, Technical University of Civil Engineering Bucharest, Faculty of Hydrotechnics, Bucharest, Romania, (2010)

[25] L.A. Rossman, R.M. Clark, W.M. Grayman, *Journal of Environmental Engineering*, 120 (1994) 2.

[26] F. Shang, J.G. Uber, L.A. Rossman, *Environmental Science & Technology*., 42 (2008) 3.

[27] E.J.M. Blokker, J.H. Vreeburg, S.G. Buchberger, J.C. Van Dijk, *Water Eng. Sci. Discuss*., 1 (2008).

[28] M.F.K. Pasha, K. Lansey, *Journal of hydro informatics*., 12 (2010) 1.

[29] I. Fisher, G. Kastl, A. Sathasivan, *Water Research*., 45 (2011) 16.

[30] C.G. Sanda, in *Proceedings of the 5th International Conference on Energy and Environment CIEM2011*, Bucharest, 11p.114 Andrei-Mugu, (2011).

[31] M.D. Kazantzis, *Centre for Applied Modelling in Water Engineering*, University of Adelaide, (2002).

[32] F.B. Daniel, *American water work Association*, (1996).

[33] K. Patil, N.D. Jariwala, *International Research Journal of Engineering and Technology (IRJET)*, 4 (2017) 3.

[34] D. Loureiro, MSc.Thesis. IST, Lisbon (in Portuguese) (2002).