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C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Enhancement of the free residual chlorine concentration at the ends of the water supply network: Case study of Souk Ahras city – Algeria

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Abstract

The drinking-water supply sector has mostly targeted the water-borne transmission of pathogens. The most common method employed is the chlorination of drinking-water at treatment plants and in the distribution systems. In Algeria, the use of chlorine in drinking water treatment is a widespread practice. To enhance the concentration of the residual chlorine in the public water-supply system of a part of Souk Ahras city (Faubourg) (Algeria) known by its low concentration of the free residual chlorine (according to the water utility – Algérienne des Eaux: ADE investigation) especially at the point of use, practical steps were carried out. The method is a combination between numerical simulation using EPANET2 software and field measurements. Using statistical analysis the hydraulic model was calibrated and the observed values were very closer to the simulated results. The concentration was improved throughout the network after the injection of the appropriate dose.

Key words: *Algeria, drinking water, EPANET2, residual chlorine decay, Souk Ahras city, water supply network*

INTRODUCTION

All people, whatever their stage of development and their social and economic conditions, have the right to have access to an adequate supply of safe drinking water [WHO 2003]. Disease statistics are stark and tragic: 80% of illness and death in the developing world is water-related; half of the world's hospital beds are occupied by people with water-related diseases; diarrhea and malaria are by far the largest causes of mortality in children <5 years of age (34%) in Africa; and the number of deaths from water-related disease approaches 5 million annually, most of them children. These deaths, most of which are preventable, largely occur among the estimated 1.2 billion people worldwide [BATTERMAN *et al.* 2009; WHO 2005].

The main goal of treatment of drinking water is produce water that meet national and WHO standards [BOUSLAH *et al.* 2017; Quebec government 2002]. Disinfection of water helps, in fact, significantly reduces pathogenic microorganisms that are responsible for water-borne diseases such as typhoid fever, hepatitis, cholera, bacillary dysentery [CRITTENDEN *et al.* 2005].

CAIRNCROSS *et al.* [1996] suggest that a distinction should also be made between transmissions in two different physical domains: the public domain (outside the household) and the domestic domain (inside the household). A desired health benefit would only be obtained if transmission of pathogens in both the domains is prevented [PETER *et al.* 2003]. Most water-supply systems in the developing countries are not working according to design, which likely allow the entrance of wastewater. The drinking-water supply sector has mostly targeted the water-borne transmission of pathogens. The water should be protected against the possible pollutions by using disinfectant residual. Disinfectant residual should be maintained in the distribution system to protect it from recontamination.

Chlorine is used worldwide as a disinfectant residual to counteract microbial contamination and proliferation in drinking water supply systems (at treatment plants and in the distribution systems) [DHAIUADI *et al.* 2015; GALAL 1996; NILUFAR *et al.* 2016; 2017]. Chlorine's residual potential not only prevents potential regrowth of microorganisms throughout water distribution systems, but also provides subsidiary protection against pathogen intrusion [KIM *et al.* 2014; WHITE 1992]. Its popularity arises from its high oxidation potential, relatively low cost, high disinfection efficiency, and ease of use.

Several studies have focused on chlorine decay and factors affecting wall decay, such as the pipe material, flow velocity, water quality, and service age of the pipe [AL-JASSER 2007; AL-OMARI, CHAUDHRY 2001; DIGIANO, ZHANG 2005; FISHER *et al.* 2011a, b; HALLAM *et al.* 2002; ISABEL *et al.* 2000; MONTEIRO *et al.* 2017; RAMOS *et al.* 2010; VASCONCELOS *et al.* 1995] and so on.

This paper aims to propose a method to improve and keep the concentration of the free residual chlorine at the ends of the water distribution network at 0.3 mg·dm^{-3} or greater [POWELL *et al.* 2000; RODRIGUEZ, SERODES 2001]. Most individuals are able to taste chlorine or its by-products (e.g. chloramines) at concentrations below 5 mg·dm^{-3}, and some at levels as low as 0.3 mg·dm^{-3} [WHO 2003]. The method is a combination between numerical simulation where the analysis software used was EPANET2 [ROSSMAN 2000], and field measurements. Series of sampling through the network were done to assess the free chlorine concentration in different points. The properly solution for the best concentration of the free residual chlorine throughout the network and especially at the ends was proposed.

METHODS

STUDY AREA

The case study was carried out in urban neighborhood – Faubourg – it lies in Souk-Ahras, North--East of Algeria as shown the Figure 1. The area is supplied from two tanks with a capacity of 400 m^3 each. It is an old urban area that has reached saturation. This area is small; it includes 398 domestic subscribers, 15 government buildings and 34 small businesses. The network is of 4.5 km long, it consists mainly of PVC, pipe diameter range from 63 to 160 mm.

DATA COLLECTION FOR HYDRAULIC MODEL

The analysis software used was EPANET2 [ROSSMAN 2000], a program that models water flow including mixing and separating of water flows in water distribution pipeline network and provides time series data analysis. Reactions can occur both within bulk flow and with pipe wall.

BULK REACTIONS

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

Fig. 1. Overview of the water distribution network of the Faubourg city/Souk Ahras, Algeria; source: own elaboration

$$R = K_b\, C^n \qquad (1)$$

Where: K_b = the reaction constant (concentration raised to the power of $(1 - n)$ divided by time), C = the reactant concentration (mass/volume).

It is positive for growth reactions and negative for decay reactions:

$$R = K_b\,(C_L - C)\,C^{(n-1)} \qquad (2)$$

EPANET can also consider reaction where a limiting concentration exists on the ultimate growth or loss of the substance. In this case the rate expression for growth reaction becomes:

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

$$R = K_b(C_L - C)\,C^{(n-1)},\ n > 0,\ K_b < 0 \qquad (4)$$

Where: C_L = the limiting concentration.

The three parameters (C, K_b and C_L) are used to characterize the bulk reaction rate.

WALL REACTIONS

The rate of the reaction occurred near the pipe wall can be considered to be dependent of the concentration of the bulk flow, using the following expression:

$$R = (A/V)K_w C^n \qquad (5)$$

The first factor is represented by a mass transfer coefficient which depends on the molecular diffusivity of the traced substance. Chlorine diffusivity is equal to $1.44\cdot10^{-5}$ $cm^2\cdot s^{-1}$ in water at 25°C, where R is the rate of reaction (mass/volume/time), A/V is the surface area per unit volume within the pipe which equals (4/pipe diameter), C is the chlorine concentration (mass/volume), n is the kinetics order = 0 or 1, and K_w is the wall reaction rate coefficient (length /time for $n = 1$ and mass/area/time for $n = 0$).

The EPANET is automatically adjusting, to account for mass transfer between the bulk flow and the wall, basing on the molecular diffusivity of reactant under study and the Reynolds number of the flow. In case of zero-order kinetics, which is recommended by the program manuals, the wall reaction rate cannot be greater than the mass transfer rate, resulting in Equation (6):

$$R = MIN\,(k_w, k_f C)\,(2/(D/2)) \qquad (6)$$

Where: R = the rate of reaction (mass/volume/time), k_w = the wall reaction rate constant (mass/area/time), k_f = the mass transfer coefficient (length/time), C = the chlorine concentration (mass/volume), D = the pipe diameter, MIN – minimum value.

A hydraulic model analysis has to be performed previously in order to provide the resulting flow distribution to the water quality module to transport the chlorine through the system.

For a precise forecasting of the real water distribution system behaviour, many steps were carried out (Fig. 2):

- an electromagnetic flow meter was mounted in the tank outlet to record the flow variation and predict the pattern of water use of the city;
- a pressure recorder was put in down point to check the consistency of flow pattern measurement;
- the water level in the tank was also measured to check the consistency of the output flow and pressure;
- the water supply was maintained during the measurement operation.

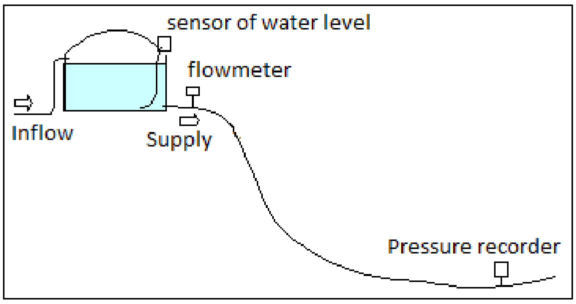

Fig. 2. Equipments used for data acquisition; source: own elaboration

A distribution network model was developed using the location and pipe line profile and demand data obtained from the pipeline information system that was organized using GIS. The results are reported in the Figure 3.

The results in the Figure 3 are explicit; a minimum flow rate was recorded in night time, which corresponded to leakage flow rate; it is about 65 $m^3\cdot h^{-1}$. The rapid consumption recorded in the first times was used to fuel the dwelling tanks. The pressure and water level in the tank behave adequately with the flow consumption, where the pressure varied oppositely with the flow.

HYDRAULIC MODEL CALIBRATION AND VALIDATION

The accuracy of water quality simulation relies on the hydraulic simulation results. The flow and pressure data of these control points, even the roughness of the pipes allow the hydraulic adjustment of the model. Once the hydraulic model is available the chlorine information is used for the chlorine model calibration, although there are no pre-established standards to calibrate a water quality model, hydraulic calibration followed by calibration of the chlorine decay model from field data is considered essential [MONTEIRO *et al.* 2014; YANG *et al.* 2007]. If the leakage flow recorded in the Figure 3 which is about 40% of the total distributed flow was taken into the account (due to the old pipes in many parts of the network) the following results were obtained.

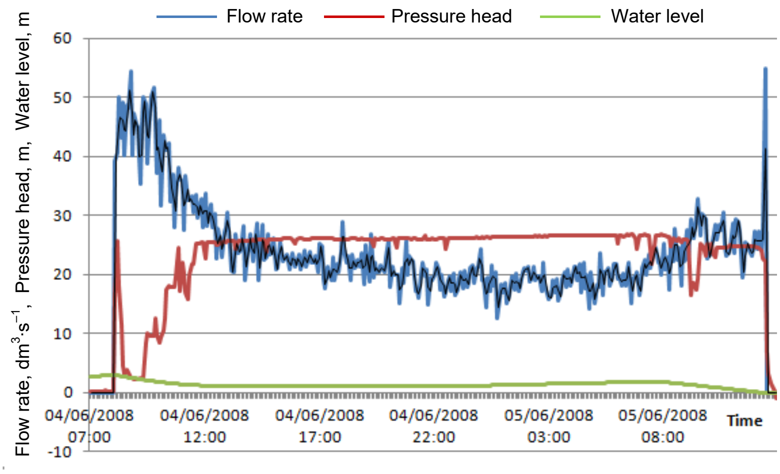

Fig. 3. Measured data for the examined distribution network; source: own study

Table 1. Calibration statistics for flow (n = 24)

Specification	Mean flow	Standard deviation	Standard error of the mean
Observed	20.32	2.241	0.458
Computed (EPANET)	21.74	2.943	0.601
Root mean square error	0.301		
Correlation coefficient	0.974		

Source: own study.

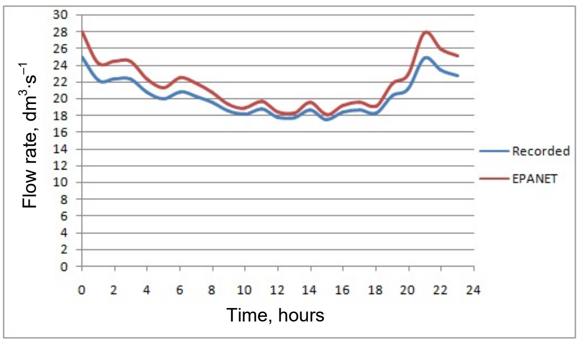

Fig. 4. Comparison between simulated and recorded flow; source: own study

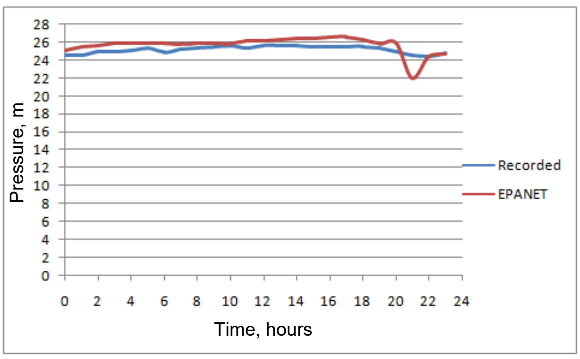

Fig. 5. Comparison between simulated and recorded pressure; source: own study

According to the statistics of Table 1 and the results presented in the Figures 4 and 5, the hydraulic model is calibrated.

RESULTS AND DISCUSSION

CHLORINE DECAY MODEL

Many efforts have been made in the last decades, the modeling of chlorine residuals is still complex, as it relies on the accuracy of hydraulic models to describe flows and flow velocities [ROSSMAN *et al.* 1994; SHANG *et al.* 2008].

Generally, the simulation tools of water quality impose a model for chlorine decay using first or second order model even EPANET [AL-JASSER 2007; FISHER *et al.* 2017; HAESTAD *et al.* 2003; NAGATANI *et al.* 2008; NAGWAN *et al.* 2013; OZDEMIR, UCAK 2002; VIEIRA *et al.* 2004]. For the chlorine bulk decay model, commonly the first order reaction is used [VASCONCELOS *et al.* 1997]; while several studies have demonstrated that a second order reaction can provide a more accurate prediction of chlorine concentrations [BOCCELLI *et al.* 2003; CLARK 1998; FISHER *et al.* 2012; SPEIGHT *et al.* 2009]. For EPANET a trial-error process was used to find the values for the best possible correlation. These are respectively 0.02 $dm^3 \cdot h^{-1}$ for K_b (the bulk decay rate coefficient) and 0.003 $dm^3 \cdot h^{-1}$ for K_w (the wall reaction rate coefficient), this later is at least 10 times lower than the values found in the literature, where POWELL *et al.* [2000] found that the K_b value ranged from 0.02 to 0.74 $dm^3 \cdot h^{-1}$, whereas HALLAM *et al.* [2002] showed that the value of K_w usually varies between 0 and 1.56 $dm^3 \cdot h^{-1}$ in practice cases, this can be explain by the materials types of the pipes where the most theme are in PVC (for a new pipes in PVC the values of K_w is negligible [POWELL *et al.* 2004]).

CHLORINE MODEL CALIBRATION AND VALIDATION

A several measurements in different points were used for the performance of the numerical model, which are: the water tank, at the middle of the network and customer's tap. The calibration results were reported in the Figure 6.

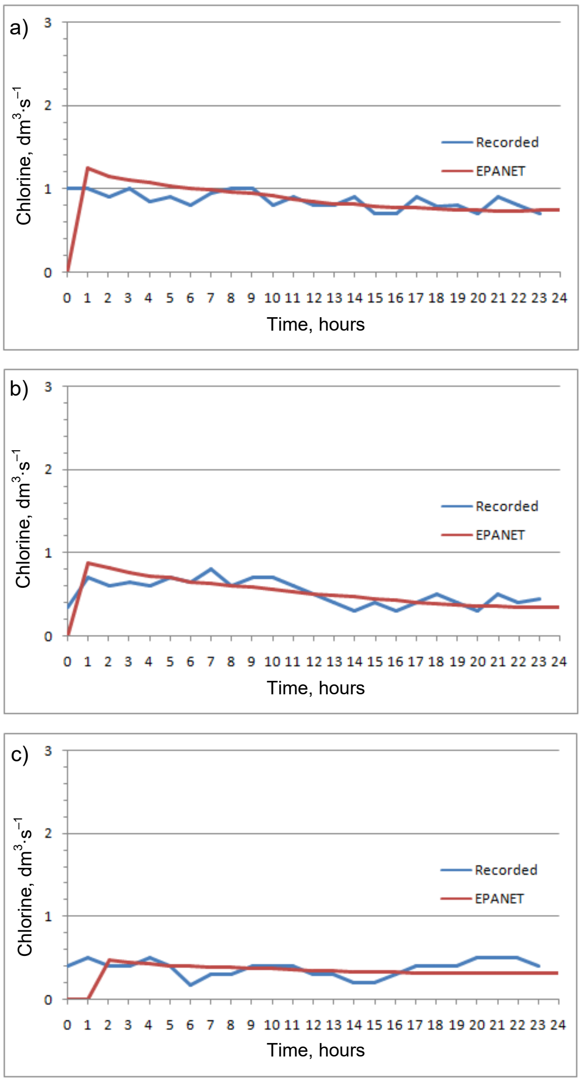

Fig. 6. Comparison between simulated and recorded chlorine concentration; a) at water tank, b) at middle of the network, c) at customer's tap; source: own study

From the Figure 6 it is noteworthy that the measured values are close to the values simulated by the EPANET model, we can draw that the model is well calibrated for free residual chlorine. The gradually decrease of the chlorine along its path means that there is a consumption of the chlorine in the network (reaction between chlorine and natural organic matter (NOM) – bulk decay).

CHLORINE DECAY AT THE END OF NET WORK

After the calibration of the hydraulic and water quality models, EPANET enable to simulate and by the way to enhance the weak points of residual chlorine concentration through the network. An amount of 0.7 mg·dm^{-3} was injected in the water tank, the simulation tool provide the following result: 9 points with low concentration in residual chlorine (<0.3 mg·dm^{-3}) were identified at the ends of the network, in order to achieve the proper concentration of the residual chlorine in these weak points, a dose of 1 mg·dm^{-3} was added to the reservoir, the results were reported in the Figure 7.

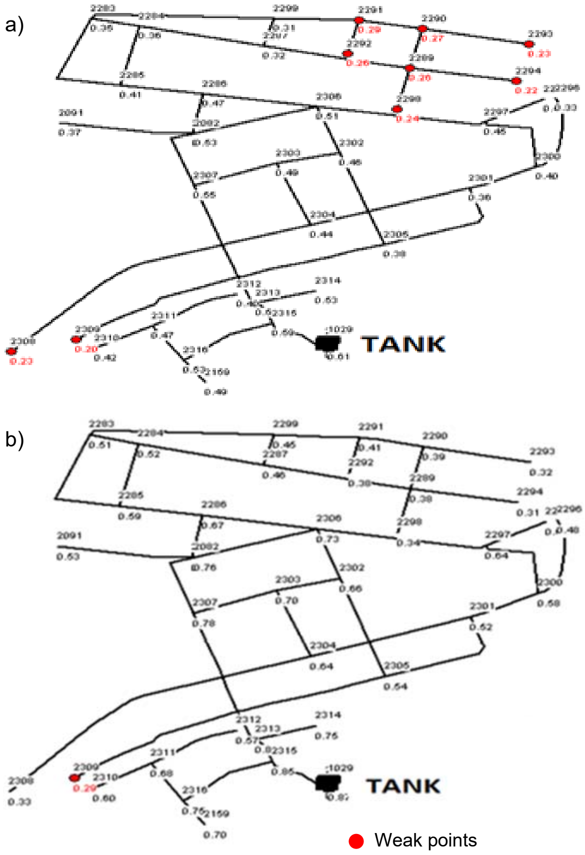

Fig. 7. Residual chlorine concentration at the far ends of the network at different doses; a) dose = 0.7 mg·dm^{-3}; b) dose = 1 mg·dm^{-3}; source: own study

As shown the Figure 7, the situation is match better than the precedent one, where the overall of the network ends have an appropriate concentration of residual chlorine, except one (1) point where the concentration is closer to 0.3 mg·dm^{-3} (= 0.29 mg·dm^{-3}).

CONCLUSIONS

The concentration of the free residual chlorine at the beginning of water distribution network is higher than that in the rest of the network. An efficient method was proposed for the enhancement of the residual chlorine concentration in the water supply network, especially at the ends points of use. Numerical tool combined with field measurements were used. Based on statistics evaluation the model was calibrated and the simulation tool became enable to predict the behaviour of the chlorine decay in the network. The concentration was matched throughout the network after the injection of the appropriate dose (1 mg·dm^{-3} instead 0.7 mg·dm^{-3}). Updates of the numerical tool are of capital importance, a several parameters could be changed during time like the roughness and flow loses.

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Zwiększanie stężenia wolnego chloru na końcach sieci wodociągowej: Przykład miasta Souk Ahras w Algierii

STRESZCZENIE

Instytucje zaopatrzenia w wodę pitną zwracają szczególną uwagę na obecne w wodzie patogeny. Najczęściej stosowaną metodą usuwania patogenów jest chlorowanie wody w stacjach uzdatniania i w systemie dystrybucji. W Algierii użycie chloru do uzdatniania wody jest powszechnie stosowaną praktyką. Podjęto praktyczne działania, aby zwiększyć stężenie pozostałego chloru w systemie publicznego zaopatrzenia w wodę części miasta Souk Ahras (Faubourg) w Algierii znanym z małego stężenia wolnego chloru (wg badań Algérienne des Eaux: ADE), szczególnie w miejscu odbioru wody. Zastosowana metoda jest kombinacją symulacji za pomocą programu EPANET2 i pomiarów terenowych. Model hydrauliczny był kalibrowany z wykorzystaniem analizy statystycznej, a obserwowane wartości były bardzo bliskie wynikom symulacji. Korzystniejsze stężenie chloru w całej sieci uzyskano po wprowadzeniu odpowiedniej jego dawki.

Słowa kluczowe: *Algieria, EPANET2, miasto Souk Ahras, rozkład pozostałego chloru, sieć wodociągowa, woda pitna*