

EVALUATION OF THE MODELLING OF CHLORINE RESIDUAL CONCENTRATION IN AN AUTOMATED TREATMENT PLANT OF A WATER DISTRIBUTION SYSTEM

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Abstract

This study examined the modelling of chlorine residual concentration over time in an automated treatment plant of municipal water distribution network. Preservation of residual chlorine concentration throughout water distribution network within the established maximum and minimum allowable chlorine levels is one of the most important challenges that face water suppliers. The simulation of the decay of chlorine residual does not only provide potable water to the consumers, but also helps to prolong and increase the life span of water treatment facilities as well as prevent waterborne related diseases. Water samples were collected from the industrial area (I.A.) of the water distribution networks in West Ogunu, Delta State and taken to SHELL Laboratory in Port Harcourt in clean iced parked containers for the physical, chemical and microbiological tests and analyses. The test results, which showed parameters of concern (low pH and high iron), were later treated to conform to the recommended water quality standards. The residual chlorine at the storage reservoir and various nodes were measured with a digital chlorine telemeter. The hydraulic data, which were obtained from the company that construct and manage the water facilities, were fed into the network of EPANET software window to run the water quality simulation for the residual chlorines and reaction rate of water in the main streams of the pipes. Residual chlorines were observed physically to validate the model results. From the results of the treated water, good water quality were observed with colour at 5.56 and 5.00Hazen, turbidity 0.02Ntu, pH 8.22 at 25⁰C, and iron less than 0.001mg/L. The values of the summation of the simulated chlorine residual along the pipes(p) were 23.83mg/l, 23.80 mg/l, 23.66 mg/l, 23.66 mg/l and 23.66 mg/l for pipes P2, P1, P3, P4 and P5 respectively. This shows that the bulk reactions were higher in the five pipes in the order of their obtained values. These results implied that the reaction rates depend on the mixing and velocities of flow in the pipes. The longer the simulation period, the more the chlorine is decaying.

Keywords: Water Distribution Network, Water Quality, Water Quality Modelling, Chlorine Decay Kinetics, Epanet software

1.0. INTRODUCTION

Water is essential for the existence of animals, human race and plants. It is the essence of life and human dignity; all life on earth depends on it. It is not only life-giving, but it can also be a life threatening, if it is contaminated. If it is not kept clean and potable, it can also be detrimental [1,2,3].

The need to ensure adequate provision of potable water over the years to Nigerians in rural, semi-urban and urban communities had been a challenge in spite of the abundance of water resources. It was observed that most water borne diseases or outbreaks that have occurred in the recent years were caused by the inadequate control of water treatment facilities, contamination of untreated supplies, storage tanks, distribution system, interrupted treatment and ceasing attention to maintenance and operating details [4]. The quality of treated water after leaving a treatment plant deteriorates as water

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travels through a water distribution network. If the water distribution network is not well designed, operated and maintained, the microbial quality of the water would be compromised adding to ingress of contaminants. Besides, the disinfectant residual concentrations within a locally predetermined range would not be maintained and the transit time would not be minimized [4].

Decay of chlorine residual, caused by reacting in the bulk of flow and at walls of network elements, may lead to disappearance of disinfectant at network extremities and hence increasing the probability of microbiological contamination of drinking water [5,6]. However, increasing the chlorine concentration during treatment process can lead to corrosion of water pipes and health hazards caused by increasing concentrations of disinfection by-products (DBPs), especially trihalomethanes (THMs) and haloacetic acids (HAA5), which are claimed to be carcinogenic substances [2,7,8]. Therefore, one of the most important challenges that face water suppliers is to preserve residual chlorine concentration throughout the distribution network within the established maximum and minimum allowable chlorine levels [9].

Typically, chlorine is added near the final stages of drinking water treatment plants to disinfect them. A certain residual amount is added to disinfect against any pathogens found in the inside walls of the distribution system piping [10]. This residual chlorine is consumed on its journey through the piping system and the chlorine concentration should be at low concentrations at the point of consumption. This is difficult to manage, due to the complexities of the distribution system and the randomness at which consumers use water [11,12]. However, excessive amounts of chlorine are harmful to human health, while chlorine concentrations too low to effectively kill bacteria and viruses will not properly disinfect the water [13]. Knowledge of residual chlorine concentration at various locations in drinking water distribution system is essential final check to the quality of water supplied to the consumers [14]. In addition, disinfection by-products have been proven carcinogenic [15].

The objectives of this study are to: determine the water quality of the water distribution network; monitor and ascertain the chlorine residual over time in the municipal water distribution network for an automated water treatment plant; model the bulk fluid reactions with zero and n-th order kinetic by simulating the movement, mixing and transformation of chemical or biochemical water quality parameters that may be considered to be completely diluted in the water carried along the distribution networks.

2.0 THEORETICAL ANALYSIS

2.1 Water Distribution System

The major goal of a municipal water distribution system is to deliver high quality water to users distributed throughout a community. These systems consist of pumps, pipes, fittings, tanks, reservoirs, and valves, all of which are the appurtenances in the service area of the distribution network. To deliver water to consumers, these systems pump the water under pressure through a series of pipes. The pipe networks are planned and built in order to provide water of sufficient quantity and quality, and under a desirable pressure. Historically, water distribution systems have also been designed to carry high flows needed for residential, industrial, and commercial uses as well as fire-fighting. As a result, the typical pipe network produces longer residence times that can erode water quality, and thus it is a challenge to design for both purposes [5]. Water distribution system account for 40-70% of the total cost of water supply scheme [16,17], hence its proper planning, design, operation and layout is of great importance.

2.2 Modelling of water quality in Water Distribution Network

Water quality constitutes the physical, chemical and biological characteristics of water. It is most frequently used by reference to a set of standards against which compliance can be assessed. The most common standards used to assess water quality relate to drinking water, safety of human contact and for the health of ecosystems. It is a simple property that shows whether water is polluted or not. Because of inadequate management, water quality is deteriorating throughout a large part of the world [18].

In modelling water quality in water distribution networks, the essential aspects are transport, mixing, production and decay. Sediment behaviour, and thus discolouration risk, in a water distribution system (WDS) is strongly related to hydraulics [19,20]. The spread of dissolved contaminants through the water distribution networks is strongly related to the flows through the network [21].

Drinking water starts its journey within catchments, and is subsequently purified at treatment plants and delivered through distribution systems. The water quality generally deteriorates while it passes through the catchment. However, the subsequent treatment processes produce water of high quality. But, within the distribution system, the quality of the water generally deteriorates again. A water quality model for a distribution system should be coupled with a hydraulic model to adequately describe the microbiology and chemistry of the system [22].

In the last few decades, the worldwide awareness about risks arising from degradation of water quality while traveling through transmission and distribution systems increased due to waterborne diseases outbreaks [23]. Chlorination became the

most common disinfection method that is usually used to disinfect drinking water, due to its germicidal potency, economy and efficiency. Chlorine disinfectants produce a lasting residual that prevent re-growth of microorganisms that managed escaping from treatment process or entered the distribution system due to external contamination [9].

During the past decades, many studies concerning developing new chlorine decay simulation techniques, modifying existing mathematical models, studying factors affecting chlorine decay, and applying decay models on existing water distribution models were conducted either in the laboratory or in the field. In the first place, chlorine decay was modelled by a first-order kinetic equation [5], which is included in most of water quality simulation programmes. Other models were developed to upgrade the simplicity of the first-order kinetic model, such as a parallel first-order kinetic model, a limited first-order kinetic model, as second-order kinetic model, and an nth order kinetic model [5, 9]. A two-dimensional steady-state transport equation was developed accounting for the bulk decay, including axial convection and radial diffusion, and wall decay [24].

A computer model called DYNAQ was developed based on the two-dimensional chlorine decay equation to track and evaluate chlorine decay in distribution systems [5]. EPANET simulating results improved by taking the effect of water prosperities, such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand(COD), TOC, Fe²⁺, and temperature, into consideration [6]. Bulk decay was approved to be affected by many factors, such as DOC, TOC, pH, temperature, flow velocity, and initial chlorine concentration (C₀), iron [5,25,26,27,28]. Wall decay was approved to be significantly affected by the thickness of the formed biofilm on the inner pipe wall which is, consequently, a function of pipe material, pipe service age, flow velocity, DOC, chlorine dosage, DO, and pH [6,7,27,28,29,30,31].

2.3. Chlorine Decay Kinetics

Research indicates that the quality of water in water distribution systems (WDSs) may deteriorate due to several changes that take place during transport of water in the distribution system [32]. These changes include: loss of disinfection residuals that can lead to bacterial re-growth [33]; formation of potentially carcinogenic disinfection by-products (DBPs) due to the reactions of the disinfectant with organic and inorganic substances in water [34]; development of taste and odour; and corrosion. The water quality concerns in combination with the rigorous standards set by regulatory bodies have pressed water companies to depend increasingly on models in the quest to understand and control the dynamics of water quality processes.

The loss of residual chlorine through the water distribution system occurs because of two main reasons [5, 35], first is the external contamination, which happens often during pipelines breaks and maintenance operations, and second is the natural decay, which is divided into the following three mechanisms [6,29, 35]: bulk reactions with chemical substances present in treated water; wall reactions with the material of the network elements; and natural evaporation in storage tanks. Chlorine decay theory [5,25,27,35, 36, 37], which is included in EPANET 2.0 manuals and used during software quality analysis, account for both bulk and wall reactions as follows:

2.3.1. Bulk Reactions

Decaying of a substance while moving through a pipe can be generally described as an nth power function of concentration as shown in Equation(1):

$$r = k_b C^n \quad (1)$$

where:

r = the rate of reaction (mass/volume/time);

k_b = the reaction constant (concentration raised to the power of [1-n] divided by time); and

C = the reactant concentration (mass/volume), and n is the reaction order.

Chlorine decay is adequately modelled by a simple first-order reaction (n = 1, k_b < 0), according to the program help manuals, and hence the equation becomes [38]:

$$r = k_b C \quad (2)$$

where:

r = the rate of reaction (mass/volume/time);

k_b = the reaction constant (1/ time); and

C = the reactant concentration (mass/volume).

2.3.2. Wall Reactions

The rate of pipe wall reaction is influenced by the mass transfer between the bulk of flow and the wall interface, and the amount of wall area available for reaction. 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 1.44x10⁻⁵ cm²/s in water at 25°C. The amount of wall area available for reaction is equal to the surface area per unit volume, which equals to 2 divided by the pipe radius (P_r).

The rate of reactant reactions that happen in the pipe walls is related to reactant's concentration in the bulk of flow as shown by (3) [38]:

$$R = (A/V) k_w C^n \quad (3)$$

where:

- R = the rate of reaction (mass/volume/time);
- (A/V) = the surface area per unit volume within the pipe which equals (4/pipe diameter);
- C = the chlorine concentration (mass/volume);
- n = the kinetics order = 0 or 1; and
- k_w = the wall reaction rate coefficient (length /time for n = 1 and mass/area/time for n = 0).

The EPANET software 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 in the program manuals, the wall reaction rate cannot be greater than the mass transfer rate, resulting in Equation (4) [38]:

$$r = \text{MIN} (k_w, k_f C) (2/R) \tag{4}$$

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);
- R =the pipe radius (length).

2.3.3 Water Quality Modelling with EPANET Software

Several conventional mathematical models such as dynamic models, Eulerian finite models, Eulerian discrete models, Lagrangian time driven models, Lagrangian event driven models, SCADA models and Trend analysis models are available to simulate water quality processes in Water Distribution Network Systems [39]. All these models require long computational time, very complex and difficult to model large networks [39]. Trend analysis determines whether the measured values of a water quality variable increase or decrease during a time period. It would be useful to describe the amount or rate of that change, in terms of changes in some central value of the distribution such as mean or median [40,41]. An adaptation of the Kendall non-parametric test to detect trends in seasonally varying water quality time series was suggested by [40]; this is often referred to as the seasonal Kendall’s test.

EPANET, a hydraulic and water quality model, developed by the U.S. Environmental Protection Agency's Water Supply and Water Resources Division is most widely used computer model for modelling water quality analysis in water distribution networks. The model enables simulation of non-reactive tracer materials, chlorine decay, disinfection byproducts (DBPs) growth and water age [42]. Primarily, EPANET is a single species model and limited to model the dynamics of chlorine residual, trihalomethane (THM) or water age that does not permit simulation of multiple interacting species [43].

EPANET models a water distribution system as a collection of links connected to nodes. The links represent pipes, pumps, and control valves [42]. It performs extended-period simulation of hydraulic and water-quality behavior within pressurized pipe networks and is designed to be a research tool that improves our understanding of the movement and fate of drinking-water constituents within distribution systems. The basic assumptions present in this type of models usually include complete instantaneous mixing at junction nodes and the absence of longitudinal mixing effects in pipes [21,39].

At each moment in time, given any two or more pipes that contribute to a particular node and that carry different concentrations of the same parameter, the concentration of that parameter in all pipes leaving the node is homogeneous and corresponds to the complete mix of the contributing concentrations in the proportion of the respective flows. The non-steady advection-dispersion-reaction process in a pipe flowing full is described by the following partial differential equation [44]:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = D \frac{\partial^2 C}{\partial x^2} - K C \tag{5}$$

where:

- C = constituent concentration (mass/volume);
- u = cross-sectional average flow velocity (length / time);
- D = dispersion coefficient (length / time);
- K = first order decay constant (1 / time);
- x = distance along pipe (length unit); and
- t = time

The following nodal equivalent of equation (6) is thus obtained:

$$\sum_{j=1}^m \left(\frac{dx_j}{2} A_j \right) \frac{\partial C}{\partial t} = \sum_{j=1}^m \left(A_j D_j \frac{\partial C}{\partial x} + Q_j C - K_j A_j C \frac{dx_j}{2} \right) - q_j C \tag{6}$$

where:

m = number of pipes connected to the node;

A_j = cross sectional area of pipe j ;

Q_j = flow rate in pipe j (volume / time);

D_j = dispersion coefficient of chlorine in pipe j (length / time);

K_j = first order decay constant of chlorine in pipe j (1/ time); and

q_j = flow rate abstracted at the node (volume / time).

In most of the studies to date, the chlorine decay mechanism has been treated as two dimensional (2-D)[24,45,46]. The first dimension is the longitudinal axis of the pipe along which chlorine is transported and decayed (bulk decay). The second dimension is the radial direction along which chlorine is transported because of velocity gradients and diffuses due to the high pipe wall consumption. The development of the chlorine decay and transport equations is summarized as follows: The one-dimensional (1-D) equation of chlorine decay at any time or distance in a pipe is given as [46].

$$C_{1D} = \frac{c_t}{c_{t-1}} = \exp \left\{ - \left(k + \frac{W_d}{r_0} \right) t \right\} \tag{7}$$

where:

C_{1D} = non-dimensional 1-D chlorine decay;

C_t = chlorine concentration at any time t (mass / volume);

C_{t-1} = chlorine concentration at time $t-1$ (or initial chlorine concentration in the pipe) (mass / volume);

W_d = pipe wall chlorine demand (length / time);

K = chlorine decay in water (bulk decay) (1 / time);

r_0 = pipe radius (length unit); and

t = travel time of water (convection).

3.0 METHODOLOGY

3.1. The Study Area

The study area is located at the Industrial Area (IA) near Jetties, West Ogonu, Warri, Delta State whose latitude lies between $5^{\circ} 32' 17.07''N$ to $5^{\circ} 32' 18.09''N$ and longitude lies $5^{\circ} 42' 21.57''E$ to $5^{\circ} 42' 23.05''E$. The industrial area consists of computerized automated water treatment plant constructed in the year 2012, many houses including production workshop, Helipad, Jetty and Warehouse 1 and 2. The map of Warri showing Ogonu Community, the study area, is presented in Figure 1.

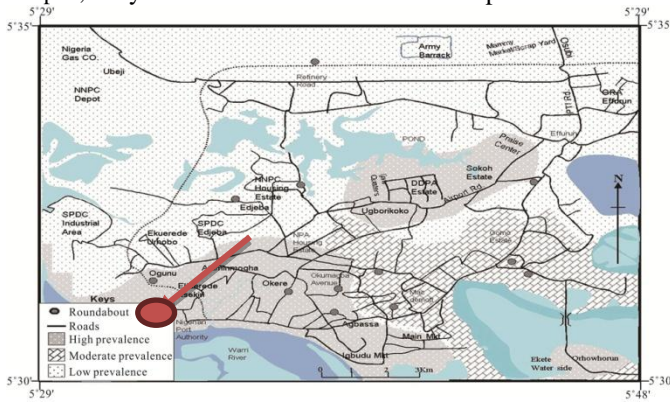


Figure 1: Map of Warri showing Ogonu Community, where the study area is located (Source: Google Earth)

3.2. Water Sampling and Laboratory Testing

Water samples were collected from the industrial area (I.A.) of the water distribution networks located at SHELL SPDC Warri (the study area). The samples were taken to SHELL Laboratory in Port Harcourt in clean iced parked containers for the physical, chemical and microbiological tests and analyses. The parameters tested and analyzed included: physical tests – colour, odour, and turbidity; chemical test – pH, chloride, iron, sulphate, copper, chromium, Zinc, total hardness and total dissolved solids; and microbiological test – total coliform count, thermo tolerant coliform or ecoli, faecal streptococcus and

clostridium perfringens spore. The WHO, NSDWQ and Massachusetts (USA) Drinking Water Standards were used for analyzing the results.

The test results of the water samples showed parameters of concern. Some of the concerned parameters included low pH and high iron. Both of them were treated. Solid Sodium Hydroxide (NaOH) was added to boost the pH, while a specialized filter vessel was used to reduce the iron to the permissible limit and the treated water met the requirements for potability when compared with the available standards.

3.3. Data Collection, Measurement of Chlorine and Water Quality Modelling with EPANET Software

Other data required for this study included the pipe length, the pipe diameter, the nodes, the reservoir elevation, the overhead tank elevation, overhead tank diameter, pumps head, design flow. These data were obtained from the consultant that often carries out the maintenance management of the water distribution system. The schematic diagram of the water distribution network in the study area is shown in Figure 2. The residual chlorine at the storage reservoir and various nodes were measured with a digital chlorine telemeter for 48 hours before distribution.

The hydraulic data were fed into the network at EPANET window to run the water quality simulation. 48 hours (2 days) simulation was performed with five (5) sampling points each in line with the research work of [14]. The demand patterns of 4 hour-time steps were used to run an extended period simulation as specified in EPANET manual 2000. This enabled it to have a clear understanding of the actual behaviour of the simulation. Using 4 hour-time steps, the values for node elevations and changing demands for five nodes were obtained.

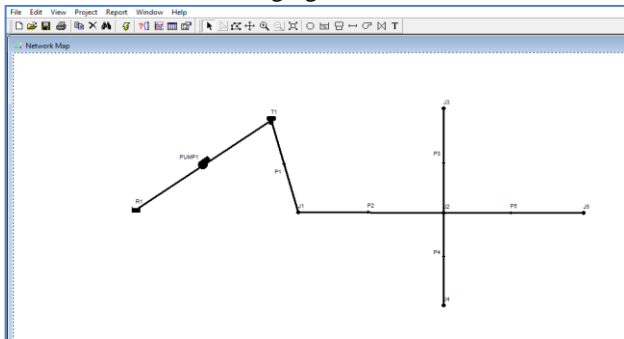


Figure 2: Schematic diagram of the Water Distribution Network of the industrial area (IA)

In order to model the residual chlorine in EPANET software, the initial free chlorine concentration measured at the reservoir of the water distribution network (0.98mg/l) was inputted into the reservoir properties editor and the first order kinetic, which is shown in equation (2), was used. This is the concentration of chlorine that continuously entered into the network. The initial water quality at the tank was set to zero because it was assumed that no chlorine has gotten there. The global bulk coefficient was set to -1.0 (default value in EPANET). This value reflects the rate at which chlorine decay due to reactions in the bulk flow over time. Negative sign indicates decay reaction. The chlorine residuals modelled overtime in EPANET software using zero and n-th order Kinetics were compared to the one measured physically at the various nodes (consumers' taps). The differences were recorded.

3.4. Model Validation for Chlorine Residual at the Industrial Area from Sampling Points

In order to validate the model, the initial lower and upper values for this parameter were restricted to $\pm 25\%$ which is in line with the research work of [47,48]. In Node J3, J4 and J5, accessible consumers' taps are located, various chlorine concentrations were recorded at different hours, the chlorine was monitored by obtaining actual physical measurements and that of the simulated results of EPANET.

The mathematical expression for the model validation is shown in equation (8).

$$MV = \frac{RC_s - RC_m}{RC_s} \times \frac{100}{1} \quad (8)$$

where:

MV= Model Validation

RC_s= Simulated Residual Chlorines

RC_m= Measured Residual Chlorines

3.4.1. Model Validation for node J3, J4, and J5 in Industrial Area

(a) Node J3

$$MV = \frac{RCs - RCm}{RCs} \times \frac{100}{1} ; MV = \frac{23.66 - 26.46}{23.66} \times \frac{100}{1} ; MV = -11.83\% \text{ Good}$$

(b) Node J4

$$MV = \frac{RCs - RCm}{RCs} \times \frac{100}{1} ; MV = \frac{23.66 - 26.52}{23.66} \times \frac{100}{1} ; MV = -12.09\% \text{ Good}$$

(c) Node J5

$$MV = \frac{RCs - RCm}{RCs} \times \frac{100}{1} ; MV = \frac{23.66 - 26.23}{23.66} \times \frac{100}{1} ; MV = -10.86\% \text{ Good}$$

4.0 RESULTS AND DISCUSSION

4.1. Results

(a) Results of the Water Quality in the Industrial Area of the study Area

The quality of the parameters for the raw water collected from the borehole and that of the treated water after passing through the treatment plant is presented in Table 1 and Table 2.

Table 1: Water Quality Analysis for the Raw Water at the Industrial Area (IA) and its Comparison with Water Quality Standards.

Water Quality Property	Parameter	Raw Water in Industrial Area	WHO, 2011. Specification for treated water (maximum limit)	NSDWQ, 2007	Massachusetts Drinking Water, USA, 2017	
Physical	Colour (Hazen)	25.00	15.0	15	15	
	Odour	Odourless	Odourless	Unobjection-able 5.0	3 threshold No	
	Turbidity (Ntu)	19.4	5.0		-	
Chemical	pH @ 25 ⁰ C	5.68	6.5-8.5	6.5-8.5	6.5-8.5	
	Chloride (mg/L)	9.89	250	250	250	
	Iron (mg/L)	3.72	0.3	0.3	0.3	
	Sulphate (mg/L)	ND	400	100	250	
	Copper (mg/L)	0.008	1.0	1.0	1.0	
	Chromium (mg/L)					
	Zinc (mg/L)	0.038	0.05	0.05	0.1	
	Total hardness (mg/L)	<0.001	1.0	3	5	
	Total Dissolved Solids (mg/L)	7.44	500	500	500	
Microbiological	Total Coliform (count/100mL)	0.00	0.00	10.00	0.00	
	Thermo tolerant Coliform or Ecoli (count/100mL)	0.00	0.00	0.00	0.00	
	Faecal Streptococcus	0.00	0.00	0.00	0.00	
	Clostridium					
	Perfringens Spore	0.00	0.00	0.00	0.00	

The results of the treated waters, which are presented in Table 2, were satisfactory when compared with the above water Quality standards.

Table 2: Water Quality Analysis for the Treated Water at the at the Industrial Area and its Comparison with Water Quality Standards

Water Quality Property	Parameter	Raw Water in Industrial Area	WHO, 2011. Specification for treated water (maximum limit)	NSDWQ, 2007	Massachusetts Drinking Water, USA, 2017
Physical	Colour (Hazen)	5.0	15.0	15	15
	Odour	Odourless	Odourless	Unobjectionable	3 threshold No
	Turbidity (Ntu)	0.02	5.0	5.0	-
Chemical	pH @ 25 ⁰ C	8.22	6.5 to 8.5	6.5 to 8.5	6.5 to 8.5
	Chloride (mg/L)	11.10	250	250	250
	Iron (mg/L)	<0.001	0.3	0.3	0.3
	Sulphate (mg/L)	ND	400	100	250
	Copper (mg/L)	0.009	1.0	1.0	1.0
	Chromium (mg/L)	0.012	0.05	0.05	0.1
	Zinc (mg/L)	<0.001	1.0	3	5
	Total hardness (mg/L)	8.96			
	Total Dissolved Solids (mg/L)	56	500	500	500
Microbiological	Total Coliform (count/100mL)	0.00	0.00	10.00	0.00
	Thermo tolerant Coliform or Ecoli (count/100mL)	0.00	0.00	0.00	0.00
	Faecal Streptococcus Clostridium Perfringens Spore	0.00	0.00	0.00	0.00

The water quality analysis for the industrial area in Table 1 showed that the pH value was 5.68 at 25⁰C, the colour was 25Hazen, the turbidity was 19.4Ntu and the Iron was 3.72mg/L. These values did not meet the required standard specified by WHO, Massachusetts Drinking Water Standard USA and NSDWQ. After treating the water with the automated treatment plant, the water quality analysis in Table 2 showed the water analysis result is satisfactory; with pH value (8.22 at 24.9⁰C), the colour (5.0, Hazen), the turbidity (0.02Ntu) and the Iron (<0.001mg/l).

(b) Results of Chlorine Concentration with Time and the bulk fluid reaction of the modelled residual chlorine along the pipes streams of the water distribution network with EPANET using Zero and n-th Order Kinetics

The chlorine concentration compared with time, and the pattern at which water reacts in the main flow streams of pipes in all pipes in the bulk fluid of the water distribution network when modelled with EPANET is shown in Table 3 and Figure 3.

Table 3: Time series for the summary of the modelled residual chlorine for Node J1 to Node J5

Time (Hours)	MODELLED RESIDUAL CHLORINE (mg/L) J1	MODELLED RESIDUAL CHLORINE (mg/L) J2	MODELLED RESIDUAL CHLORINE (mg/L) J3	MODELLED RESIDUAL CHLORINE (mg/L) J4	MODELLED RESIDUAL CHLORINE (mg/L) J5
0:00	0	0	0	0	0
1:00	0.67	0.67	0.66	0.66	0.66
2:00	0.68	0.69	0.69	0.69	0.69
3:00	0.7	0.68	0.69	0.69	0.69
5:00	0.68	0.67	0.67	0.67	0.67
6:00	0.67	0.67	0.66	0.66	0.66

7:00	0.66	0.66	0.65	0.65	0.65
8:00	0.65	0.65	0.63	0.63	0.63
9:00	0.63	0.63	0.62	0.62	0.62
10:00	0.62	0.62	0.61	0.61	0.61
11:00	0.6	0.6	0.6	0.6	0.6
12:00	0.59	0.59	0.59	0.59	0.59
13:00	0.58	0.58	0.58	0.58	0.58
14:00	0.57	0.57	0.57	0.57	0.57
15:00	0.56	0.56	0.56	0.56	0.56
16:00	0.55	0.55	0.55	0.55	0.55
17:00	0.54	0.54	0.54	0.54	0.54
19:00	0.52	0.52	0.52	0.52	0.52
20:00	0.51	0.51	0.51	0.51	0.51
21:00	0.5	0.51	0.5	0.5	0.5
23:00	0.49	0.49	0.49	0.49	0.49
24:00	0.48	0.48	0.48	0.48	0.48
25:00	0.47	0.48	0.47	0.47	0.47
28:00	0.45	0.46	0.45	0.45	0.45
31:00	0.43	0.44	0.43	0.43	0.43
34:00	0.41	0.42	0.41	0.41	0.41
38:00	0.39	0.39	0.39	0.39	0.39
41:00	0.37	0.37	0.37	0.37	0.37
45:00	0.35	0.35	0.35	0.35	0.35
47:00	0.34	0.34	0.34	0.34	0.34
48:00	0.34	0.34	0.34	0.34	0.34
SUM	23.8	23.83	23.66	23.66	23.66
	-2.43	-2.4	-2.8	-2.86	-2.57

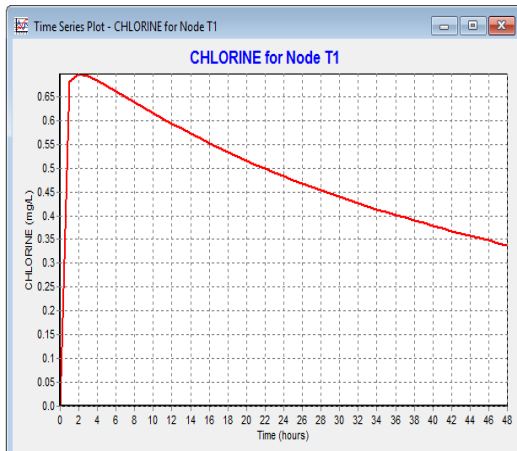


Figure 3: Time series of modelled residual chlorine at the tank in Epanet

The simulated chlorine residual along the nodes(Js) and the pipes (Ps), in Table 3, showed that the residual chlorine values in pipes and nodes were higher in the following order P2 J2, P1 J1, P5 J5, P3 J3, P4 J4 in that order. The bulk fluid reaction of the chlorine along the pipes streams in Table 3, and Figure 3 showed the reaction values were almost similar in all the pipes, 64% of chlorine decayed after reacting with water in pipe 1 to pipe 5. The summation of the simulated residual chlorine further showed that the bulk reactions were higher in P2, P1, P3, P4, and P5 in that order with the values of 23.83, 23.80, 23.66, 23.66, and 23.66 respectively. This implied that the reaction rates depend on the mixing and velocities of flow in the pipes.

(c) Comparison of the Simulation of Chlorine Concentration with EPANET to the Actual Physical Chlorine Concentration at Consumer Taps to Validate Model

Tables 4 shows the simulated results with EPANET to the measured results of the actual physical for residual chlorine at consumers' taps at interval of 1 hour in 48 hours. The value in the row of the last column in each of the tables is the percentage validation.

Table 4 : Time series for Modelled and Measured Residual Chlorine for Node J5

Time (Hours)	MODELLED RESIDUAL CHLORINE (mg/L)	MEASURED RESIDUAL CHLORINE (mg/L)
0:00	0	0
1:00	0.66	0.67
2:00	0.69	0.68
3:00	0.69	0.69
4:00	0.68	0.69
5:00	0.67	0.68
6:00	0.66	0.68
7:00	0.65	0.68
8:00	0.63	0.68
9:00	0.62	0.67
11:00	0.6	0.66
13:00	0.58	0.65
14:00	0.57	0.65
15:00	0.56	0.64
16:00	0.55	0.64
17:00	0.54	0.63
18:00	0.53	0.62
20:00	0.51	0.6
23:00	0.49	0.58
24:00	0.48	0.55
25:00	0.47	0.55
26:00	0.46	0.51
27:00	0.46	0.5
28:00	0.45	0.49
29:00	0.44	0.48
30:00	0.44	0.47
32:00	0.42	0.46
33:00	0.42	0.46
34:00	0.41	0.46
35:00	0.4	0.45
38:00	0.39	0.44
39:00	0.38	0.44
40:00	0.38	0.43
43:00	0.36	0.41
47:00	0.34	0.4
48:00	0.34	0.4
	23.66	26.23
	-2.57	-10.86

As shown in Table 4, the water quality in node 5 was good up to 27 hours in the measured residual chlorine and 22 hours in the modelled residual chlorine after the water entered the network. It implied that after these hours, the water quality cannot be guaranteed as the water has the possibility of being re-contaminated with the chlorine residual values less than 0.5mg/L. These findings in this study conform with the results of the findings of [50,51] which states that, for effective disinfection, there should be a residual concentration of free chlorine of greater or equal to 0.5mg/L after at least 30 minutes contact time at pH less than 8.0. This means that chlorine needs to be re-introduced into the network after some hours interval or booster pump for chlorination are added at some node sections to be able to maintain the value of greater or equal to 0.5mg/L at the consumers' taps for a longer time than the observed.

Conclusion

The modelling of chlorine residual concentration in an automated treatment plant of municipal water distribution network located at West Ogonu community of Warri, Delta State was evaluated. Good water quality with respect to chlorine concentration was achieved within the study area. The automated treatment plant in the study area was able to treat water effectively based on the water quality analysis carried out. The water quality at the consumers' tap in the treatment plant is only acceptable to a certain period, after which the water has the potential of being re-contaminated. The automated treatment plant method produced good results when the measured and simulated residual chlorine values were compared.

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