

Modelling of chlorine residual in the water distribution network at Bukit Tunku, Kuala Lumpur

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ABSTRACT The purpose of this study was to investigate the fate of the residual chlorine in the water distribution system. Network simulation model was developed using EPANET 2.0 software to investigate and compare two commonly used chlorine decay models which is single decay coefficient and the combined bulk and wall demand model. A study area at Bukit Tunku, Kuala Lumpur was chosen based on the public complaints data on the degradation of water quality provided by PUAS Berhad. Fifteen samples were taken from the treated water exit at Bukit Nanas Water Treatment Plant and the residual chlorine was tested daily. The bulk decay constant was determined from the experiment to be $-0.312/d$. And, the wall decay coefficient which determined by trial and error from the model was $-0.91 m/d$. From the model result, the decay coefficient was clearly shown to be varying at different pipe section and the system demand of chlorine was higher than bulk chlorine demand.

ABSTRAK Tujuan utama kajian ini adalah untuk mengkaji nasib klorin dalam sistem bekalan air. Model jaringan telah dibentuk dengan menggunakan perisian EPANET 2.0 untuk mengkaji dan membandingkan dua jenis model kehilangan klorin yang biasa digunakan iaitu model kehilangan klorin tunggal dan model gabungan kehilangan klorin air dan dinding. Kawasan kajian terletak di Bukit Tunku, Kuala Lumpur telah dipilih dengan berdasarkan data aduan orang ramai tentang kemerosotan kualiti air yang diterima oleh PUAS Berhad. Lima belas sampel air telah dikutip pada logi rawatan air Bukit Nanas dan nilai klorin diuji setiap hari. Pemalar kehilangan klorin dalam air yang telah ditentukan secara eksperimen ialah $-0.312/hari$. Pemalar kehilangan klorin pada dinding paip yang telah ditentukan secara cuba dan ralat daripada model pula adalah $-0.91 m/hari$. Daripada keputusan model, pemalar kehilangan klorin kelihatan jelas berubah bagi bahagian paip yang berbeza dan keperluan sistem adalah lebih tinggi daripada keperluan air pukal.

(Modelling, chlorine decay, chlorine concentration, water quality, EPANET 2.0)

INTRODUCTION

Water distribution system was primarily designed and optimised based on major consideration of hydraulic performance. However, water quality deterioration on reaching the consumer's taps can result in partial loss of trust on our water supply system. Recently, PUAS Berhad received numerous complaints regarding the deterioration of water quality and smelly water supply at Bukit Tunku, Kuala Lumpur. Additional concern when delivering water capacities shifted to water quality changes when managing a water distribution system.

Disinfection is the standard practice in water treatment to kill or render harmless pathogenic organisms and thereby reduces the threat of waterborne disease outbreak. Chlorination is the

most widely used primary and secondary disinfectant in Malaysia, because it is cheap, readily available and provides a persistent residual. The free residual chlorine should be greater than 0.2 mg/L throughout the network to maintain an adequate disinfectant capability [1]. This is consistent with the standard applied by PUAS Berhad in maintaining the water distribution system in whole Selangor.

As chlorine travel along the pipeline, it may react with the naturally occurring chlorine demanding compounds in the bulk phase and with the pipe wall as well to produce disinfection by-products such as trihalomethanes and haloacetic acids. According to previous research elsewhere, factors which influence the consumption of chlorine in the distribution network are as follow:

1. Initial chlorine concentration [2]
2. Pipe material and diameter [3]
3. Reaction with organic and inorganic substances [4]
4. Reaction with biofilm at the pipe wall [4]
5. Consumption by the corrosion process [4]
6. Loss of residual due to the excess storage time [5].

Model Development

Many disinfectant decay models have been developed by taking into account for both bulk and wall decay reactions. The rates of these combined bulk and wall decay can be different, the overall rate of the wall reaction also being affected by the rate at which chlorine can be transported from the bulk water to the pipe wall. A mathematical framework account for the physical transport of chlorine from the bulk fluid to the pipe wall (mass transfer effect) and also the chemical reactions occurring there was developed by Rossman *et al.* [6].

The one dimensional conservation of mass equation of residual chlorine in water flowing through a section of a pipe is [3,6,7]:

$$\frac{\partial C}{\partial t} = -u \frac{\partial C}{\partial x} - k_b C - \frac{k_f}{r_h} (C - C_w)$$

Where;

- C = Chlorine concentration in the bulk fluid (M/L^3)
- t = Time (T)
- u = Flow velocity (L/T)
- x = Distance along pipe (L)
- k_b = Bulk decay coefficient (1/T)
- k_f = Mass transfer coefficient (L/T)
- r_h = hydraulic radius of pipe (L)
- C_w = Chlorine concentration at the pipe wall (M/L^3)

Frequently, the residual chlorine along the distribution network was simulated according to the first order reaction kinetics in the bulk water with respect to chlorine as defined by the following equation [7,8,9,10]:

$$\frac{\partial C}{\partial t} = \pm KC$$

Where;

- C = concentration of chlorine (M/L^3)
- K = Overall decay coefficient (1/T)
- T = Time of the reaction (T)

The reaction rate coefficient K is a function of the bulk reaction coefficient and wall coefficient, as indicated in the following equation [6,7,8,9]:

$$K = k_b + \frac{k_w k_f}{r_h (k_w + k_f)}$$

Where,

- k_w = Wall reaction coefficient (L/T)

The rate of chlorine decay at the pipe wall will depend on how fast the chlorine is transported to the pipe wall and the reaction rate once it reaches there. A dimensionless mass transfer coefficient called Sherwood number was used to determine the rate at which the chlorine is transported to the pipe wall [6,7].

$$k_f = \frac{S_H d}{D}$$

Where;

- S_H = Sherwood number (dimensionless)
- d = Molecular diffusivity of constituent in bulk fluid (L^2/T)
- D = Pipe diameter (L)

$$\text{For } Re > 2,300: S_H = 0.023 Re^{0.83} \left(\frac{v}{d}\right)^{0.333}$$

For $Re < 2,300$:

$$S_H = 3.65 + \frac{0.0668 \left(\frac{D}{L}\right) Re \left(\frac{v}{d}\right)}{1 + 0.04 \left[\left(\frac{D}{L}\right) Re \left(\frac{v}{d}\right)\right]^{2/3}}$$

Where

- Re = Reynolds number (dimensionless)
- v = Kinematic viscosity of water (L^2/T)
- L = Pipe length (L)

For a set of i^{th} pipes in the distribution system with the known set hydraulic conditions for a hydraulic time step, the mass conservation equation in a single pipe is represented [5,6,7]:

$$\frac{\partial C_i}{\partial t} = -u_i \frac{\partial C_i}{\partial x} - K_i C_i = 0$$

Where C_i is the chlorine concentration in pipe or link i at a distance x along the pipe at time t , u_i is the flow velocity in pipe or link i and K_i is an overall decay constant [5].

The loss of residual chlorine in the storage tank can be modelled as a well mixed and variable volume reactors where the changes in volume and concentration over time are [6,11]:

$$\frac{\partial V}{\partial t} = \sum_{k=I} q_k - \sum_{j=O} q_j$$

$$\frac{\partial(VC)}{\partial t} = \sum_{k=I} q_k C_k - \sum_{j=O} q_j C - k_b C$$

Where;

V = Tank volume (L^3)

I = Set of pipes with flow into the tank

O = Set of pipes with flow out of the tank

EPANET 2.0

One of the more reliable and widely used network analysis programs is EPANET 2.0 [3] which was used in this study to solve the chlorine transport equation at steady state, using a constant average flow rate. The equations governing EPANET 2.0 are based on the principles of conservation of mass coupled with reaction kinetics can be represented as follows [3,12]:

1. Advective Transport in Pipes
2. Mixing at Pipe Junction
3. Mixing in Storage Facilities
4. Bulk Flow Reactions
5. Pipe Wall Reactions
6. System of Equations

Details of discussion on EPANET 2.0 can be found in Rossman [3].

MATERIALS AND METHODS

This study has been carried on the water distribution system at Bukit Tunku, Kuala Lumpur with PUAS Berhad assistance with the field sampling data collection. This distribution system is fed by the treated water from Bukit Nanas and Batu Estate reservoir which is sourced from Selangor River. Two treated flow exit from the

treatment plant were mixed at Maxwell Booster Station and finally transferred to Bukit Tunku area.

The water network was digitised in EPANET 2.0. The network consists of about 57 nodes and 57 pipes with total pipe length of around 10 km. The distribution system is composed of 8 to 48 in main as shown in Figure 1. The hydraulic time step used was 1 hour and the average velocity was 0.68 m/s.

Input data, such as bulk decay coefficient which is determined in the laboratory and initial quality (residual chlorine) variations were monitored at four locations to be used as calibration data in the model. Since there are no standard method in measuring the wall decay coefficient, estimation had been made based on upon field concentration measurements and water quality simulation results as part of a calibration analysis. It was postulated that wall reaction coefficient is related to the pipe roughness according to the following equation [7]:

$$k_w = \alpha / C$$

Where;

k_w = wall decay coefficient (L/T)

α = Fitting coefficient (dimensionless)

C = Hazen-William C factor (dimensionless)

The fitting coefficient was determined in the simulation by trial and error during calibration. The initial value of wall decay coefficient for each pipes was estimated and the simulation was then carried out. The wall decay coefficient was adjusted until a suitable match was obtained between the observed chlorine concentration and computed results.

Sampling was conducted at the outlet of Bukit Nanas Water Treatment Plant and four locations throughout the service area as shown in Figure 1. The rate constant for chlorine decay in the bulk flow had been estimated by performing a bottle test [7,12,13,14,15] in the laboratory of University of Malaya. Fifteen samples were collected in dark bottles from the outlet of Bukit Nanas Water Treatment Plant. The initial water quality and chlorine concentration were measured immediately as initial time zero. The remaining fourteen samples were then stored at ambient temperature ($28.5 \pm 0.5^\circ C$) in an incubator kept at a constant temperature. The free chlorine

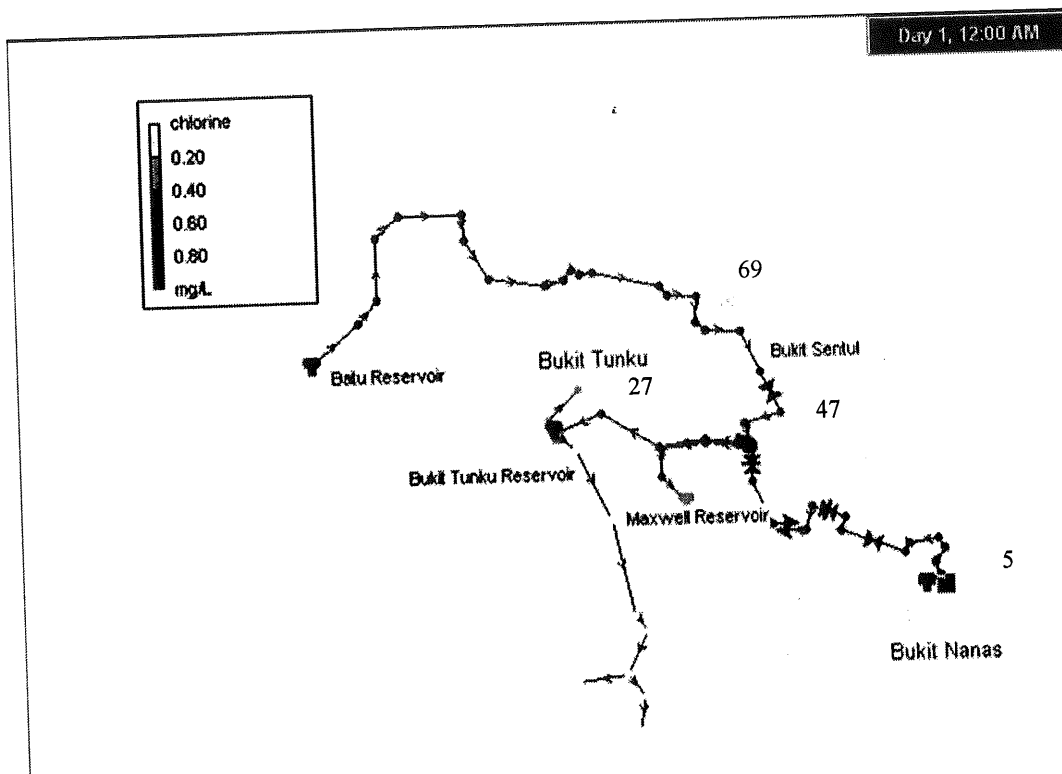


Figure 1. Schematic Distribution Map of Bukit Tunku.

concentration were measured on duplicate subsamples by adding the *N,N*-diethyl-*p*-henylnediamine (DPD) tablets and measured using the DPD colourimetric meter until it became undetectable (APHA Standard Method 4500-Cl) [16].

RESULTS AND DISCUSSION

The average water quality produced by Bukit Nanas water treatment plant was observed to be better than the WHO International Standards for

Drinking Water. It can be said to be World Class standard comparable to those of developed countries [17]. Table 1 below gives the comparison of WHO standards and the actual quality data collected during the study.

Chlorine decay constant

From the plot of the observed decay in chlorine in bottles test over time (Figure 2), chlorine was decaying according to the first-order equation:

$$C_t = C_0 e^{-kt}$$

Table 1. Average water quality at Bukit Nanas water treatment plant.

| Parameters | Actual Quality | WHO Standards (1984) |
|----------------|----------------|----------------------|
| Turbidity, NTU | 0.36 | <5 |
| Colour, TCU | <5 | <15 |
| pH | 7.21 | 6.5-9.0 |
| Chlorine, mg/L | 1.78 | 0.2 |

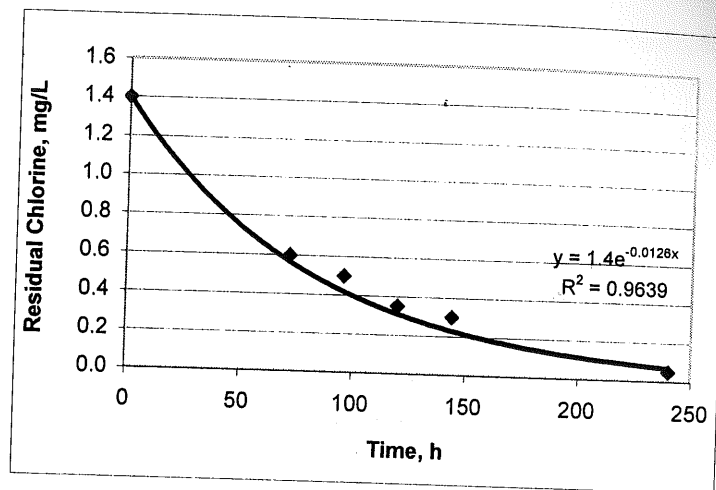


Figure 2. Profile of chlorine Decay for Bukit Nanas Water Treatment Plant, Batu Estate reservoir and Bukit Tunku reservoir.

Since the chlorine was shown to be well approximated by first-order reaction (Figure 2), the reaction rate coefficient was then found by using linear regression techniques (Figure 3). The best fit first order bulk decay coefficient for Bukit Nanas Water Treatment Plant was 0.013/h and reach 0.1 mg/L would equal 10 days. Therefore the bulk decay constant k_b of 0.013/h was assigned to all the pipes and tanks even though it is conceivable that k_b may vary from pipe to pipe. To simplify the model, the k_b value was kept constant in this study. However, the extrapolate findings from the model still satisfied.

Model verification

Simulation was carried with EPANET 2.0 program for both single bulk decay model and combined bulk and wall decay model. For the combined bulk and wall decay model, the wall decay coefficient k_w was adjusted by trial and error method, and the simulated EPANET 2.0 results was compared with the observed field data at corresponding sampling points. Table 2 and 3 shows the calibration statistics for single bulk decay chlorine model and combined bulk and wall decay model respectively. It could be observed that good agreement was obtained

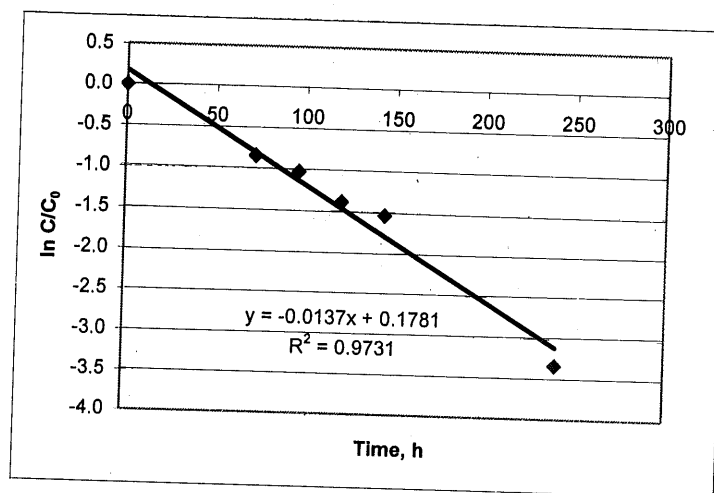


Figure 3. Graph $\ln C/C_0$ versus time at Bukit Nanas, Batu Estate and Bukit Tunku.

Table 2. Calibration Statistics for Single Bulk Chlorine Decay Simulation

| Location | Observed Mean (mg/L) | Computed Mean (mg/L) | Mean Error | RMS Error |
|----------|----------------------|----------------------|------------|-----------|
| 5 | 1.69 | 1.68 | 0.050 | 0.058 |
| 27 | 0.85 | 1.15 | 0.303 | 0.304 |
| 48 | 0.88 | 1.17 | 0.287 | 0.288 |
| 69 | 1.07 | 1.20 | 0.129 | 0.129 |
| Network | 1.12 | 1.30 | 0.192 | 0.221 |

Table 3. Calibration Statistics for Combined Bulk and Wall Chlorine Decay Simulation

| Location | Observed Mean (mg/L) | Computed Mean (mg/L) | Mean Error | RMS Error |
|----------|----------------------|----------------------|------------|-----------|
| 5 | 1.69 | 1.65 | 0.050 | 0.070 |
| 27 | 0.85 | 0.66 | 0.187 | 0.189 |
| 48 | 0.88 | 0.74 | 0.135 | 0.136 |
| 69 | 1.07 | 0.82 | 0.254 | 0.245 |
| Network | 1.12 | 0.97 | 0.157 | 0.176 |

between the observed and computed chlorine concentration for two models with the correlation between means was 0.990 and 0.985 respectively.

The results in Tables 2 and 3 show that the combined decay models performs better than single decay model. Therefore, the accuracy of models was improved by using the combined bulk and wall decay model. The values of k_w was determined to be -0.91 m/d.

Analysis of results

Table 4 shows the length of pipes, chlorine residence time, average velocity and the chlorine residual at the upstream and downstream nodes at various section of the distribution network at Bukit Tunku.

From the chlorine concentration data at upstream and downstream, and the average residence time, the decay coefficient was calculated for various

Table 4. Residual Chlorine Condition along the Network.

| Link beginning/ending nodes | Length (m) | Chlorine concentration residence time (d) | In mg/L (Upstream/Downstream) | Decay Coefficient (1/d) | Ratio of pipe to bulk decay |
|-----------------------------|------------|---|-------------------------------|-------------------------|-----------------------------|
| BN/12 | 873.96 | 0.160 | 1.78/1.64 | 0.512 | 1.640 |
| 12/17 | 750.04 | 0.137 | 1.64/1.55 | 0.411 | 1.316 |
| 17/20 | 750.04 | 0.137 | 1.55/1.25 | 1.565 | 5.017 |
| 20/34 | 506.35 | 0.093 | 1.25/0.91 | 3.422 | 10.967 |
| 34/BT | 1629.73 | 0.299 | 0.91/0.46 | 2.845 | 7.323 |
| BT/40 | 548.64 | 0.101 | 0.46/0.38 | 1.900 | 6.092 |
| BE/81 | 45.00 | 0.008 | 1.40/1.32 | 7.136 | 22.782 |
| 81/78 | 885.04 | 0.162 | 1.32/1.04 | 1.470 | 4.712 |
| 72/68 | 2633.00 | 0.147 | 1.02/0.97 | 0.342 | 1.096 |

Notes: BN – Bukit Nanas Water Treatment Plant
 BT – Bukit Tunku Reservoir
 BE – Batu Estate Reservoir
 Average velocity = 0.68 m/s

sections of the network. Chlorine demand at each section was calculated according to first order decay equation. The bulk decay rate was determined from the bottles test to be $-0.312/d$. It can be noticed from the column "ration of pipe to bulk decay", the total system demand of chlorine was higher than the bulk decay rate. This high chlorine demand was most probably due to the chlorine demanding materials.

From the decay coefficient calculated, it is clearly shown that the first order decay rate would not predict chlorine residual adequately. Hua *et al.* [5] has suggested a semi-empirical approach of combined first and second-order model to have better description of chlorine decay.

Distribution of chlorine

Distribution curve of chlorine was simulated with the initial concentration of 1.78 mg/l and 1.40 mg/l at the water treatment plant and Batu Estate Reservoir respectively. Figure 4 shows the distribution of the bulk average chlorine concentration in the Bukit Tunku distribution systems. The chlorine concentration decreased gradually from the water treatment plant until it

reaches a level ≤ 0.38 mg/l at some points of Bukit Tunku area.

Figure 4 clearly showed that chlorine was decaying at higher rate initially at Bukit Nanas water treatment outlet and Batu Estate Reservoir. This could be due to the higher initial chlorine concentration at both locations [2,10]. Two other locations which caused rapid decay of residual chlorine were Maxwell Booster Station and Bukit Tunku storage tank. The mixing process at the booster station or some chlorine demanding matters may cause this. Future experimental investigation at these locations will explore the kinetic of selected chlorine demanding substances, mixing of the storage tank and residence time of the tank.

Implication of water distribution pipe management

Use of single wall decay constant for all the pipes in a distribution system may not be suitable. Further research on the influencing factors of pipes characteristics such as material, diameter, age and biofilm growth should be carried out in order to have a better understanding on the fate of residual chlorine at the pipe wall.

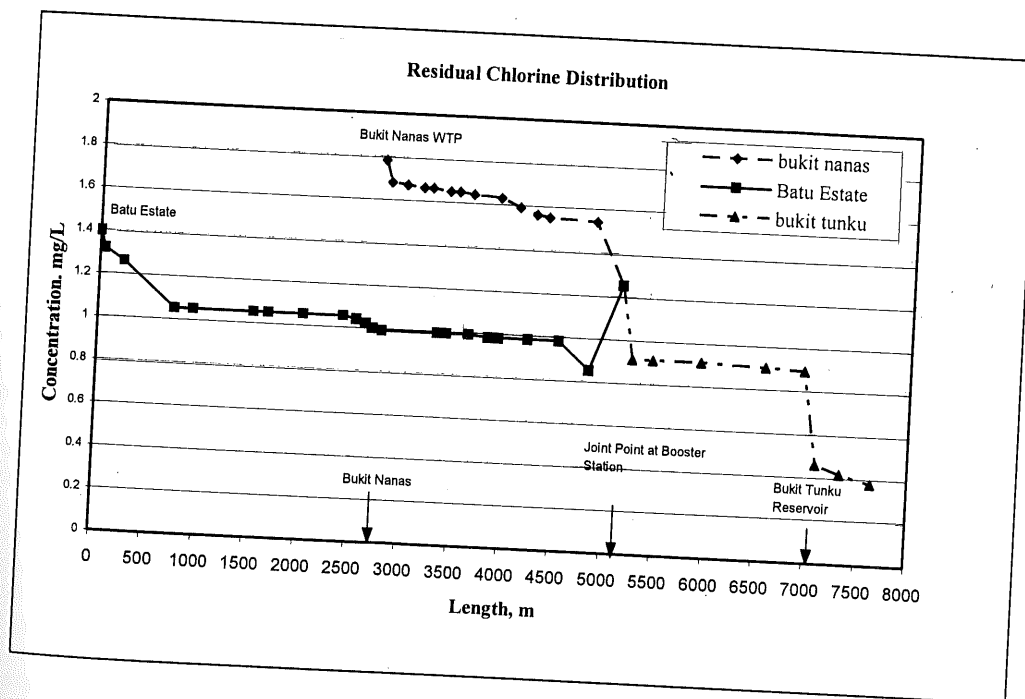


Figure 4. Residual Chlorine Distribution along the Network.

Other aspects requiring further study included operating and management of the water distribution system. A number of operating and maintenance adjustment scenarios can be evaluated for the water distribution system. The model developed here could be used for further planning such as evaluation of storage tank impacts, biofilm growth, modification during pipeline rehabilitation and use of chlorine injector along the network.

CONCLUSIONS

The model under study was useful to predict the behaviour of a typical water treatment plant treated water exit through the distribution pipeline in ensuring the desired water quality at consumer taps.

Results of this study are summarised as follows:

- The water quality of treated water from treatment plant was in accordance with the WHO International Standards for Drinking Water.
- Chlorine distribution curve showed that this network was operated well and maintain a good degree of disinfecting capability at most part of the study area.
- Laboratory evaluation of treated water from Bukit Nanas water treatment plant showed that it has very low chlorine decay (-0.312/d).
- Better calibration was obtained from the combined bulk and wall decay simulation, the wall decay coefficient was -0.91 m/d and they are relatively low.
- Loss of chlorine residuals in the distribution pipeline is assumed to be caused by the pipe material or other chlorine demanding matter.
- Chlorine decay rate was higher at initial higher chlorine concentration.
- First-order equation alone would not predict the chlorine decay satisfactorily. However, most simulation work that assumes first-order decay would still yield realistic results that mirror field situation.

ABBREVIATIONS AND SYMBOLS

PUAS: Perbadanan Urus Air Selangor
SDWA: Safe Drinking Water Act
SDWAA: Safe Drinking Water Act Amendment

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