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ORIGINAL ARTICLE

Analysis of residual chlorine in simple drinking water distribution system with intermittent water supply

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Abstract 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. This paper presents a methodology to find out the residual chlorine concentration at various locations in simple branch network by integrating the hydraulic and water quality model using first-order chlorine decay equation with booster chlorination nodes for intermittent water supply. The explicit equations are developed to compute the residual chlorine in network with a long distribution pipe line at critical nodes. These equations are applicable to Indian conditions where intermittent water supply is the most common system of water supply. It is observed that in intermittent water supply, the residual chlorine at farthest node is sensitive to water supply hours and travelling time of chlorine. Thus, the travelling time of chlorine can be considered to justify the requirement of booster chlorination for intermittent water supply.

Keywords Drinking water distribution system (DWDS) · Intermittent water supply · Residual chlorine · Booster chlorination

Introduction

Everywhere in the world, the drinking water utilities face the challenge of providing water of good quality to their consumers as significant water quality changes can occur within drinking water distribution systems due to contamination. Disinfectant like chlorine can control growth of pathogens but it reacts with organic and inorganic matter in water, the chlorine concentration decreases in time called the chlorine decay (Males et al. 1988; Rossman et al. 1994; Clark et al. 1995; Boccelli et al. 2003). Because chlorine is such a strong oxidizer, it reacts with a wide range of chemicals and naturally occurring organic (and/or inorganic) matter (NOM) in the treated and/or distributed water to form potentially harmful disinfection by-products (DBPs). Some of these DBPs are suspected carcinogens and having adverse reproductive and developmental health effects (Krasner et al. 1989; Abdullah et al. 2003, 2009; Rehan Sadiq and Rodriguez 2004; Uyak et al. 2007; Brian Carrico and Singer 2009; Shihab et al. 2009; Shakhawat Chowdhury et al. 2009; Jianrong Wei et al. 2010). Therefore, it is very essential for any water supply authority to manage the chlorine disinfection within lower and upper limit of residual chlorine to safeguard the consumers from water-borne diseases and harmful DBPs simultaneously. Thus, the concentration of residual chlorine at various locations in drinking water distribution system may be considered as the final check to the quality of water supplied to the consumers.

Because of the importance of disinfection, a number of investigators have conducted research for the development of models to predict chlorine decay in drinking water (Feben and Taras 1951; Johnson 1978; Haas and Karra 1984; Biswas et al. 1993; Islam et al. 1997, 1998; Hallam et al. 2002; in Clark 1994, 2012, 1998; Rossman et al. 1994; Rossman and Boulos 1996; Hua et al. 1999; Ozdemir Osman and Alper Ucak 2002; Boccelli et al. 2003; Gibbs et al. 2006; Huang and McBean 2006, 2008). The most popular model is the first-order decay model in which the

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chlorine concentration is assumed to decay exponentially (Feben and Taras 1951; Johnson 1978; Clark 1994; Rossman et al. 1994; Hua et al. 1999; Boccelli et al. 2003). The performance of six different kinetic models for the decay of free chlorine in over 200 bulk water samples from a number of different sources found that the performance benefit over the simple first-order model was marginal (Powell et al. 2000a, b).

EPANET (Rossman et al. 2000) simulation model which uses first-order chlorine decay for prediction of residual chlorine in drinking water distribution system has been applied by many researchers (Clark et al. 1995; Castro and Neves 2003 ; Romero Gomez et al. 2006; Toru Nagatani et al. 2008; Shihab et al. 2009; Tomovic et al. 2010). The water quality model can be used as effective tool by water utilities for the predication of residual chlorine and may guide water supply authority for proper maintenance of residual chorine to balance between excessive disinfectant concentration near the source to avoid excessive disinfection by-products and minimum residual chlorine throughout the distribution network to avoid the microbial contamination.

The booster chlorination is found advantageous in maintaining proper balance between the minimum and maximum concentration. Researchers have examined different methods for determining the optimal schedule of disinfection boosters to maintain adequate levels of residual chlorine throughout the distribution system (Boccelli et al. 1998, 2003; Tryby et al. 1999, 2002; Munavalli and Kumar 2003; Ozdemir and Ucaner 2003; Propato and Uber 2004; Parks and Shannon 2009; Ostfeld et al. 2010). Thus, knowledge of residual chlorine concentration throughout the distribution network suggests the water utilities regarding selection of chlorine application strategy i.e. conventional or booster chlorination to avoid the recontamination of water in DWDS.

Indian scenario of drinking water supply

Large numbers of households in Indian cities do not have access to one of the most basic of human needs—a safe and reliable supply of drinking water. As per McKenzie-Ray (2009), only half of all Indian urban households have a piped water connection, even those with a connection generally do not receive a regular supply of good quality water. The municipal water supply in most Indian cities is only available for a few hours per day, pressure is irregular, and the water is of questionable quality. No major Indian city has a 24 h supply of water, intermittent supply with 4–5 h of supply per day being the norm as compared to the Asian- Pacific average of 19 h per day supply (McKenzie-Ray 2009). Intermittent supply of water leads to health risks for users due to the higher likelihood of contamination of water pipelines through joints and damaged segments during periods when the system is not pressurized. Due to excessive growth in population, the service area is divided into few zones and each zone is supplied the water for limited hours which leads to the stagnation of water during non-supply hours and decay of chlorine for rest of the hours. Also, there is a problem related to maintenance of pressure at the farthest node in intermittent water supply. To cope up with the decay in chlorine, higher mass rate of chlorine is applied at the source to maintain the minimum residual chlorine up to the farthest end, which results in harmful DBP formation at the nearest locations to the source and less concentration of residual chlorine at farthest location. Thus, the objectives of microbial-free water with proper quantity and pressure is difficult to achieve through conventional water supply networks without targeting continuous water supply and constantly pressurized system (CPHEEO 1999; MoUD 2009) Given the health imperatives and other inconveniences caused by intermittent water supply, it is unfortunate that virtually no city in India has continuous water supply (CPHEEO 1999).

For Indian conditions of intermittent water supply, the use of explicit equations and available water quality model software to find out the residual chlorine is necessity. Booster chlorination is essential as if, supply hours are less than travelling time of chlorine up to the last location, the chances of chlorine decay results in contamination as mass rate of chlorine supplied at source by conventional method may not reach to the farthest node due to less supply hours. In such cases, the adoption of Booster chlorination as well to choose proper supply hours is very essential from health point of view of consumers. The prediction of residual chlorine at various locations can be useful to decide the selection of mode of water supply i.e. Intermittent (Supply hours in intermittent water supply) or continuous 24 $\times$ 7 water supply as well as chlorine application strategy i.e. conventional or booster chlorination.

In this study, a sample network is prepared and problem is formulated to find out the residual chlorine concentration at various locations of simple DWDS network with intermittent water supply of 2 h for two different strategies of chlorine applications i.e. of conventional and booster chlorination. The concept is developed to integrate the hydraulic and water quality model using first-order chlorine decay for intermittent water supply with booster nodes. Long travelling time and low velocities of water cause excessive decay of chlorine and the reaction of chlorine with organic and inorganic matter in water forms harmful DBPs. The effect of travelling time on concentration of residual chlorine is checked for both the chlorine application strategy which guides the selection of supply hours of

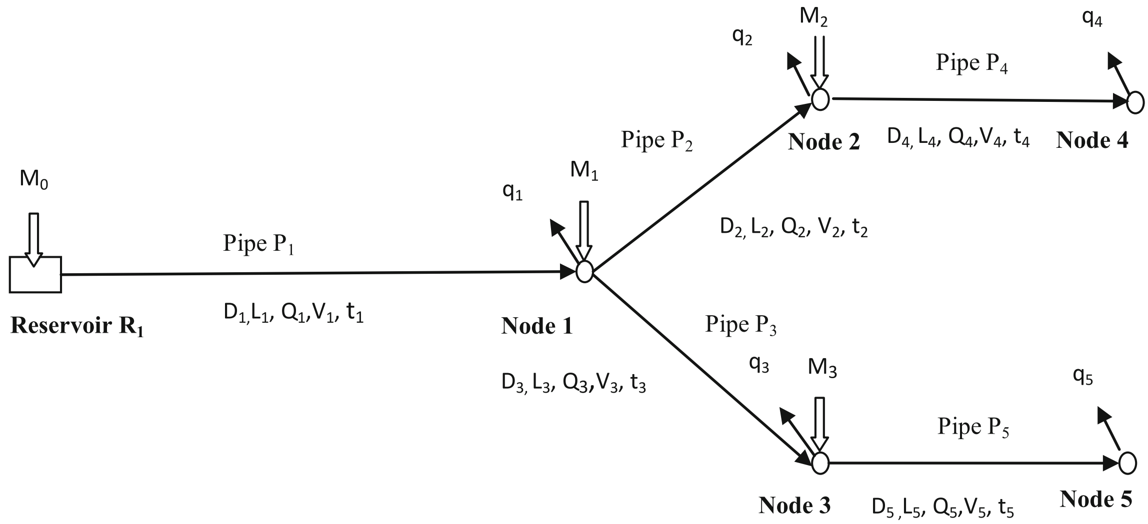

Fig. 1 Sample network for calculation of chlorine concentration at each node

Table 1 List of the variables use in model equations

Sr No	Variables	Description
1	M_0, M_1, M_2, M_3	Mass rate of chlorine applied at source i.e. reservoir R_1, node 1, node 2, node 3, respectively, mg/min
2	D_1, D_2, D_3, D_4, D_5	Diameter of Pipe P_1, P_2, P_3, P_4, P_5, respectively, m
3	L_1, L_2, L_3, L_4, L_5	Length of Pipe P_1, P_2, P_3, P_4, P_5, respectively, m
4	q_1, q_2, q_3, q_4,q_5	Demand at node 1,2,3,4,5, respectively, m^3/h
5	Q_1, Q_2, Q_3, Q_4, Q_5	Flow in pipe P_1, P_2, P_3, P_4, P_5, respectively, m^3/h
6	V_1, V_2, V_3, V_4, V_5	Velocity of flow in pipe P_1, P_2, P_3, P_4, P_5, respectively, m/s
7	t_1, t_2, t_3, t_4, t_5	Travelling time of chlorine to reach up to each node 1,2,3,4,5, respectively, from preceding node, days
8	T_1, T_2, T_3, T_4, T_5	Travelling time of chlorine to reach up to node 1,2,3,4,5, respectively from the source i.e. reservoir, days
9	C_o, C_{1i}, C_{2i}, C_{3i}, C_{4i}, C_{5i}	Concentration of chlorine at reservoir R_1, and inlet of node 1, 2, 3, 4, 5, respectively, mg/l
10	C_{10}, C_{20}, C_{30}, C_{40}, C_{50}	Concentration of chlorine at outlet of node 1, 2, 3, 4, 5 respectively, mg/l
11	X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9	Constants

water to achieve the effectiveness of booster chlorination strategy for the intermittent water supply which represents the common scenario of water supply in most of the Indian cities.

Problem formulation

A sample network of simple DWDS is adopted for the generalization of different equations in terms of chlorine mass rate injection and coefficients to obtain the residual chlorine concentration at different nodes (Fig. 1). Two different strategies in application of chorine are adopted. Case I describes conventional chlorination in which the chlorine is applied only at source R_1. Case II represents the booster chlorination with chlorine applied at source as well as at nodes 1, 2, and 3. Intermittent water supply with 2 h water supply in a day is considered which represent the general mode of water supply in Indian city. The water remains stagnant for rest of the 22 h during which the decay in chlorine takes place. The initial quality of water at all the nodes is kept as 0.2 mg/l to avoid the contamination of water at various locations.

List of the variables used in model equations is presented in Table 1.

Computation of residual chlorine

Explicit equations are developed to find out the residual chlorine concentration at inlet and outlet of the nodes 1, 2, 3, 4 and 5 for total 2 h of water supply for two different strategies of application of chorine i.e. case I having conventional chlorination in which the chlorine mass rate of M_0

is applied at only source R_1 and case II is Booster chlorination with mass rates of chlorine applied at source R_1 and at nodes 1, 2 and 3 are M_0, M_1, M_2 and M_3, respectively.

Following assumptions are made for developing the explicit equations for the computations of residual chlorine.

(1) First-order chlorine decay equation (Feben and Taras 1951; Johnson 1978; Clark 1994; Rossman et al. 1994; Hua et al. 1999; Boccelli et al. 2003) is used for computing residual chlorine at various nodes,

$$C = C_O e^{-Kbt} \tag{1}$$

where,

C = Concentration of chlorine in the water, mg/l.

t = Travelling time, days.

C_o = Chlorine concentration at the beginning of the transportation, mg/l.

Kb = Bulk decay coefficient, day^{-1}.

(2) Value of bulk decay coefficient Kb is adopted as 0.55 day^{-1} (Rossman et al., 1994).

(3) Flow is steady state for each demand pattern during supply of water for 2 h.

(4) At booster station node, the demand is taken first and then booster dose is applied.

(5) Initial concentration at starting of the day i.e. 0 h is 0.2 mg/l at every node.

The procedure for developing equations to compute residual chlorine at node 1 is described as follows.

For node 1

Case I (conventional chlorination)

Concentration of chlorine at inlet of node 1 is given by.

$$C_{1i} = Coe^{-kt}1$$

Travelling time of chlorine from source to node 1

$$t1 = \frac{L_1}{V_1} = \frac{L_1}{\frac{Q_1}{A_1}} = \frac{L1\pi D1^2}{4Q_1}$$

Mass rate of chlorine, M_o (mg/min) is added at source,

$$\therefore Co = \frac{M_0}{Q_1} \quad C_1 = \frac{M_0}{Q_1} e^{-kL1\pi D1^2}/4Q_1$$

Taking Constant $X_1 = \frac{1}{Q_1} e^{-kL1\pi D1^2}/4Q_1$

$$C_{1i} = M_0 X_1 \tag{2}$$

Concentration at the end of travelling time

$$t_1 = \frac{L1\pi D1^2}{4Q_1}, \quad C_{1i} = C_{10} = M_0 X_1 \tag{2A}$$

Case II (booster chlorination)

(1) Concentration after addition of and M_1 at node $1 = \frac{M_1}{Q_2+Q_3} + 0.2$

(2) Concentration at the inlet and outlet of the node 1 after end of total travelling time $T_1 = t_1$,

$$C_{1i} = M_0 X_1 \tag{2B}$$

$$C_{10} = M_0 X_1 + \frac{M_1}{Q_2 + Q_3} \tag{2C}$$

Similarly, various equations are further developed as explained above to compute the residual chlorine concentration at various nodes at different time for case I and II (Table 2).

If the distribution network consists of many loops and branches, the development of explicit equations for computing residual chlorine is cumbersome. In such cases, computer-based methods such as EPANET software is resorted to. The governing equations for EPANET's water quality solver are based on the principles of conservation of mass coupled with reaction kinetics.

Example problem

For application of equations developed as mentioned in Table 2, an example network which resembles the upper part of distribution system of South Baroda, Gujarat, India is adopted with some modification in flow rates and lengths to simplify the problem. Figure 2 shows the network details with water demand at different nodes. Initial concentration of chlorine at all the nodes is assumed to be 0.2 mg/l. The mass rate of chlorine supplied at all the nodes for both the cases is shown in Table 3.

Analysis and discussion of results

Using equations (Table 2), residual chlorine concentration at different time period is obtained for example problem at each node. Figures 3 and 4 indicate the residual chlorine concentration obtained for farthest node 4 for case I and case II, respectively, having travelling time >2 h i.e. water supply duration. Figures 5 and 6 show residual chlorine concentration obtained for farthest node 5 for case I and case II, respectively, having travelling time <2 h i.e. water supply duration. The simulation is also done on widely applied simulation model i.e. EPANET software for the same network to validate the results obtained using equations. The results obtained using the equations are exactly matching with the results obtained by EPANET software.

Table 2 Concentration of residual chlorine at various locations at the end of different travelling time

Cases	Concentration of residual chlorine at the end of different travelling time		
	Node I	Inlet of node 1	Outlet of node 1
Case I	Concentration at the end of travelling time t_1	$C_{1i} = M_0X_1$	$C_{10} = M_0X_1$
Case II	Concentration after addition of and M_1 at J_1	$\frac{M_1}{Q_2+Q_3} + 0.2$	
	Concentration at the end of travelling time t_1 which is equal to total travelling time T_1	$C_{1i} = M_0X_1$	$C_{10} = M_0X_1 + \frac{M_1}{Q_2+Q_3}$
where, $X_1 = \frac{1}{Q_1}e^{-kL_1\pi D_1^2}/4Q_1$			
	Node 2	Inlet of node 2	Outlet of node 2
Case I	Concentration at the end of total travelling time from source, $T_2 = t_1 + t_2$	$C_{2i} = M_OX_1X_2$	$C_{20} = M_OX_1X_2$
Case II	Concentration after addition of M_2 at node 2	$\frac{M_2}{Q_4}$	
	Concentration after addition of M_1 at node 1 and M_2 at node 2 after travelling time t_2	$\frac{M_2}{Q_4} + M_1X_3 + 0.2$	
	Concentration at the inlet and outlet of node 2 after end of total travelling time from source $T_2 = t_1 + t_2$,	$C_{2i} = M_OX_1X_2 + M_1X_3$	$C_{20} = M_OX_1X_2 + M_1X_3 + \frac{M_2}{Q_4}$
where, $X_2 = e^{-kL_2\pi D_2^2}/4Q_2$, $X_3 = \frac{X_2}{Q_2+Q_3}$			
	Node 4	Inlet of node 4	Outlet of node 4
Case I	Concentration at inlet and outlet of node 4 after the end of total travelling time from source $T_4 = t_1 + t_2 + t_4$	$C_{4i} = M_0X_1X_2X_4$	$C_{40} = M_0X_1X_2X_4$
Case II	Concentration after addition of M_2 at node 2 after travelling time, t_4	$M_2X_5 + 0.2$	
	Concentration after addition of M_1 at node 1 and M_2 at node 2 after travelling time, $t_2 + t_4$	$M_1X_3X_4 + M_2X_5 + 0.2$	
	Concentration at inlet and outlet of node J_3 after the end of total travelling time from source $T_3 = t_1 + t_2 + t_4$	$C_{4i} = M_0X_1X_2X_4 + M_1X_3X_4 + M_2X_5$	$C_{40} = M_0X_1X_2X_4 + M_1X_3X_4 + M_2X_5$
	If $T_3 >$ water supply duration then M_o will not reach to the node and concentration will be $C_{4i} = C_{40} = M_1X_3X_4 + M_2X_5$		
where, $X_4 = e^{-kL_4\pi D_4^2}/4Q_4$, $X_5 = \frac{X_4}{Q_4}$			
	Node 3	Inlet of node 3	Outlet of node 3
Case I	Concentration at the end of total travelling time from source $T_3 = t_1 + t_3$	$C_{3i} = M_OX_1X_6$	$C_{30} = M_OX_1X_6$
Case II	Concentration after addition of M_3 at node 3,	$\frac{M_3}{Q_5} + 0.2$	
	Concentration after addition of M_1 at node 1 and M_3 at node 3 after travelling time t_3	$\frac{M_3}{Q_5} + M_1X_7 + 0.2$	
	Concentration at inlet and outlet of node 3 after the end of Total travelling time from source $T_3 = t_1 + t_4$	$C_{3i} = M_OX_1X_6 + M_1X_7$	$C_{30} = M_OX_1X_6 + M_1X_7 + \frac{M_3}{Q_5}$
where, $X_6 = e^{-kL_3\pi D_3^2}/4Q_3$, $X_7 = \frac{X_6}{Q_2+Q_3}$			
	Node 5	Inlet of node 5	Outlet of node 5
Case I	Concentration at the end of total travelling time from source, $T_5 = t_3 + t_5$	$C_{5i} = M_OX_1X_6X_8$	$C_{50} = M_OX_1X_6X_8$
Case II	Concentration after addition of M_3 at node 3 at the end of travelling time, t_5	$M_3X_9 + 0.2$	
	Concentration after addition of M_1 at node 1 and M_3 at node 3 at the end of travelling time, $t_3 + t_5$	$M_1X_7X_8 + M_3X_9 + 0.2$	
	Concentration at inlet and outlet of node J_5 after the end of total travelling time from source, $T_5 = t_1 + t_3 + t_5$	$C_{5i} = M_OX_1X_6X_8 + M_1X_7X_8 + M_3X_9$	$C_{50} = M_OX_1X_6X_8 + M_1X_7X_8 + M_3X_9$
	If $T_5 >$ Water supply duration then M_1 will not reach to the node and concentration will be $C_{5i} = C_{50} = M_2X_7X_8 + M_4X_9$		
where, $X_8 = e^{-kL_5\pi D_5^2}/4Q_5$, $X_9 = \frac{X_8}{Q_5}$			

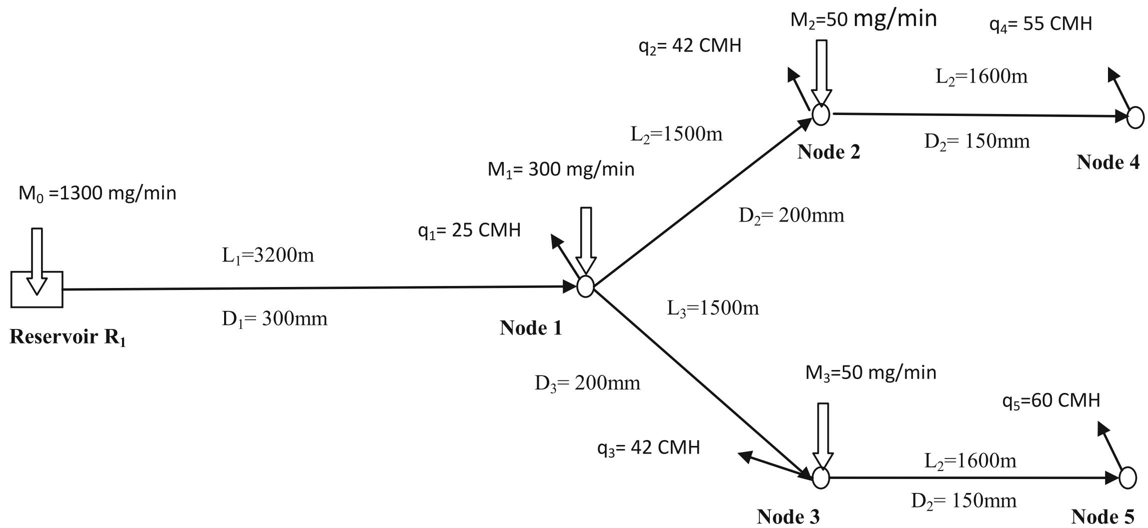

Fig. 2 Example network for calculation of chlorine concentration at each node for case II

Table 3 Mass rate of chlorine applied at various locations

Cases	Total mass rate applied (gm/day)	Chlorine application period	Source and booster locations/injection rate at			
			Source M_o (mg/min)	Node 1 M_1 (mg/min)	Node 2 M_2 (mg/min)	Node 3 M_3 (mg/min)
Case I (only source chlorination)	267.6	2 h	2,230	–	–	–
Case II (source and booster chlorination)	204 (23.78 % reduction in total mass rate of chlorine)	2 h	1,300	300	50	50

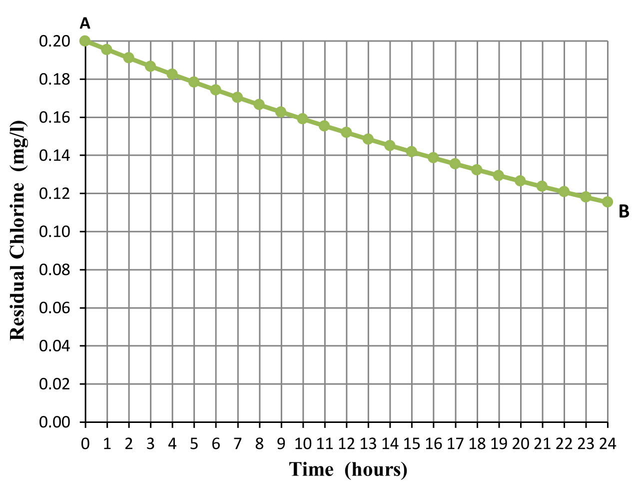

Fig. 3 Residual chlorine concentration at node 4 for case I

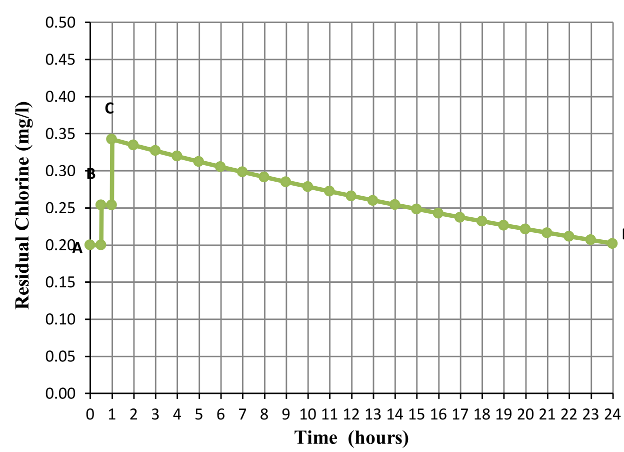

Fig. 4 Residual chlorine concentration at node 4 for case II

In the Figs. 3, 4, 5, 6, point A indicates initial concentration of chlorine at 0 h i.e. 0.2 mg/l. The observations for both the farthest nodes, node 4 and node 5, for case I and case II are as under.

Node 4 with case I and case II

As observed from Fig. 3 for node 4, the concentration after 24 h (Point B) is less than 0.2 mg/l as the travelling time of chlorine is greater than water supply hour of 2 h and

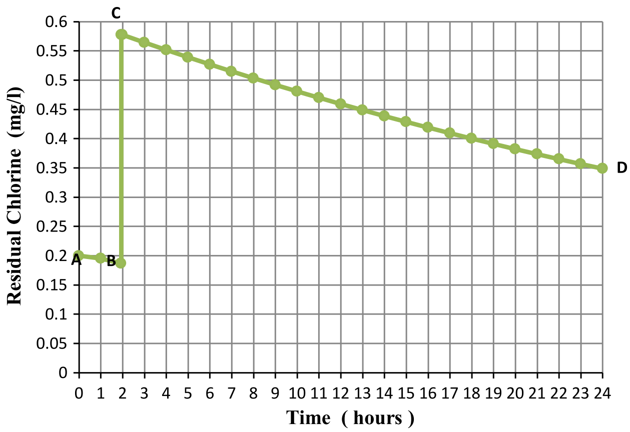

Fig. 5 Residual chlorine concentration at node 5 for case I

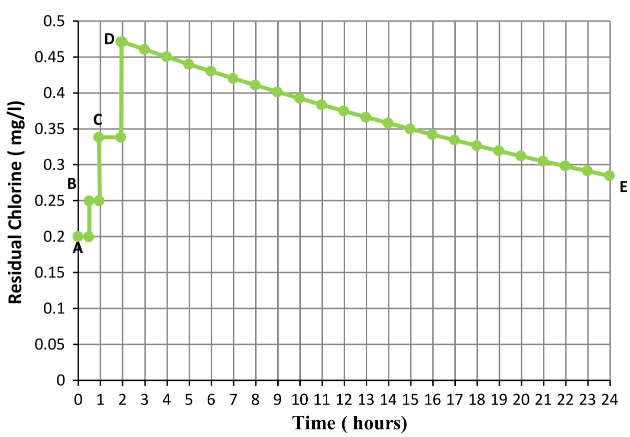

Fig. 6 Residual chlorine concentration at node 5 for case II

chlorine decay of initial concentration of chlorine i.e. 0.2 mg/l takes place. If we add more concentration at source then also there will not be any effect on final concentration as the travelling time is greater than supply hours (i.e. 2 h). In such cases, the booster chlorination helps to attain the required minimum concentration of chlorine.

As shown in Fig. 4 for node 4, point B shows the effect of addition of M_2 at node 2 which will reach first to node 4 after travelling time of t_4. Peak of point C is the effect of M_1 added at node 1 which will reach after travelling time of $t_4 + t_2$. As travelling time of chlorine is more than 2 h, the effect of M_o is not felt at node 4. After 2 h, the chlorine decay will take place for rest of 22 h of stagnant period and point D gives the final concentration of chlorine at node 4 after 24 h. As compared to case I due to addition of booster doses at node 1 and 2, chlorine concentration of 0.2 mg/l is achieved after 24 h which was not possible in case I due to less supply hours than travelling time.

Node 5 with case I and case II

In Fig. 5 for node 5, point B shows the initial decay of initial chlorine concentration of 0.2 mg/l. The peak (point C) is observed due to addition of M_0 at source and it will reach to node 5 as its travelling time is <2 h. After 2 h, the decay of chlorine will take place for 22 h of stagnant period and point D shows the final concentration after 24 h. Here, the supply hours are more than travelling time of chlorine which suggests that conventional chlorination may be effective in maintaining minimum residual chlorine at farthest node in such case.

As shown in Fig. 6 for node 5, point B shows the effect of addition of M_3 at node 3 which will reach first to node 5 after travelling time of t_5. Point C is the effect of M_1 added at node 1 which will reach after travelling time of $t_3 + t_5$. As travelling time of chlorine is <2 h for node 5, the effect of M_o is observed at node 5 which gives the peak at point D. After 2 h, the chlorine decay will take place for rest of 22 h of stagnant period and point E gives the final concentration of chlorine at node 5 after 24 h. As time of travelling at node 5 is less than supply hours, there is no major effect of booster chlorination observed on final concentration of chlorine. Thus, Booster chlorination is effective only for the farthest nodes, if the travelling time of chlorine is greater than supply hours as observed for node 4.

Conclusions

A simple network is adopted to generate explicit equations in terms of flow and chlorine mass rate for quick computation of the residual chlorine concentration at various nodes. This computation tool is also useful to decide the effect of booster chlorination on residual chlorine concentration. The sensitivity of water supply hours and the travelling time to residual chlorine can be understood for the selection of supply hours for intermittent water supply system. The major conclusions drawn from the results are:

(1) For conventional chlorination method if the travelling time of chlorine is greater than supply hours of water, the residual chlorine cannot reach to the farthest node like node 4 after 24 h. In case I, even though high mass rate of chlorine (2,230 mg/min) is supplied, chlorine will not reach to node 4 after 24 h as its travelling time is greater than supply duration of 2 h. In such cases, the selection of the water supply hours may be critical consideration for intermittent water supply system.

(2) Provision of booster chlorination is only effective in such conditions where farthest nodes are not receiving minimum desired residual chlorine concentration due to greater travelling time than supply hours.

(3) Application of booster chlorination strategy helps to maintain the residual chlorine of 0.2 mg/l at node 4 having travelling time >2 h water supply after 24 h

at the same time gives 23.78 % reduction in total mass rate of chlorine application.

Explicit equations based on first-order chlorine decay can provide very useful decision-making tool to justify the chlorine mass injection rate and selection of booster chlorination strategy. These linear equations can be further coupled with optimization technique for further use. It is noted that in this analysis the bulk decay coefficient and roughness values are assumed and minor losses are neglected. The calibration of these parameters with field observations is suggested for the better performances of model application.

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