Analysis of water quality characteristic for water distribution systems

Yumin Wang, Guangcan Zhu and Zhonglian Yang

ABSTRACT

Since governments all over the world are paying more attention to water quality in water distribution systems (WDS), a method based on mass balance and first-order chlorine decay model was proposed to assess the efficiency of WDS involving water quality (represented by residual chlorine). The concepts of surplus chlorine factor (*S*) for nodes in individual pipes and comprehensive surplus chlorine factor (*CS*) for nodes in WDS were put forward to represent the water quality characteristic of nodes in WDS based on the assumption that the structure of the pipe network and quantity of chlorine dose are definite. The proposed method was applied to two examples of WDS and sensitivity analysis regarding chlorine decay coefficient (k_0) was discussed. The results indicated that values of *CS* for nodes in WDS are affected by the inflow of nodes, which is determined by water demand and pipe length from water sources to nodes. In addition, the value of *CS* increases with k_0 when the inflow of the node is larger than the optimized inflow. The results verified that the deduction of *S* for a single pipe can be generalized to WDS, and can measure the water quality characteristics for nodes in WDS easily.

Key words | comprehensive surplus chlorine factor (*CS*), residual chlorine, surplus chlorine factor (*S*), water distribution system (WDS)

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NOMENCLATURE

WDS	Water distribution system
DOM	Dissolved organic matter
m	Chlorine decay quantity
q	Flow within the pipe
Q_{in}	Pipe inflow
Q_{out}	Pipe outflow
C_{in}	Residual chlorine concentration at the inlet
C_{out}	Residual chlorine concentration at the outlet
m_{in}	Chlorine entering the pipe at the inlet
m_{out}	Chlorine leaving the pipe at the outlet
k_0	First-order kinetic decay coefficient
L	Pipe length
D	Pipe diameter
$(C_{out})_{max}$	Maximum chlorine concentration at the outlet
k	Chlorine transfer efficiency
$(Q_{in})_{opt}$	Optimized pipe inflow
S	Surplus chlorine factor
CS	Comprehensive surplus chlorine factor

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INTRODUCTION

Water quality in water distribution systems (WDS) is currently of widespread concern, which is influenced by a number of factors including the water age, water storage facility, and disinfectant methods (Mau *et al.* 1996). Chlorine is the most widely used disinfectant for preventing finished water from regrowth of microbial pathogens (Kim *et al.* 2015). Most of the chlorine dosed is consumed in reactions with other substances remaining in the water after treatment, particularly dissolved organic matter (DOM) (Fisher *et al.* 2012). Therefore, the concentration of residual chlorine is required to be kept at a certain level, especially in the extremities of WDS (Li *et al.* 2013; Blokker *et al.* 2014). The most widely used chlorine decay model in WDS is the first-order decay model, expressed by Equation (1) as follows:

$$\frac{dC}{dt} = -k_0 C \tag{1}$$

where C is the concentration of chlorine, t refers to time, and k_0 stands for the chlorine decay coefficient (Hallam *et al.* 2002; Al-Jasser 2007; Fisher *et al.* 2011; Kim *et al.* 2014). In this paper, water quality characteristics of nodes in WDS based on the first-order chlorine decay equation mentioned above were analyzed.

The hydraulic characteristic and mechanical reliability of WDS have been much studied in the literature (Vaabel *et al.* 2006; Tanyimboh & Templeman 2007; Wu *et al.* 2011; D'Ercole *et al.* 2018). Mechanical reliability was defined as the probability that a component (new or repaired) experiences no structural failures (Kansal & Kumar 1995). The hydraulic reliability refers to the probability that a water distribution pipe can meet a required water flow level at a required pressure at each nodal demand (Ostfeld 2001). In order to increase the hydraulic capacity of a network and overcome sudden failures in WDS, the concept of hydraulic power capacity with consideration of both flow and pressure was identified (Vaabel *et al.* 2006). The hydraulic characteristic of nodes represented by the concept of surplus power factor based on hydraulic power was defined and applied to measure network resilience (Wu *et al.* 2011). However, both flow and water quality are of equal importance for WDS. The capacity concerning water quality for WDS has not been researched sufficiently in past studies (Gupta *et al.* 2012). Models have been developed of the chlorine concentrations at nodes in WDS with consideration of chlorine decay (Boulos *et al.* 1995; Mau *et al.* 1996; Hallam *et al.* 2002). The fraction of delivered quality (FDQ) was expressed to influence the water quality reliability, which is the ratio of simulation runs of supplied concentration below the threshold concentration to all the simulation runs (Ostfeld *et al.* 2002). Similarly, the ratio of days that the residual chlorine fulfills the residual chlorine standards to simulated days was proposed to represent water quality reliability (Zhao *et al.* 2010). The concept of node chlorine availability was proposed to define the water quality reliability of WDS (Li *et al.* 2013). The optimal operations of booster stations were proposed with the objective of minimizing the chlorine injection quantity (Tryby *et al.* 2002; Ostfeld & Salomons 2006; Kang & Lansey 2010). However, from the aspect of water quality management, the chlorine injection to WDS often remains fixed with no relationship to water demand. Under such circumstances, the water quality characteristics of nodes are affected by many factors, such as distance from water source to nodes, diameters and flows of pipes connecting with nodes, water demand of nodes, and chlorine decay coefficient, etc. The contribution of this paper is to research the degree of effect of various factors on water quality characteristics of nodes in WDS.

In this paper, first, based on the concepts of surplus chlorine factor (S) for nodes in single pipes deduced from a mass balance and first-order chlorine decay model, the concept of comprehensive surplus chlorine factor (CS) for nodes in WDS is proposed to analyze water quality characteristic of nodes in WDS. Second, CS was applied to measure the water quality characteristics in two examples of WDS based on an EPANET hydraulic and water quality extended simulation, and a sensitivity analysis of k_0 to CS is presented. Finally, values of CS of nodes in WDS were measured and compared, and the factors affecting CS are indicated and discussed.

METHODOLOGY

Surplus chlorine factor (S) for individual pipe

The ideal parameter for assessing water quality reliability should have clear physical meaning, be able to distinguish nodes in WDS, and be easy to calculate. Based on mass balance and the chlorine-decay model, we can obtain

Equations (2) and (3) from the individual pipe shown in Figure 1. The quantity of decayed chlorine is termed m, and the flow within the pipe is termed q.

$$m_{in} = Q_{in}C_{in} \tag{2}$$

$$m_{out} = Q_{out}C_{out} \tag{3}$$

where Q_{in} is the inflow of the pipe (L/s), Q_{out} is the outflow of the pipe (L/s), C_{in} is the concentration of residual chlorine at the inlet of the pipe (mg/L), C_{out} is the concentration of residual chlorine at the outlet of the pipe (mg/L), m_{in} is the quantity of chlorine entering the pipe per second at the inlet (mg/s), and m_{out} is the quantity of chlorine leaving the pipe per second at the outlet (mg/s). Suppose residual chlorine decay follows the first-order kinetic reaction equation, the concentration of residual chlorine at the outlet is expressed by Equation (4) as follows:

$$C_{out} = C_{in}\exp(-k_0 t) = \frac{m_{in}}{Q_{in}}\exp\left(-\frac{k_0 L\pi D^2}{4Q_{in}}\right) \tag{4}$$

where k_0 is the first-order kinetic decay coefficient (s^{-1}), L and D are the length (m) and diameter (m) of the single pipe, respectively.

Obviously, we can obtain Equations (5) and (6) for an individual pipe (shown in Figure 1), expressed as follows:

$$Q_{in} = Q_{out} = q \tag{5}$$

$$m = m_{in} - m_{out} \tag{6}$$

In Equation (4), L, D, k_0, and m_{in} are usually known; however, Q_{in} varies depending on the event. Therefore, C_{out} in Equation (4) can be expressed as a function of Q_{in} expressed by $C_{out}(Q_{in})$. The aim of this paper is to study the variation of C_{out}, and try to find the variation pattern of C_{out} with Q_{in} under the condition that the injection quantity of chlorine is definite. The optimized value of Q_{in} is to make the outlet chlorine concentration C_{out} reach the maximum value so as to get the water quality at the best operational condition. Therefore, according to Equation (4), with the assumption that $\frac{\partial C_{out}}{\partial Q_{in}} = 0$, we can deduce that C_{out} gets its maximum value when Q_{in} can satisfy the condition expressed by Equation (7), as follows:

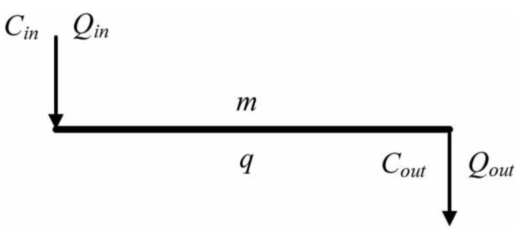

Figure 1 | Flows, concentration and chlorine loss for individual pipe.

$$(Q_{in})_{opt} = \frac{k_0 L\pi D^2}{4} \tag{7}$$

where $(Q_{in})_{opt}$ is the optimized value of Q_{in}.

Accordingly, C_{out} reaches the maximum value, which can be expressed by Equation (8) as follows:

$$(C_{out})_{\max} = \frac{m_{in}}{e(Q_{in})_{opt}} = \frac{4m_{in}}{ek_0 L\pi D^2} \tag{8}$$

where $(C_{out})_{\max}$ is the available maximum value of C_{out}, corresponding to $(Q_{in})_{opt}$. From Equation (8) we can find out that $(C_{out})_{\max}$ has relationships with the pipe characteristics (length L and diameter D), chlorine decay constant k_0, and the input chlorine quantity m_{in}. Therefore $(C_{out})_{\max}$ is a definite value for a given pipe. Usually the actual flow in a pipe is different from $(Q_{in})_{opt}$, thus the actual chlorine concentration C_{out} at the outlet is often different from $(C_{out})_{\max}$. Therefore, to assess the chlorine transfer efficiency, we can obtain Equation (9), expressed as follows:

$$k = \frac{C_{out}}{(C_{out})_{\max}} \tag{9}$$

where k refers to the chlorine transfer efficiency.

By combining Equations (4) and (7), the coefficient k can also be expressed by Equation (10) as follows:

$$k = \frac{\exp(-k_0 L\pi D^2/4Q_{in})ek_0 L\pi D^2}{4Q_{in}} \tag{10}$$

In order to simplify Equation (10), parameter η was defined by Equation (11) as follows:

$$\eta = \frac{k_0 L\pi D^2}{4Q_{in}} \tag{11}$$

In addition, η can also be expressed by Equation (12) as follows:

$$\eta = \frac{(Q_{in})_{opt}}{Q_{in}} \tag{12}$$

Therefore, Equation (10) was transformed into Equation (13) as follows:

$$k = \frac{e\eta}{\exp(\eta)} \tag{13}$$

The relationship curve between k and $\frac{Q_{in}}{(Q_{in})_{opt}}\left(\text{i.e.}\frac{1}{\eta}\right)$ is shown in Figure 2, where k is presented as a function of $\frac{Q_{in}}{(Q_{in})_{opt}}$ or η. The scope of k is between 0 and 1.0. In effect, the water quality characteristics of WDS get better when the chlorine concentration at the outlet is higher. If $k = 1$, C_{out} reaches the maximum value $(C_{out})_{\max}$, which means that the pipe works at the best condition from the viewpoint of water quality corresponding to value of $\frac{Q_{in}}{(Q_{in})_{opt}}$ being 1.0 (also shown in Figure 2).

Since the coefficient k characterized the potentiality of chlorine concentration of the node, the concept of surplus chlorine factor (S) was proposed to represent the water quality characteristic of the node, expressed by Equation (14) as follows:

$$S = 1 - k = 1 - \frac{e\eta}{\exp(\eta)} \tag{14}$$

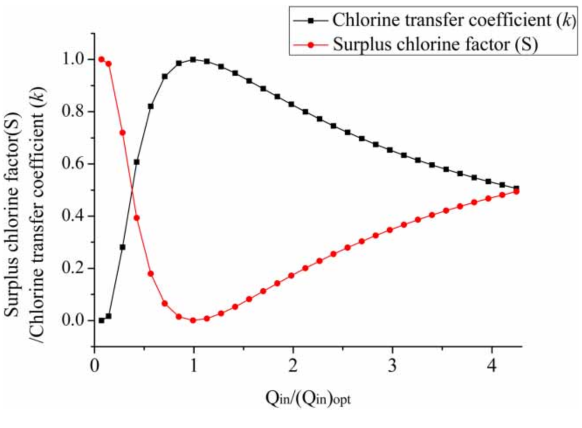

Figure 2 | Relationship curves of surplus chlorine factor (S) and chlorine transfer coefficient (k) with $Q_{in}/(Q_{in})_{opt}$.

where S refers to surplus chlorine factor (S), which is applied to assess the characteristic of the node in view of water quality. The scope of S is between 0 and 1, which is similar to k. If S decreases, water quality reliability of WDS will be improved. When S decreases to 0, C_{out} reaches $(C_{out})_{\max}$, which means WDS work with maximum chlorine concentration at the outlet.

From Figure 2, we can also find that when Q_{in} decreases or increases from $(Q_{in})_{opt}$, C_{out} always decreases. Combining Equations (13) and (14), we can also conclude that if η or $\frac{Q_{in}}{(Q_{in})_{opt}}$ is fixed, k and S remain unchangeable. When $\frac{Q_{in}}{(Q_{in})_{opt}}$ varies in the range from 0 to 1.0, with the rise of $\frac{Q_{in}}{(Q_{in})_{opt}}$, k increases and S decreases. On the contrary, when $\frac{Q_{in}}{(Q_{in})_{opt}}$varies in the range from 1.0 to ∞, with the rise of $\frac{Q_{in}}{(Q_{in})_{opt}}$, k decreases and S increases. The reason can be explained as follows. From Equation (14), we can deduce Equation (15), expressed as follows:

$$\frac{dS}{d\eta} = -(1-\eta)\exp(1-\eta) \tag{15}$$

From Equation (15), we can find that when η is bigger than 1.0, i.e. $\frac{Q_{in}}{(Q_{in})_{opt}}$ is in the scope of (0, 1.0), $\frac{dS}{d\eta}$ is greater than 0, which means that S decreases with the decrease of η or the rise of $\frac{Q_{in}}{(Q_{in})_{opt}}$. Similarly, when η is smaller than 1.0, i.e. $\frac{Q_{in}}{(Q_{in})_{opt}}$ is in the scope of (1.0, ∞), $\frac{dS}{d\eta}$ is smaller than 0, which means that S increases with the decrease of η or the rise of $\frac{Q_{in}}{(Q_{in})_{opt}}$.

Relationship between surplus chlorine factor (S) and Q_{in} under different chlorine decay constant k_o

From Equations (10), (11), and (14), we can find parameters k and S vary with the decay coefficient k_O for the individual pipe. The chlorine decay coefficient k_O varies with flow velocity and temperature (Blokker et al. 2014). From Equation (8) we can draw the conclusion that $(C_{out})_{\max}$ always decreases with the increase of k_0 when the other factors remain the same, which means that chlorine decay coefficient k_0 affects the reachable maximum chlorine concentration negatively. In addition, with the increase of k_0, the value of $(Q_{in})_{opt}$ increases according to Equation (7), which means that water flow in the pipe will increase to meet the chlorine concentration of $(C_{out})_{\max}$ at the outlet. With the increased chlorine decay coefficient of k_0, the chlorine concentration at the outlet C_{out} decreases. Therefore, the variation of k and S with k_0 depends on the relative increased degrees of C_{out} and $(C_{out})_{\max}$. The relationship curves between S and Q_{in} under different values of k_0 are shown in Figure 3. The values of k_0 ranged from +20% to −20%.

With the increase of Q_{in}, S decreases from 1.0 to 0 initially, then increases with the rise of Q_{in}. When the value of S is 0, Q_{in} reaches the best value of $(Q_{in})_{opt}$. For a specific curve with certain k_0, when Q_{in} is less than $(Q_{in})_{opt}$, S decreases with the rise of Q_{in}. On the contrary, if Q_{in} is greater than $(Q_{in})_{opt}$ for certain k_0, S increases with the rise of Q_{in}. The values of $(Q_{in})_{opt}$ vary with k_0. When k_0 increases, $(Q_{in})_{opt}$ also increases, which is in accordance with Equation (7). Among all the values of $(Q_{in})_{opt}$, $(Q_{in})_{opt1}$ is the smallest, corresponding to $0.8k_0$, and $(Q_{in})_{opt2}$ is the biggest, corresponding to $1.2k_0$. From Figure 3 we can also find that when Q_{in} is less than $(Q_{in})_{opt1}$, the higher the chlorine decay coefficient k_0 is, and the greater S is for the same Q_{in}. However, when Q_{in} is greater than $(Q_{in})_{opt2}$, the higher the chlorine decay coefficient k_0 is, and the smaller S is for the same Q_{in}. The reason can be explained by the fact that when Q_{in} is less than $(Q_{in})_{opt1}$, η is always bigger than 1.0. From Equation (15), we can obtain that $\frac{dS}{d\eta}$ is greater than 0. Therefore, if k_0 increases, then η increases correspondingly according to Equation (11), which leads to the rise of S that coincides with the curve in Figure 3. Moreover, when Q_{in} is greater than $(Q_{in})_{opt2}$, then η is always smaller than 1.0, which leads to $\frac{dS}{d\eta}$ being less than 0. Therefore, if k_0 increases, then η increases correspondingly according to Equation (11), which leads to the decline of S that also coincides with the curve in Figure 3.

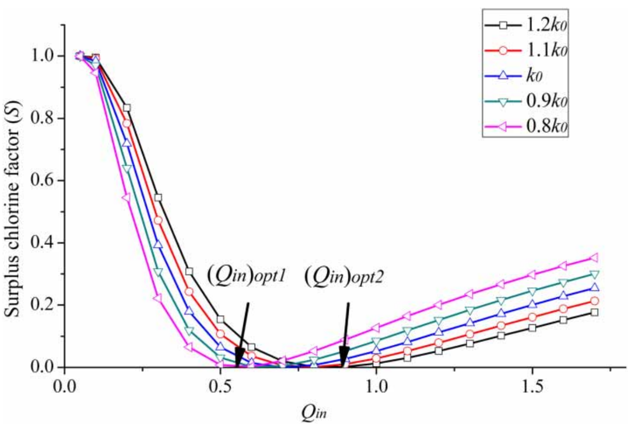

Figure 3 | Relationship curves between surplus chlorine factors (S) and Q_{in} under different k_0.

Comprehensive surplus chlorine factor (*CS*) for water distribution network

The consideration for the individual pipe can also be generalized for WDS. For a pipe net consisting of two pipes, shown in Figure 4, node n was connected with two single pipes.

From Figure 4, we can obtain Equations (16)–(18), expressed as follows:

$$Q_{in1} + Q_{in2} = Q_{out} \tag{16}$$

$$Q_{in1} = q_1 \tag{17}$$

$$Q_{in2} = q_2 \tag{18}$$

where Q_{out} is the flow of node n, Q_{in1} is the flow in pipe ① connecting with node n, Q_{in2} is the flow in pipe ② connecting with node n.

The value of CS for node n is calculated by Equation (19) as follows:

$$CS = \sum_{i=1}^{K} w_i S_i = \sum_{i=1}^{K} \left(\frac{Q_i}{\sum Q_i} \right) S_i \tag{19}$$

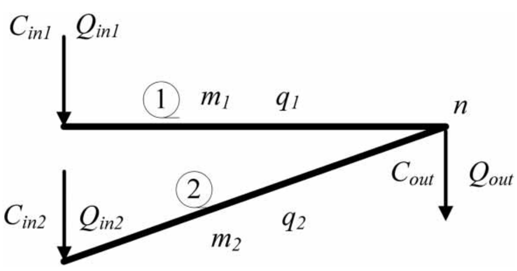

Figure 4 | Flows, concentration, and chlorine loss for a pipe net.

where CS is the comprehensive surplus chlorine factor for node n, S_i ($i = 1, 2, \ldots, K$) is the surplus chlorine factor for node n through the i^{th} pipe, Q_i ($i = 1, 2, \ldots, K$) is the flow of the i^{th} pipe connecting with node n, and K is the number of pipes connected with node n.

For a given WDS that consists of multiple pipes, water sources and nodes, CS for nodes varies with the inflow to nodes, length of pipes from water sources to nodes, diameters of pipes connecting with nodes, water demand of nodes, and chlorine decay coefficient k_0, etc. For a certain node in WDS, the length of pipes from water sources to nodes and the diameters of pipes connecting with nodes are determined beforehand. However, the inflow Q_{in} of a node is variable depending on water demand by users, including residents and industrial enterprises. The chlorine decay coefficient k_0 varies with the water quality, water temperature, and the pipe material. Therefore, values of CS for nodes in a given WDS usually vary with water demand and chlorine decay coefficient k_0. For nodes in a WDS, the length of pipes from water sources to nodes and the diameters of pipes connecting with nodes are different. The values of CS for nodes vary with the differences in pipe lengths and pipe diameters.

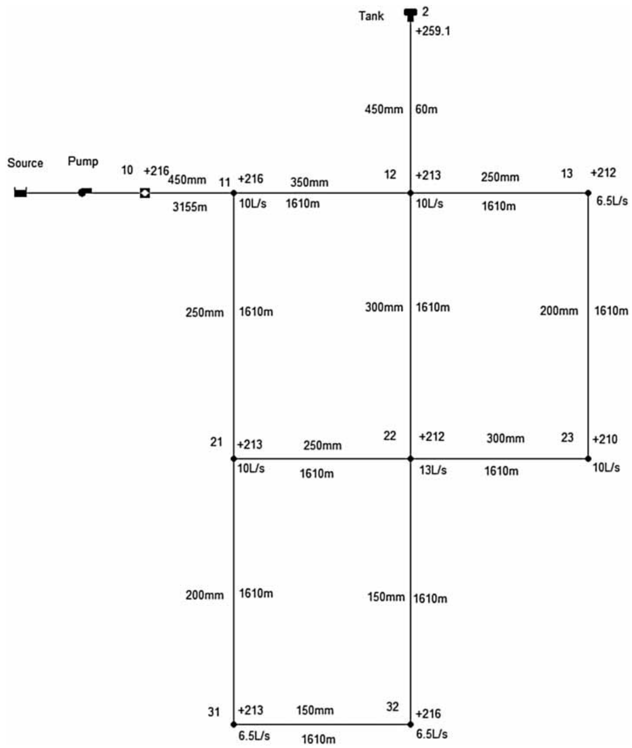

Figure 5 | Example 1 (Rossman 1994).

RESULTS AND DISCUSSION

Example 1

Base run

The proposed methodology was demonstrated for a small illustrative system shown in Figure 5 (Rossman 1994). The initial residual chlorine of the water works was supposed to be 0.5 mg/L. During the hydraulic simulation progress of EPANET2, the Hazen–Williams function was used as the hydraulic simulation model, and the roughness coefficient was assumed to be 100. During the water quality simulation progress, the chlorine decay coefficient k_0 was set to be -1.55/day (Rossman 1994).

The system consists of 12 pipes, a water source, a pump, and an elevated storage tank. The system is subject to a 24-h representative demand pattern shown in Table 1.

The pump is fed by a source that is at a constant water level of 243.8 m. The water is delivered to a storage elevated tank at node 2 (at a ground level of 259.1 m), and to eight consumers located at nodes 11, 12, 13, 21, 22, 23, 31, and 32. The pump has a shutoff head value of 101.3 m and a maximum flow rate of 189.3 L/s. The tank is cylindrical with a diameter of 15.4 m. Its minimum, initial, and maximum levels above ground are 30.5 m, 36.6 m, and 45.7 m, respectively. The results of the base run for the case study are shown in Figure 6 and Table 2.

Table 1 | 24-h demand pattern characteristics for example (Rossman 1994)

Time of day	1–2	3–4	5–6	7–8	9–10	11–12	13–14	15–16	17–18	19–20	21–22	23–24
Multiplier of base demand	1.0	1.2	1.4	1.6	1.4	1.2	1.0	0.8	0.6	0.4	0.6	0.8

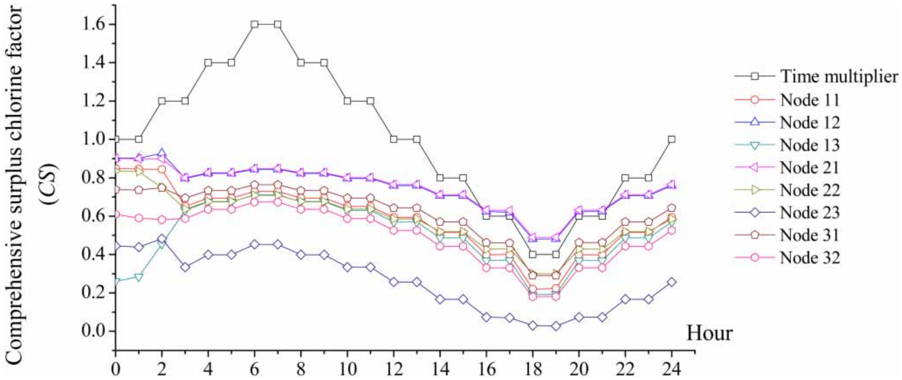

Figure 6 | Variation curves of time multiplier and comprehensive surplus chlorine factor (*CS*).

Table 2 | Average comprehensive surplus chlorine factors (*CS*) in 24 h for nodes in Figure 5

Nodes	11	12	13	21	22	23	31	32
Average values of *CS*	0.55	0.71	0.49	0.68	0.55	0.25	0.59	0.47

The variation curves of the time multiplier and comprehensive surplus chlorine factors (*CS*) for all nodes in 24 h calculated by Equation (19) are shown in Figure 6. We can also find that for almost all nodes besides node 13, values of *CS* were the smallest at the 19th–20th hour when water demand is also the least, which means that values of *CS* for nodes vary with characteristics of the demand pattern for these nodes. It can be explained that when water demand decreases, the flow Q_{in} decreases accordingly, which leads to direct increase of C_{in} under the condition that chlorine injection m_{in} is fixed. The outlet concentration C_{out} increases with C_{in}, which leads to the increase of k and decrease of S. The condition is consistent with the case for a single pipe, shown in Figure 3, when Q_{in} is greater than $(Q_{in})_{opt}$.

For comparing water quality characteristics of nodes in WDS, the average values of *CS* for nodes in 24 h are shown in Table 2.

From Table 2, we can find that the average value of *CS* for node 23 is significantly less than other nodes. The reason for this is that values of Q_{in} for all nodes are greater than $(Q_{in})_{opt}$ obtained by Equation (7), and η is always less than 1.0, but Q_{in} for node 23 is closer to $(Q_{in})_{opt}$, since node 23 is the terminal node of the pipe network. Therefore, η for node 23 is closer to 1.0 than other nodes according to Equation (11), which leads to a smaller value of *CS*. The conclusion is in accordance with the case shown in Figure 3 for a single pipe; that is, the closer the node inflow is to $(Q_{in})_{opt}$, the smaller *CS* is for the node.

Sensitivity analysis

Since chlorine decay coefficient k_0 is of significant importance in WDS, the sensitivity analysis of k_0 to *CS* is performed. The decay coefficient k_0 is set to vary from −20% to +20% compared with k_0 in the base run keeping other data the same as that in the base run. The results of average values of *CS* for all nodes are shown in Table 3.

Table 3 | Average comprehensive surplus chlorine factor (*CS*) for all nodes in Example 1 (k_0 varies from −20% to +20%)

	Chlorine decay coefficient				
Nodes	$0.8\,k_0$	$0.9\,k_0$	k_0	$1.1\,k_0$	$1.2\,k_0$
11	0.64	0.61	0.55	0.54	0.51
12	0.79	0.76	0.71	0.72	0.70
13	0.59	0.55	0.49	0.48	0.45
21	0.79	0.77	0.71	0.72	0.70
22	0.63	0.60	0.55	0.55	0.52
23	0.34	0.30	0.25	0.23	0.20
31	0.68	0.64	0.59	0.58	0.55
32	0.57	0.53	0.47	0.46	0.43

We can observe that values of *CS* for nodes 11, 13, 22, 23, 31, and 32 decrease with the increase of k_0. Although node 12 and node 21 do not comply with the conclusion completely, the variation trends of *CS* with k_0 are the same as other nodes. Based on Figure 3, the relationship between *S* and k_0 depends on Q_{in} for individual pipes. According to the analysis above, that values of Q_{in} for all nodes are greater than $(Q_{in})_{opt}$, *S* decreases with the rise of k_0. Although a water distribution network is more complex than an individual pipe, the calculations of *CS* are on the basis of *S* of individual pipes. Therefore, the variation trend of average values of *CS* for all nodes with chlorine decay coefficient k_0 can be explained by the conclusions resulting from individual pipes.

In addition, the hourly variations of *CS* for node 21 and node 23 are shown in Figure 7(a) and 7(b).

We can find from Figure 7(a) that although node 21 does not comply with the conclusion that average values of *CS* decrease with the increase of k_0, the hourly variation of *CS* corresponding to k_0 is the same as other nodes; that is, *CS* decreases with the increase of k_0, which is in accordance with the case shown in Figure 3 when Q_{in} is greater than $(Q_{in})_{opt}$.

We can also find from Figure 7(b) that although average values of *CS* for node 23 follow the conclusion that average values of *CS* decrease with the increase of k_0, the hourly variation of *CS* does not follow the same conclusion for the valley hour of 18 h–19 h. The reason is that the inflow of node 23 is smaller than other nodes, and when the water demand is lower, the inflow of node 23 becomes lower than $(Q_{in})_{opt}$, which leads to the increase of *CS* with k_0. The conclusion is also is in accordance with the case shown in Figure 3, when Q_{in} is less than$(Q_{in})_{opt}$; that is, the higher the chlorine decay coefficient k_0, the bigger the water quality characteristic *CS* for the node.

Comparing results in Figure 7(a) and 7(b), hourly values of *CS* for node 21 are greater than hourly values of *CS* for node 23. The reason is that Q_{in} at node 23 is smaller than Q_{in} at node 21, and is closer to $(Q_{in})_{opt}$, which leads to the values of *CS* for node 23 being less than the values of *CS* for node 21, which means that the water quality characteristic of node 23 is better than node 21.

The variations of *CS* for all nodes under various k_0 corresponding to peak hour (8th hour) and valley hour (19th hour) were analyzed and are shown in Figure 8(a) and 8(b).

From Figure 8(a), we can conclude that at peak hour (8th hour), values of *CS* for all nodes decrease with the increase of k_0, which is in accordance with the results above. Moreover, under various k_0, values of *CS* decrease in the order of node 21 > node 12 > node 31> node 11 > node 13> node 22 > node 32> node 23, which means that at peak hour the water quality characteristic is best at node 23, and worst at node 21. However, from Figure 8(b) at the valley hour (19th hour), we can find that the variation trend of *CS* for almost all nodes decreases with the rise of k_0 except for node 23, which is similar to the peak hour (8th hour). For node 23 at the valley hour (19th hour), the values of *CS* increased with the rise of k_0, which means that the water quality characteristic of node 23 became worse with the increase of k_0. The values of *CS* decreased in the order of node 21 > node 12> node 22 > node 31 > node 11 > node 32> node 13 > node 23.

Comparing results in Figure 8(a) and 8(b), values of *CS* at the peak hour (8th hour) are greater than at the valley

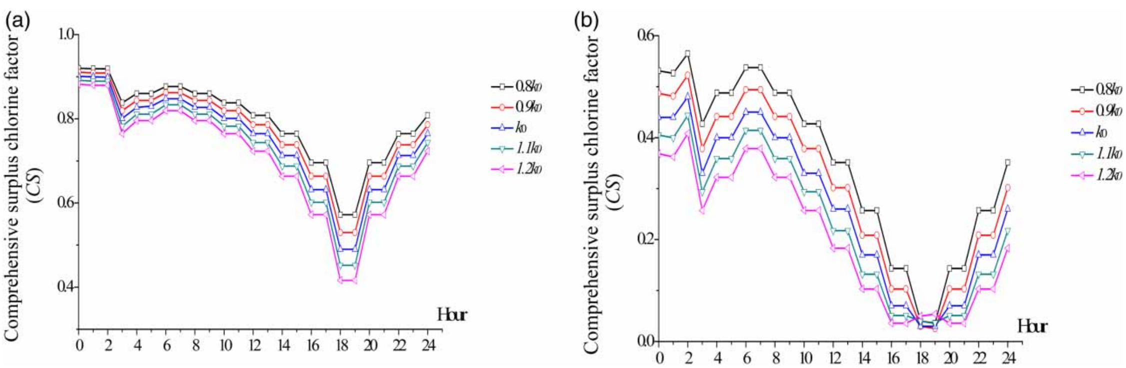

Figure 7 | Variation of comprehensive surplus chlorine factor (*CS*) for (a) node 21 under various k_0 and (b) node 23 under various k_0.

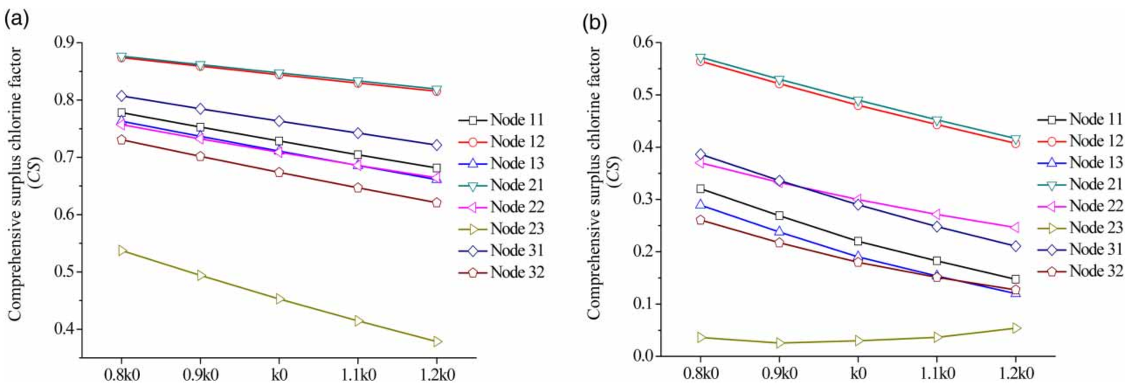

Figure 8 | Variation of comprehensive surplus chlorine factor (*CS*) at (a) peak hour (8th hour) for all nodes under various k_O and (b) valley hour (19th hour) for all nodes under various k_O.

hour (19th hour), which is in accordance with results obtained from Figure 6. When water demands at the valley hour are lower than water demands at the peak hour, the water quality characteristics of nodes are improved.

Example 2

In this case, the concept of *CS* for the node was applied to a real-life network shown in Figure 9 (Example 3 of EPANET software (Rossman 1994)). The system consists of two sources, one elevated tank, 117 pipes, 97 demand nodes, and two pumps (the complete data used were exactly as that of Example 3, in Rossman (1994), and thus are not repeated here). The coefficient of chlorine decay was set to be −1.55/day.

The results of *CS* for typical nodes in Example 2 are shown in Table 4.

For nodes at the extremities of the WDS in Example 2, the average values of *CS* were lower than other nodes, which are

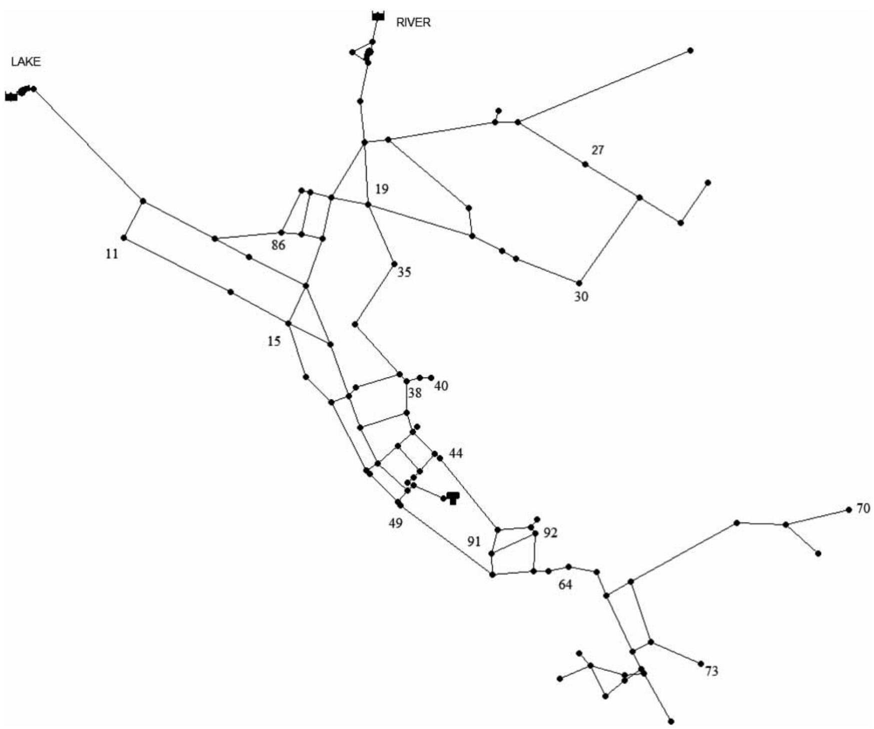

Figure 9 | Example 2.

Table 4 | Average comprehensive surplus chlorine factor (*CS*) for nodes in Example 2

Nodes	Water demand of nodes (*L/s*)	Inflow of nodes (*L/s*)	Outflow of nodes (*L/s*)	Diameters of pipes connected with nodes (mm)	Average comprehensive surplus chlorine factor (*CS*)
11	11.245	11.245	0.000	400, 400	0.848
15	11.983	34.687	22.704	300, 300, 300, 300	0.964
19	14.869	470.546	455.677	750, 750, 300, 300	0.969
27	0.497	8.890	8.393	200, 200	0.873
30	2.332	6.953	4.621	300, 300	0.662
35	4.372	384.523	380.151	750, 750	0.957
38	0.795	359.491	358.696	750, 750, 350	0.990
40	0.219	0.219	0.000	350	0.211
44	0.000	75.843	75.843	750, 600	0.998
49	0.000	5.069	5.069	200, 300	0.998
64	0.000	45.475	45.475	300, 300	0.996
70	3.488	3.488	0.000	350	0.698
73	1.391	1.391	0.000	300	0.520
86	0.000	36.040	36.040	300, 200, 300	0.976
91	0.000	31.084	31.084	300, 200, 300	0.972
92	0.000	30.837	30.837	300, 200, 300	0.996

0.662, 0.221, 0.698, and 0.52 for node 30, 40, 70, and 73, respectively. The reason is that the inflows of nodes 30, 40, 70, and 73 are 6.953, 0.219, 3.488, and 1.391 *L/s*, respectively, lower than other nodes, which leads to the decrease of *CS*, and improvement of the water quality characteristic of nodes. Moreover, the smaller inflow of nodes leads to a lower value of *CS*. For example, the inflows of the four nodes increase in the order of node 40 < node 73 < node 30 < node 70. Accordingly, the values of *CS* for the four nodes increase in the same order. Although the inflow of node 27 is less than node 11, the pipe diameter connecting to node 27 is smaller than node 11, which leads to the value of *CS* at node 27 being larger than the value of *CS* at node 11. The reason for this is that η is affected by pipe diameter, pipe length from water sources to node, and inflow of nodes together, which is shown in Equation (11). The value of η determines the water quality characteristic of nodes expressed by *CS*.

CONCLUSION

In this paper, the concept of surplus chlorine factor (*S*) for a node in a single pipe based on the mass balance and first-order chlorine decay model was deduced. The relationship between *S* and $\frac{Q_{in}}{(Q_{in})_{opt}}$, and the variation under different k_0 for a single pipe were revealed. In addition, comprehensive surplus chlorine factor (*CS*) for nodes in WDS based on *S* was put forward, and applied to two examples of WDS during 24 h in a day (shown in Figures 5 and 9). The results indicated that the value of *CS* decreases with the decrease of inflow at the node, which is caused by lower water demand and longer pipe length from water sources to node. In addition, average values of *CS* decrease with the increase of chlorine decay coefficient k_0. The conclusions are in accordance with the results obtained from a single pipe when Q_{in} is greater than$(Q_{in})_{opt}$. When the inflow at the node which is further from water sources becomes lower than $(Q_{in})_{opt}$ at the valley hour, the value of *CS* increases with the increase of chlorine decay coefficient k_0. In addition, the diameters of pipes connecting with nodes also affect the water quality characteristics of nodes; that is, the larger the pipe diameter, the better the water quality characteristics of nodes. The proposed method was proved to be efficient and easy to use for analyzing the water quality characteristic of nodes in WDS.

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