Framework for optimizing chlorine dose in small- to medium-sized water distribution systems: A case of a residential neighbourhood in Lahore, Pakistan

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ABSTRACT

To maintain desirable residual chlorine for a groundwater source, optimizing the chlorine dose in small- to medium-sized water distribution systems (SM-WDS) is a daunting task in developing countries. Mostly, operators add a random chlorine dose without recognizing the smaller size of their distribution network. In this research, a modelling framework for optimizing chlorine dose in SM-WDS is developed. In order to evaluate its practicality, the proposed framework has been applied in a case study of a residential neighbourhood in Lahore (Pakistan) with a small network spanning over 0.35 km^2. Three datasets for residual chlorine were monitored at 6 locations spread over the study area. EPANET 2.0 software was used for hydraulic and residual chorine modelling. The bulk decay coefficient (K_b) was determined in the laboratory, whereas the wall decay coefficient (K_w) was estimated by calibrating the simulation results with the residual chlorine determined in the field. Based on the calibrated EPANET simulations, a fuzzy rule-based model was developed for pragmatic application of the proposed framework. Scenario analyses for different situations have also been carried out for achieving residual chlorine required at the consumer end. This exercise revealed that much lower chlorine doses than the existing practice can generate detectable chlorine residuals. Moreover, the model can be used to deal with emergency situations, which may arise in developing countries due to viral outbreaks and cross-contamination events in SM-WDS.

Keywords: small- to- medium-sized water distribution systems, residual chlorine modelling, water quality, chlorine decay coefficients, fuzzy rule-based modelling, EPANET

INTRODUCTION

Water service providers must practise disinfection before supplying water to consumers to prevent the outbreak of waterborne infectious diseases (Clark, 1998). Bacteriological contamination of water is the major contributor to waterborne diseases. Millions of such cases occur annually in developing countries, including Pakistan (Haider et al., 2014; WHO, 2004). In Lahore alone, 10 000 people die annually due to the drinking of bacteriologically-contaminated water (PCRWR, 2002). Eighty per cent (80%) of all illnesses in developing countries are linked to poor water quality and sanitation conditions (e.g., cholera, typhoid, hepatitis, dysentery, guinea worm infections, etc.) (PCRWR, 2007). The major reasons for this contamination include: (i) poorly maintained/leaking pipe networks, (ii) laying of water supply pipelines parallel to or beneath sewers, and (iii) groundwater contamination due to disposal of untreated sewage into the water bodies which recharge the nearby water wells (Haydar and Qasim, 2013).

For surface water sources, conventional methods of primary disinfection for public water supplies are: (i) ultraviolet radiation; (ii) ozonation; and (iii) chlorination. The first two methods do not generate significant residuals when compared with chlorine. Thus, they fail to protect consumers if any contamination enters the distribution system after disinfection has been carried out (at the source of water supply). Moreover, the first two products are costly and thus not suitable for public water supplies (dealing with large volumes of water) in developing countries (Haider, 2006). On the other hand, chlorine produces residuals that remain in the distribution system till the water reaches the consumers. It is relatively easy to handle, requires low capital and operational costs, and is simple to operate, measure and control (Freese and Nozaic, 2004).

Groundwater sources (particularly deep bore pumping in urban areas) are generally free from bacterial contaminants. Nevertheless, a disinfectant residual is maintained throughout the distribution system to inactivate microorganisms and to control the growth of biofilm in pipes. This practice is known as secondary disinfection. Presently, free chlorine is the most commonly used secondary disinfectant around the world (USEPA, 2012). Residual chlorine concentration within the distribution system depends on a number of site-specific factors: including type and initial concentration of the disinfectant; physical, chemical and biological quality of the water; decay of chlorine; type of pipe material; and contact time (i.e., time spent by a parcel of water reacting with the disinfectant in the distribution system). Chlorine decay occurs due to its reactions with organic and inorganic matter and other environmental factors in the water distribution system (Castro and Neves, 2003; Rossman et al., 1994).

Different agencies have established a minimum concentration of disinfectant at the point of entry, depending on the type of contaminant under consideration, pH and temperature of water and type of disinfectant used (USEPA, 2012). For example, chlorine dioxide needs a longer contact time for inactivation of viruses than free chlorine, but can inactivate *Giardia* much earlier than free chlorine, and also provides some protection against *Cryptosporidium* oocysts. As per national standards for drinking water quality (NSDWQ), the regulatory

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requirement for chlorine residual at the consumer end ranges between 0.2 to 0.5 mg·ℓ⁻¹ in Pakistan (PEPA, 2008).

In order to meet these regulatory requirements, the normal practice of plain chlorination in small- to medium-sized water distribution systems (SM-WDS) is to select an arbitrary value of chlorine dose reported in the literature (say 1.0 mg·ℓ⁻¹) at the source without considering the size of the network and the possible pattern of decay in the distribution system. This sometimes results in either under-dosing, exposing the consumer to bacterial threat, or over-dosing which can increase the economic cost of disinfection and taste and odour problems. Moreover, excess chlorine can react with natural organic matter and other chemicals (e.g., bromide) to form halogenated organic compounds which are harmful to human health, such as trihalomethanes (THMs), haloacetic acids, and chlorophenols (USEPA, 1999; Weisel et al., 1999). Chlorine can also form other compounds which are not halogenated, such as aldehydes, carboxylic acids, ketones and alcohols (Richardson, 1998). Hence, both over and under dosing are undesirable. Therefore, the residual chlorine should be modelled to optimize the chlorine dose in SM-WDS operating in urban residential neighbourhoods. Chlorine residual modelling can provide valuable insights into the consumption of applied dose in a system, and also help to identify the problematic areas within the given water distribution system. Modelling results can be used to optimize dose to maintain the minimum desirable chlorine residual throughout the system.

In the past, several steady-state and dynamic models have been used to simulate residual chlorine in water distribution systems (Chun and Selznick, 1985). Dynamic models include several parameters and thus require extensive data requirements. Most of the models simulate chlorine residual using first-order kinetics; however, researchers have also developed two-dimensional (2D) chlorine transport and decay equations (Özdemir, 2000), which again is a complex task when data are limited. EPANET, developed by the United States Environmental Protection Agency (USEPA) has been extensively used for hydraulic and water quality simulations over the last two decades (Ahn et al., 2012). The model can be used to determine residual chlorine concentration at any time and location in the distribution system. Chlorine decay is a site-specific phenomenon, and depends on several variables, i.e., initial chlorine concentration, source water characteristics, water temperature, type of chlorine, and type of pipe material. Thus, estimating chlorine residual decay coefficients through laboratory studies and the model calibration process (i.e., comparison of model results with measured ones) is important to determine the optimum chlorine dose. Moreover, the uncertainties in data and variations in system parameters should also be addressed in the modelling process.

The main objective of the present study was to propose a simple chlorine residual modelling framework to optimize the chlorine dose at the source to produce minimum (required) chlorine residual at the user end. The proposed framework integrates EPANET software results (for estimating the model parameters through field and laboratory studies) with a fuzzy rule-based model (FRBM) to optimize chlorine dose for routine operations. The proposed framework is applied to a case study of a residential neighbourhood in Lahore, Pakistan, to evaluate its practicality for real-world scenarios.

METHODOLOGY

The modelling framework to optimize chlorine dose in SM-WDS is shown in Fig. 1. The public domain model 'EPANET 2' developed by USEPA was used for hydraulic and water quality simulations. The MATLAB fuzzy logic tool box is used to optimize the chlorine dose under the given physical

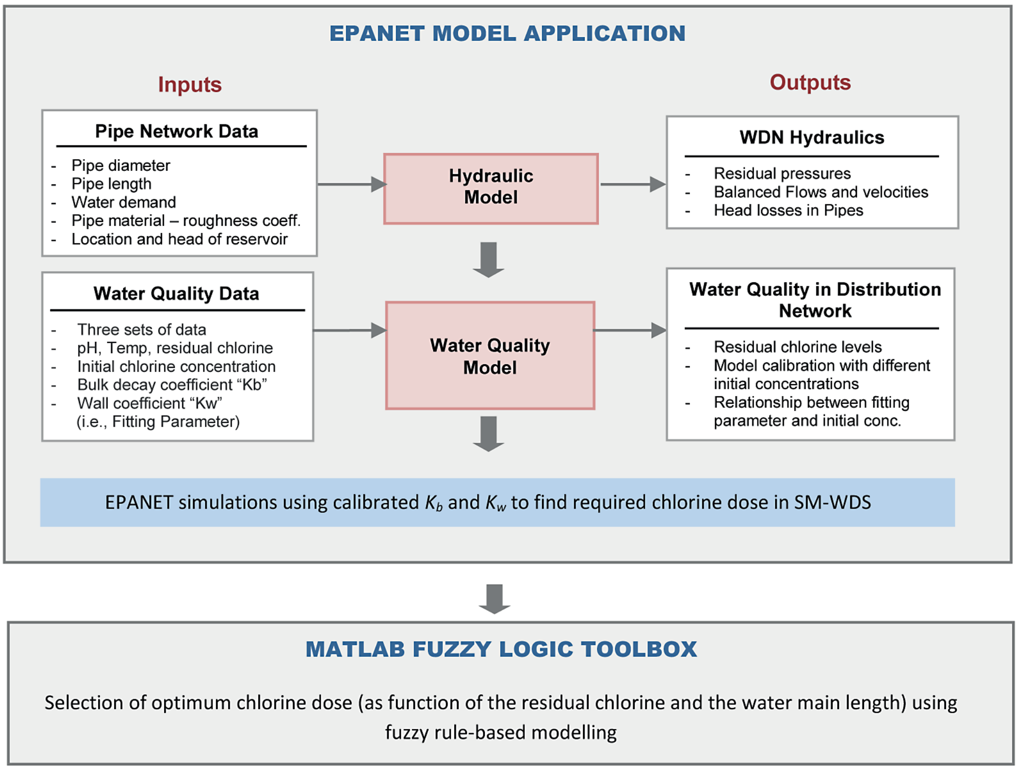

Figure 1
Chlorine residual modelling framework developed in this study for SM-WDS

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and environmental conditions. Details of these components of the framework are given in the following sections.

Hydraulic and water quality modelling

Hydraulic modelling is a prerequisite for water quality modelling. The hydraulics of the water distribution network consists of pipes, valves, overhead reservoirs (OHRs), and pumps. The hydraulic model in EPANET 2 requires input data for all of these components, such as pipe length, pipe diameter, location and initial head of OHRs, and locations and input heads of the pumps for the network under study (Rossman, 2000). The hydraulic simulation model outputs include flows at the junctions, velocities and major head losses in the pipes. Head losses are calculated by using the Hazen-Williams or the Darcy-Weisbach formulae. The model also estimates the minor head losses occurring due to turbulence at bends and fittings.

Due to the variable flow requirements over time, water distribution networks are designed to meet peak hourly demands by multiplying the average water demand with a peaking factor. The selected hydraulic model therefore uses a time pattern, which essentially is a collection of multipliers that can be applied to a quantity to deal with the flow variations during the assessment period. The heads and flows are calculated for a specific reservoir level and water demand. Later, these are updated with the changes in the next reservoir level and demand, according to the prescribed time pattern. This overall process is known as hydraulic balancing, and requires the solution of multiple nonlinear equations. Details can be found in the EPANET 2.0 Manual developed by USPEA (Rossman, 2000).

In addition to the hydraulic model, EPANET requires various inputs to simulate residual chlorine in a distribution system, e.g., initial chlorine concentration, water temperature, pH, etc. The simulator uses a Lagrangian time-based approach to determine the fate of discrete water parcels during their movement along the pipes, and when they mix together at junctions. Time steps in the chemical transport process are very short (i.e., minutes instead of hours). There are 4 different models available to deal with mixing in the reservoir. The complete mixing model is the most commonly used, and hence is the one used in this study. This assumes that all of the water which enters into the tank is completely mixed before entering into the distribution system. EPANET simulates the chlorine decay as the water travels through the distribution system. This decay depends on both the rate of decay and the initial chlorine concentration. The rate of decay depends on: (i) organic and inorganic compounds (e.g., ammonia, sulphides, manganese, iron, humic acid, etc.), (ii) the pipe material itself and both the biofilm and tubercles formed on the walls of the pipe (Al-Jasser, 2007; AWWA, 1997). The corresponding rates for these processes are known as the bulk chlorine decay coefficient (K_b) and wall reaction rate coefficient (K_w) respectively. Their estimation is imperative to simulate chlorine residual accurately in a given situation.

Bulk chlorine decay coefficient (K$_b$)

The EPANET model deals with the decay of chlorine in the bulk flow using first-order kinetics. K_b is a function of water temperature and initial chlorine concentration. Although some researchers have investigated K_b using second-order and combined first and second-order kinetics (Kastl et al., 1999, Clark 1998, Hua et al., 1999), first-order kinetics for K_b has been the most the commonly used thus far. The instantaneous rate of reaction is assumed to be concentration-dependent as:

$$R_1 = K_b C^n \tag{1}$$

where: R_1 is the bulk rate of reaction, C is the chlorine concentration, and n is the order of reaction.

At the limiting chlorine concentration C_L, the expression becomes:

$$R_1 = K_b(C_L - C)C^{(n-1)} \quad ; \quad C_L = 0, K_b < 0, n = 1 \tag{2}$$

In this study, K_b was determined assuming first-order kinetics, with the help of a colorimeter, in the laboratory. For a detailed review of the kinetics of chlorine decay coefficients interested readers are referred to Al-Jasser (2007), Hua et al. (1999), and AWWA (1997).

Wall chlorine decay coefficient (K$_w$)

The wall reaction coefficient depends on temperature, pipe age and material. It is well established that roughness increases due to the encrustation and tuberculation of the products caused by the corrosion and aging of the pipes. The chlorine reaction rate occurring along the pipe wall R_2 depends on chlorine concentration in the bulk flow. The EPANET simulates this reaction as (Rossman, 2000):

$$R_2 = (A/V)K_w C^n \tag{3}$$

where: A/V is the surface area per unit volume within a pipe, and C and n are the chlorine concentration and order of reaction, respectively.

EPANET relates K_w to the Hazen-Williams coefficient (i.e., pipe friction depending on the material and age) and the wall reaction or pipe roughness coefficient (i.e., site-specific phenomena depending on the reaction of chlorine with the pipe wall). The value of K_w may range widely between 0 and 0.15 m·day^{-1} (Rossman, 2000). As the pipes become old, the process of wall chlorine decay becomes more difficult to quantify as the pipes are buried under the soil, particularly when resources and data are limited. In this study, an empirical method is adopted to determine K_w as the only unknown parameter by comparing the model simulation results with the measured residual chlorine concentrations at different sampling points spread across the study area. Different K_w values were used to best fit the model results to the field values using the minimum sum of square of residuals (SSR) method.

Fuzzy rule-based modelling

With known values of K_b and K_w, different simulations can be performed to estimate residual chlorine spatially (at different locations) as well as temporally (at different time intervals) in the water distribution system. For routine field applications, there is a need for a more pragmatic solution based on the results of field investigations and water quality simulations. Moreover, there is a need to accommodate different types of uncertainties involved in laboratory and sampling errors, data limitations, and variations in process parameters.

The fuzzy set theory was first developed by Zadeh (1978) to methodically incorporate human reasoning in decision making. Sadiq et al. used fuzzy rule-based modelling to model water quality failure potential in water mains (Sadiq et al., 2014). Fuzzy set theory can efficiently deal with the above-mentioned uncertainties. Based on the field investigations and modelling results for this research, a fuzzy system with 2 inputs (antecedents) and a single output (consequent) can be described as 'IF x is A and y is B THEN z is C'; where x and y are input variables and z is the output variable for the corresponding fuzzy sets A, B, and C. Each input may span over more than one level, e.g., low, medium, high, etc. These levels are correspondent to fuzzy numbers on a numeric range depending on the modelling results and the size of the distribution network. In order to define the number of levels for each input and output, different types of membership functions can be used, such as Gaussian, triangular, trapezoidal, sigmoid, S-shape or Z-shape. However, for simplicity, a trapezoidal function shown in Fig. 2 is used in this study. A fuzzy set A can be defined as:

$$A = \{x, \mu(x)_A \mid x \in X\} \tag{4}$$

where: X is the universe of discourse for fuzzy set A, x are the elements in X, μ is the value of membership of a specific input to each level, and $\mu(X)$ is the membership function. The most commonly used fuzzy operators are 'OR' and 'AND'. As all of the model parameters are independent and not mutually exclusive, the fuzzy operator 'AND' is used in this study as:

$$\mu_{A \cap B}(x) = \min(\mu x)_A; \mu(x)_B) \tag{5}$$

The Fuzzy Logic Toolbox graphical user interface (GUI) in MATLAB is used in this study to build Mamdani Systems for optimizing chlorine dose for a required residual chlorine concentration in SM-WDS. The model follows the following steps:

- ***Step 1:*** Fuzzification of the data inputs using membership functions based on the field investigations, and EPANET residual chlorine modelling results
- ***Step 2:*** Defining 'IF-THEN' rules for all the inputs and outputs with 'AND' operator; for instance, IF the initial concentration is medium AND the water main length is large THEN the residual chlorine is medium
- ***Step 3:*** To obtain crisp output of fuzzified inputs and outputs, de-fuzzification of the output function using the following centre of area (COA) method:

$$X_{COM} = \frac{\Sigma_{i=1}^{n} x_i \cdot \mu i\,(x_i)}{\Sigma_{i=1}^{n} \mu_i\,(x_i)} \tag{6}$$

A CASE STUDY OF A RESIDENTIAL NEIGHBOURHOOD IN LAHORE

Study area

A portion of the planned residential neighbourhood of Lahore, namely R-Block, Defence Housing Authority (DHA) (Fig. 3), was selected to appraise the proposed framework shown in Fig. 1. Lahore is a city with flat terrain and its elevation is 217 m amsl. Lahore experiences high temperatures (40–45°C) during the months of May, June, and July. In August, the monsoon seasons starts, with heavy rainfalls. December, January, and February are cold months, when temperatures can drop to below 0°C

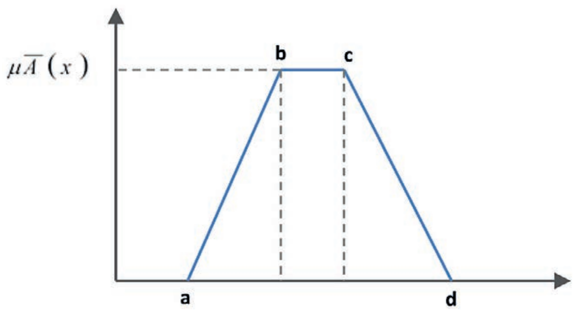

Figure 2
Standard trapezoidal membership function used in this study

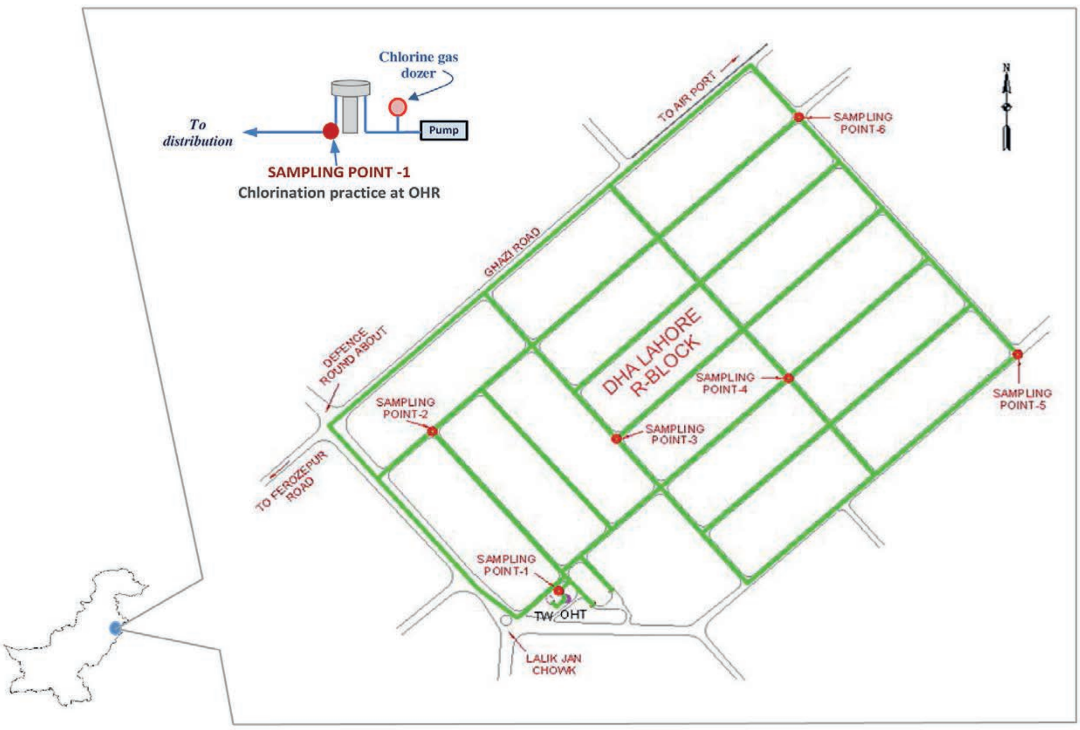

Figure 3
Location plan of the study area within DHA Lahore showing sampling points

(Weatherspark, 2014). The distribution system in the selected study area is the grid iron (loop) type, and the type of supply is continuous (i.e., pumping with storage). The system consists of a pumping station with OHR, and then gravity distribution to the command area. The total area of the distribution system is approximately 0.35 km^2. The system consists of galvanized iron (GI) pipes with diameters ranging from 75 mm to 250 mm (3 in to 10 in). For the groundwater source, plain chlorination is carried out through the gas chlorinator.

Water quality sampling and laboratory analyses

A flow-paced chlorine doser is installed at the delivery pipe of the pump (refer to Fig. 3). A total of 6 sampling points, shown in Fig. 3, distributed over the entire study area, were selected for water quality monitoring. One sample was collected from the OHR, and the other 5 samples were collected from different points located between 100 and 1 200 m distance away from the pumping station (i.e., point of chlorination). A total of 3 datasets (on 3 different days) were collected for the model calibration process during the hot summer months of June and July. In each dataset, 3 samples were collected from each sampling point at 6:00, 9:00 and 12:00, respectively. This was done to accommodate the variations in external conditions (i.e., initial concentration and environmental conditions) and resultant water quality (i.e. residual chlorine) in the distribution system.

Water samples were taken from the consumers' taps which were directly connected to the distribution mains, mostly through garden hoses, in order to avoid the chlorine variations in the plumbing system. The tap was fully opened to let water run for 2 min before collecting the sample. All of the sampling and preservation procedures were performed as per the Standard Methods for the Examination of Water and Wastewater (1998) and the WHO drinking water quality guidelines, 2004 (WHO, 2004; APHA, 1998). All of the water samples were analysed for temperature, pH and residual chlorine concentration. The pH is an important parameter which determines the effectiveness of the chlorine disinfection; the chlorination becomes ineffective in water with a pH of 9 (WHO, 2004). The pH was measured using a HACH 51935-00 pH meter. Residual chlorine concentration in the field and laboratory was measured using a HANNA HI-93734.

Hydraulic modelling

There are a total of 325 households with an average size of 10 persons per household in the selected study area. The period for hydraulic and water quality modelling was selected from 6:00 to 12:00. The daily water demand as per operating staff was 300 ℓ/person, which needed to be converted into the peak hourly demand, keeping in mind hourly demand variations. Selected peak factors ranged between 1.0 and 2.25, to establish the demand pattern for hydraulic simulations during the study period. A value of 1.5 was allocated to the hours of 6:00 to 7:00 and 10:00 to 11:00; the maximum value of 2.25 was used for 8:00 to 10:00; the minimum value of 1.0 was applied to the duration between 11:00 and 12:00; and for the hour (7:00 to 8:00) a peak factor of 2.0 was used.

The height and capacity of the OHR were 20 m and 380 000 ℓ respectively. The pumping station has a discharge capacity of 57 ℓ/s (2 cfs). The water level of the OHR was maintained during the sampling period with continuous pumping. However, in normal operating conditions, the pump might be turned off during off-peak hours, which can cause variations in chlorine concentration. As described above, the pipe network consists of GI pipes of size varying between 75 and 250 mm. Rossman (2000) reports a Hazen-Williamns roughness coefficient value of 120 for new GI pipes. As the coefficient changes with aging of the distribution mains, a corresponding value of 110 for the Hazen-Williams roughness coefficient has been assumed in this study.

Residual chlorine modelling

The measurements were conducted in the laboratory for 8 to 12 h. This method is also useful to avoid interference from external factors such as temperature, contamination, ultraviolet light and evaporation. In this method, the chlorinated water sample was obtained from the OHR (Fig. 3) with a concentration of 0.75 mg·ℓ$^{-1}$, and was placed in a 1-ℓ dark glass bottle. Chlorine decay was measured by drawing samples from the bottle at fixed time intervals. The average pH and temperature of the sample were observed as 7.2 and 21°C, respectively. The data were plotted on a semi-log graph of chlorine residual vs. time (Fig. 4). Over a total period of 13 h, the chlorine concentrations were found to be 0.75 mg·ℓ$^{-1}$ and 0.52 mg·ℓ$^{-1}$ at the start and end of the experiment, respectively. The results of the graph shown in Fig. 4 affirm the first-order kinetics, with a high R^2 value of 0.99. The value of K_b determined from the graph is −0.03 h^{-1} (−0.72 day^{-1}), and the same is used for water quality simulations. The first sampling point (SP-1) contains the chlorine concentration after the complete mixing in OHR and represents the actual initial chlorine entering the system. Secondly, the chlorine may react with the natural organic matter (if present) in the source water which might be a contributing factor as well for the first-order kinetics obtained in Fig. 4.

K_w is determined by calibrating the modelling results with the field measurements. The residual chlorine was measured at 3-h intervals (i.e., at 0, 3 and 6 h, between 6:00 and 12:00) at 6 sampling points in the study area (Fig. 5). It is clear from Fig. 5 that the chlorine dose was not maintained at the point of injection, which resulted in different initial chlorine concentrations in each dataset. During the sampling period, the pH and temperature varied from 6.5 to 7.0 and 22°C to 25°C, respectively. It was assumed that after 6 h the system approached an equilibrium state; however, much longer durations might be required to achieve absolute equilibrium.

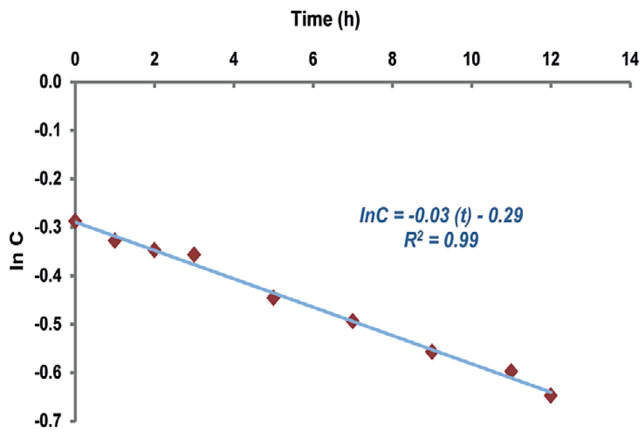

Figure 4

Semi-log of chlorine vs. time, used to estimate bulk decay coefficient K_b

Chlorination was not being practised at night and started at 6:00 in the morning on a routine basis. Therefore, at the start of sampling (i.e., 0 h) the residual chlorine is very low throughout the network (SP-2 to SP-6), except at SP-1, which depicts the chlorine entering the distribution system (Fig. 5). Consequently, the first sampling point (SP-1), i.e., the delivery pipe leaving OHR, shows higher chlorine concentration than the rest of the network at 0 h. The concentration of residual chlorine increases after 3 h and then reaches steady-state conditions (i.e., assumed) at 6 h. A similar pattern can be observed for all three datasets in Fig. 5.

Different values of K_w were used for a simulation period of 6 h to obtain a minimum SSR against the field measurements. The results for the estimation of K_w for the 3 datasets at 6 h are shown in Fig. 6a-c. The results show that K_w increases with an increase in the chlorine concentration, i.e., the value of K_w ranges between −0.06 and −0.15 m·day^{-1} with the chlorine concentration variation from 1.1 to 0.6 mg·ℓ$^{-1}$. These values of K_w lie within the reported range (i.e., 0 to −0.15 m·day^{-1}) in the EPANET manual (Rossman, 2000). The following relationship between K_w and initial chlorine concentration has been derived (Fig. 7):

$$K_w = 0.605 \text{ (initial chlorine)} - 0.871 \qquad (7)$$

It is evident from Figs 6a-c that the chlorine residual even after 6 h of contact time was significantly higher than the required residual chlorine of 0.1 mg·ℓ$^{-1}$ (or 0.2 mg·ℓ$^{-1}$).

With the given value of K_b (−0.74 day-1), the K_w is calculated using Eq. 7 for the chlorine dose required to produce a residual of 0.1 mg·ℓ$^{-1}$ at the farthest sampling points. This was done by varying the initial chlorine dose and the corresponding K_w values using multiple EPANET simulations. The results showed that an initial chlorine dose of 0.3 mg·ℓ$^{-1}$ would be sufficient to maintain a residual close to 0.1 mg·ℓ$^{-1}$. In contrast, the present practise of chlorine dosing showed an initial concentration between 0.6 and 1.1mg·ℓ$^{-1}$ (refer to Fig. 5), which appears to be quite high. Therefore, for such SM-WDS, where the farthest end user is located at a distance between 100 and 1 200 m for the point of chlorination, a smaller chlorine dose can produce identifiable residual chlorine throughout the distribution system.

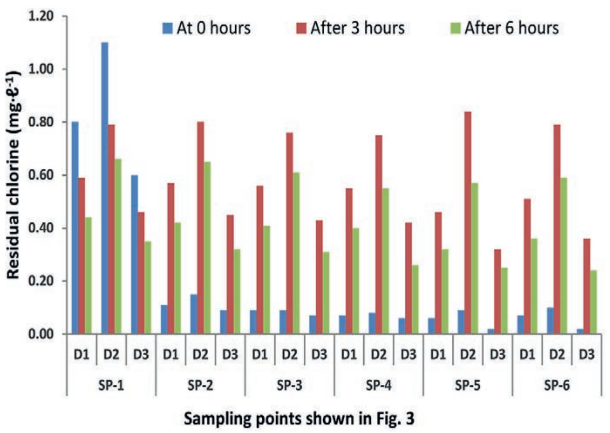

Figure 5
Summary of observed field measurements of 3 datasets for residual chlorine at different sampling points shown in Fig. 3; 'D' repsents data set and 'SP' represents sampling point

Optimization of chlorine dose

It is evident from Eq. 7 that residual chlorine in SM-WDS is a function of chlorine dose and K_w. Practically, this makes it difficult for the managers and operators of a distribution system to perform modelling on routine basis. Also, the model itself possesses uncertainties associated with data inaccuracies, human error, and variations in model parameters. Therefore, based on the field and laboratory studies and EPANET modelling results,

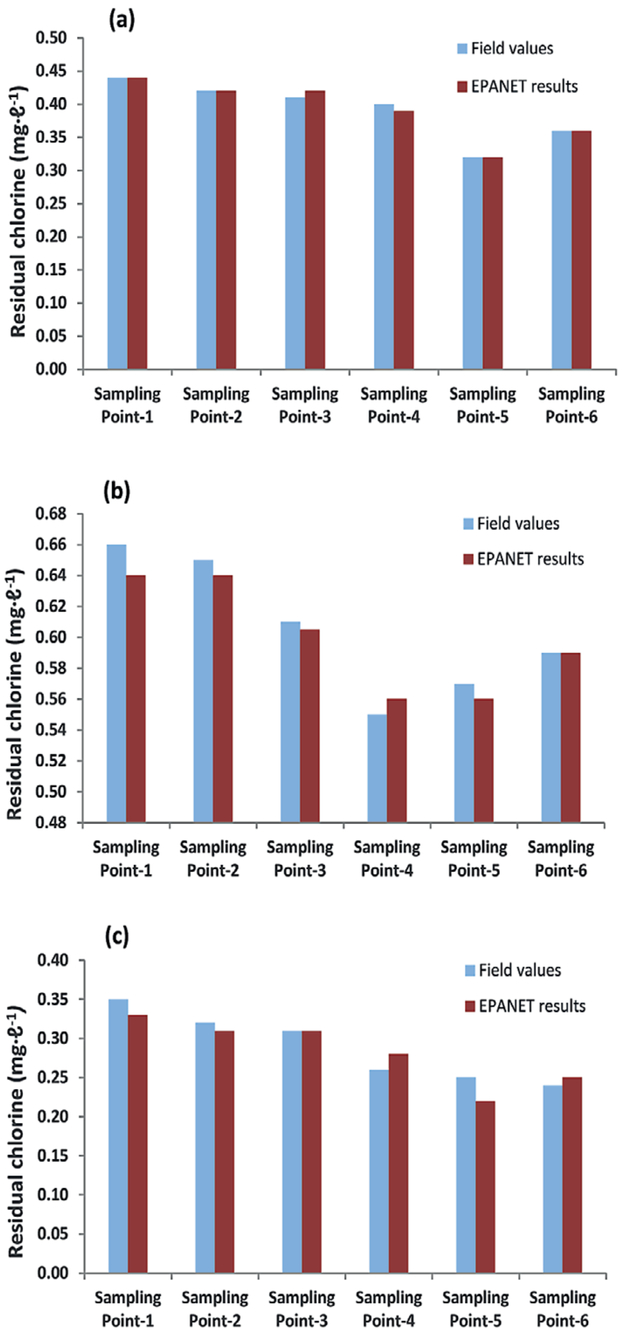

Figure 6
Estimation of K_w, (a) Dataset-1, K_b = −0.74 day^{-1}, K_w = −0.12 m·day^{-1}, and initial chlorine concentration of 0.8 mg·ℓ$^{-1}$; (b) Dataset-2, K_b = −0.74 day^{-1}, K_w = −0.06 m·day^{-1}, and initial chlorine concentration of 1.1 mg·ℓ$^{-1}$; (c) Dataset-3, K_b = −0.74 day^{-1}, K_w = −0.15 m·day^{-1}, and initial chlorine concentration of 0.6 mg·ℓ$^{-1}$

and in order to deal with these uncertainties, a FRBM is developed for scenario analysis and more pragmatic application of the proposed modelling framework. The FRBM is developed for chlorine dose (CD) as a function of required residual chlorine (RC), and the distance of the end user from the point of chlorination, in terms of length (LEN) of water mains, as:

$$CD = f\,(RC, LEN) \tag{8}$$

Both of the factors in Eq. 8 are directly proportional to the chlorine dose, i.e., if the required RC is low and the LEN is low then the CD is low. The universe of discourse (UOD) for the input factors in Eq. 8 is presented in Table 1.

The model is developed for SM-WDS with lengths of mains ranging between 100 and 1 200 m; these lengths correspond to the sampling points shown in Fig. 3, where SP-1 is the closest point, and SP-6 is the farthest from the point of chlorination. The fuzzy rule-based matrix is shown in Table 2. The proposed model has been used to simulate 5 different scenarios for the evaluation of model performance. The input values along with the corresponding crisp (defuzzified) outputs for all the scenarios are presented in Table 3.

The proposed model can be used for similar SM-WDS with the same physical and environmental conditions. In Scenario 1, a chlorine dose of 0.5 mg·ℓ-1 can produce detectable residual chlorine of 0.1 mg·ℓ-1 at the farthest user (1.2 km). This chlorine dose is almost half of the existing dose being applied in the study area. For smaller systems than the study area, the results for Scenarios 2 and 3 revealed gradual reductions in required chlorine dose, i.e., 0.3 and 0.25 mg·ℓ-1 for the consumers located at 500 m and 200 m, respectively. The simulation results shown in Fig. 8 for Scenario 4 reveal that in order to achieve higher residual chlorine of 0.5 mg·ℓ-1 in emergency situations, such as a cholera outbreak or intrusion of sewage through cross connections, the chlorine dose should be accordingly increased to 1.0 mg·ℓ-1. The same dose is being added presently without such emergency conditions, and is thus increasing the taste and odour problems for consumers.

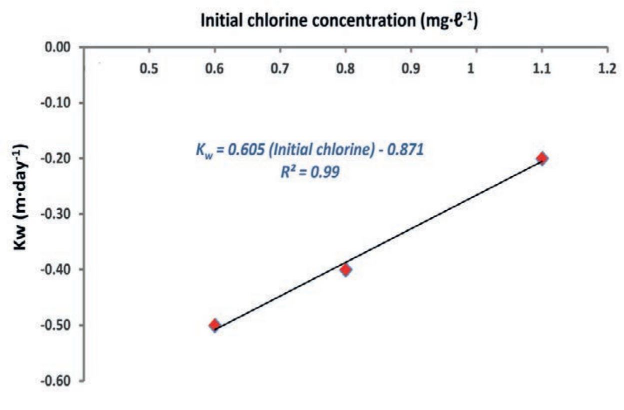

Figure 7

Relationship between K_w and initial chlorine concentration

The interaction between inputs (RC and LEN) and the output (CD) analysed with the help of surface viewer in MATLAB is presented in Fig. 9. It is evident from Fig. 9 that in order to obtain the required residual chlorine at distant points, higher chlorine doses are required. The technical management and operators of SM-WDS can effectively use Fig. 9 to adjust the chlorine dose depending on the size of the network, source water quality and required chlorine dose.

MODEL LIMITATIONS

The results of the case study described above validate the practicality of the proposed framework for optimizing chlorine dose in SM-WDS. However, modelling (hydraulic and residual chlorine) performed in the present study holds the following assumptions and limitations:

- As described above, K_b is the function of water temperature and initial chlorine concentration; K_b increases with increase in temperature and decreases with a decrease in initial chlorine concentration. Thus, for a given study area, K_b needs to be determined for all of the seasonal variations in water temperature and the different initial chlorine concentrations, through extensive laboratory studies. In the present study, K_b was determined in the laboratory for a single sample obtained from OHR. Therefore, the relationship established in the present study for K_w in Eq. 7, i.e., considered as a fitting parameter in the calibration process, will be different for varying K_b values.
- The water quality in the OHR is assumed to be completely mixed, whereas with a change in ambient temperature variations in the water quality within the overhead tank are possible due to stratification. This variation can also alter the decay coefficients and modelling results to some extent.
- Due to constraints associated with time and resources, the sample collection and system modelling were performed for a 6-h period; however, the system may need much longer times to approach equilibrium. In this regard, extended sampling (including at night) and simulations need to be performed to further validate the proposed model.
- The hydraulic model can be calibrated using a simulation-optimization method. Tabesh et.al. (2011) evaluated 4 variables for their calibration studies using EPANET, (i) Hazen-Williams coefficient, (ii) nodal demand, (iii) both the Hazen-William coefficient and nodal demand, and (iv) pipe diameters. However, in this study the hydraulic model has not been calibrated due to data limitations.
- The surface viewer developed on the basis of FRBM to determine chlorine dose is applicable for the experimental and modelling conditions analysed in this study, i.e., 20 to 25°C water temperature, pH between 6.5 and 7.5, initial chlorine of 0.6–1.1mg·ℓ⁻¹ and the above stated limitations for estimation of chlorine decay coefficients. Similar viewers can be developed to cater for seasonal variations and different environmental conditions using the methodology developed in this study.

TABLE 1
Universe of discourse (UOD) of input and output factors used in FRBM

Input/ output Parameters	Units	Low (L)	Medium (M)	High (H)	Very high (VH)
Residual chlorine (RC)	mg·ℓ⁻¹	0.01 – 0.1	0.05 – 0.2	0.15 – 0.45	0.35 – 0.6
Main length (LEN)	m	0 – 300	150 – 600	450 – 900	750 – 1 200
Chlorine dose (CD)	mg·ℓ⁻¹	0.1 – 0.25	0.15 – 0.45	0.35 – 0.65	0.55 – 1.2

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TABLE 2 Matrix-defining fuzzy rules used in this study			
Rule No.	**Residual chlorine (RC)**	**Distance of farthest end user (LEN)**	**Chlorine dose (CD)**
1	Low	Short	Low
2	Low	Medium	Low
3	Low	Large	Low
4	Low	Very large	Medium
5	Medium	Short	Low
6	Medium	Medium	Medium
7	Medium	Large	Medium
8	Medium	Very large	High
9	High	Short	Medium
10	High	Medium	Medium
11	High	Large	High
12	High	Very large	High
13	Very high	Short	High
14	Very high	Medium	High
15	Very high	Large	High
16	Very high	Very large	Very high

TABLE 3 Scenario analyses using proposed FRBM approach				
No.	**Description of scenario**	**Desirable residual chlorine (mg·ℓ⁻¹)**	**Distance of farthest end user in WDN (m)**	**Chlorine dose required (mg·ℓ⁻¹)**
Scenario 1	Minimum detectable residual chlorine required in routine operations in a relatively larger distribution network	0.1	1200	0.5
Scenario 2	Minimum detectable residual chlorine required in routine operations in a smaller distribution network	0.1	500	0.3
Scenario 3	Minimum detectable residual chlorine required in routine operations in a very small distribution network	0.1	200	0.25
Scenario 4	Higher residual chlorine required due to water quality failure (e.g., cholera outbreak) in a relatively larger distribution network	0.5	1 200	1.0
Scenario 5	Higher residual chlorine required due to water quality failure (e.g., cholera outbreak) in a very small distribution network	0.5	200	0.75

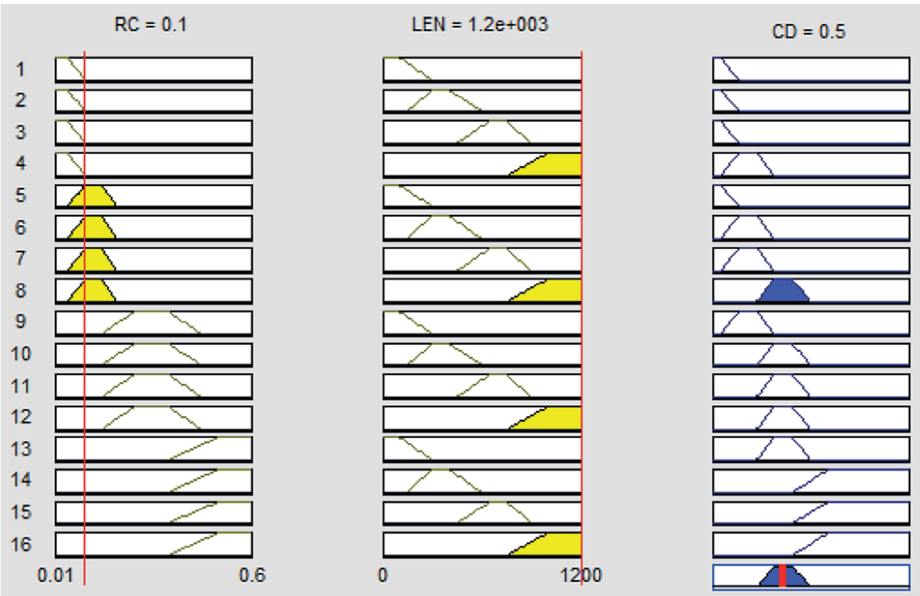

Figure 8

FRBM results for Scenario 1 with given inputs (residual chlorine 'RD', and location of end user 'LEN') and defuzzified crisp output (chlorine dose 'CD')

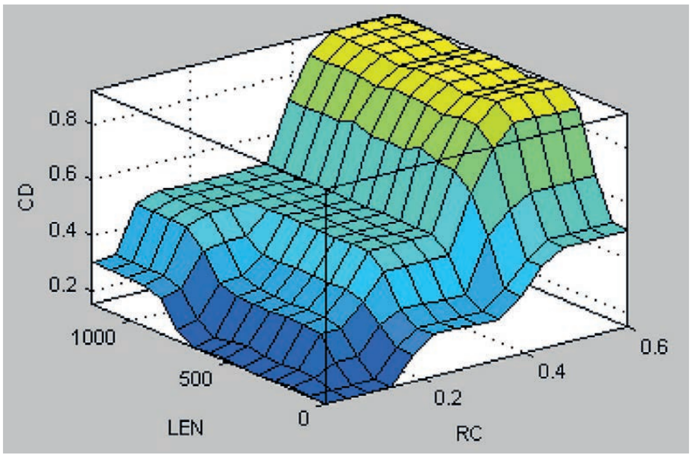

Figure 9

Interaction shown between given inputs (residual chlorine 'RD', and location of end user 'LEN') and the output (chlorine dose 'CD') using surface viewer in MATLAB fuzzy logic toolbox

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn from the above study:

- The values of the chlorine decay coefficients, including the bulk decay coefficient (K_b) and the wall decay coefficient (K_w) were found to be 0.74 day^{-1} and 0.06 to 0.15 m·day^{-1}, respectively. It was revealed by the modelling process that the K_w depends upon initial chlorine concentration.
- Using the calibrated chlorine model, the desirable initial dose of chlorine at OHR was found to be 0.25 to 0.5 mg·ℓ$^{-1}$ (i.e., almost half of the existing practice) to maintain a residual of about 0.1 mg·ℓ$^{-1}$ for the nodes located at 200 m and 1 200 m, respectively.
- The methodology used in this research work can be applied to the distribution networks to maintain a desirable residual of 0.1 mg·ℓ$^{-1}$ at all of the network nodes with an optimum chlorine dose. This would result in a substantial cost saving to the service provider, and an improvement in aesthetic water quality, and will also safeguard the health of consumers. Moreover, the model can also estimate the increase in chlorine dose required during emergency outbreaks.
- The chlorination practice at the source (pumping station), in the study area, was not regulated properly, which resulted in different initial chlorine concentrations at the OHR in all three datasets. High chlorine residuals show excess chlorine doses which may result in high operational cost for the service providers, objectionable taste and odour problems, and possible health issues for the consumers.
- Although the results of the case study validate the practicality of the proposed framework for the given conditions in developing countries, chlorine decay coefficients and hydraulic models need to be further calibrated for different conditions (e.g., pipe material, initial chlorine, seasonal variations in temperature, etc.) than those used in the case study.

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