

Wall decay of chlorine in water distribution system

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ABSTRACT

Chlorination is a widely practised method of disinfection in India. The chlorine consumption in a distribution pipe is due to bulk and wall reactions. The chlorine decay due to wall reactions is particularly significant in old distribution systems with unlined metallic pipes. The estimation of the wall reaction parameter is difficult and is a product of calibration. The approaches adopted for the estimation are pipe column studies and calibration of the chlorine transport model for the water distribution system model. In the present study both these approaches are carried out for a real-life water distribution system. The relative decay of chlorine in cast iron and PVC pipes of different diameters were determined using laboratory experiments. The pipe column studies showed that the chlorine decay rates were significantly higher in CI pipes than in PVC pipes and vary inversely with initial chlorine concentration. The field data on pressure and chlorine residuals was collected for the hydraulic and water quality calibration of the system. The hydraulic calibration of the system was carried out successfully using network flow and a pressure simulation model. Global and zoned wall reaction parameters were estimated using an inverse model applied onto the distribution system. The estimated zoned parameters are marginally better in simulating the chlorine residuals. The wall reaction parameters are found to be inversely proportional to the pipe diameter. The calibration of distribution system for hydraulic flow conditions and water quality is essential for better operation, maintenance and control.

Key words | calibration, distribution system, residual chlorine, wall reaction parameter, water quality

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INTRODUCTION

Chlorine in a distribution system mainly disappears due to reactions with the constituents in the water (bulk decay) and reactions with the material deposited on the inner side of the pipe wall (wall decay). In India, most of the distribution systems are old and made up of unlined cast iron pipes. The wall component of the reaction plays an important role in chlorine reaction kinetics. Studies on chlorine decay rates in single lengths of pipe have revealed that the decay rate in a pipe is several times greater than the decay rate of the same water in a flask (Wable *et al.* 1991). The deposits, corrosion by products on the pipe surface and the pipe itself may react with chlorine. The chlorine consumption by pipes depends on the pipe material, age

and water velocity (Zhang *et al.* 1992). These studies suggest that the pipe wall or material attached to the pipe wall is contributing to the overall chlorine demand observed in distribution systems. The approach taken for modelling the possible reactions of chlorine with material on or released from the pipe wall assumed that the active reaction zone is located on the wall itself or in an adjacent molecular layer. Free (or combined) chlorine molecules are transported from the bulk flow to the wall and can react by following either first- or zero-order kinetics (Vasconcelos *et al.* 1997).

Calibration of an existing water distribution system is necessary to predict its behavior under different field conditions. Calibration is the process of adjusting a model

so that the simulation reasonably predicts system behaviour. The physical and operating characteristics of an existing system should be simulated, as accurately as possible, in a mathematical model so that the input to the model would predict realistic results. Before calibrating a distribution system with respect to water quality, hydraulic calibration should be complete, as inaccuracies in the flow/velocity values provided by the hydraulic model will lead to inaccuracies in water quality predictions. The accuracy in the flow prediction is a prerequisite for the calibration of the system and thereby estimating the wall reaction parameter. However, no simple standard laboratory procedure currently exists for estimating pipe wall reaction parameters, associated with the applicable reaction kinetics. An approximate estimate of these parameters can be made by simultaneous performance of a chlorine reduction study in a glass bottle and pipe column (Wable *et al.* 1991). The other way to estimate these parameters is to obtain field data on chlorine concentration and back-fit a model against them by estimating the parameters (Munavalli & Mohan Kumar 2003).

Most of the water distribution systems in India are operated in a routine manner with little or no consideration of the assessment of actual system behaviour. There is a need to model the distribution system with respect to hydraulics and water quality. The modelled system should be calibrated for studying the performance and operation of the system. There are very few studies where the hydraulic calibration of the system is carried out in India. But no studies are reported for the hydraulic and water quality calibration of the same system in an Indian context. Also there are no attempts reported to quantify the wall decay of chlorine for a real-life water distribution system. There is a need to set a procedure, which will be a guideline for the other distribution systems. In the present study, an attempt is made to perform hydraulic calibration, to quantify the wall reaction parameter by pipe column and calibration approaches for a real-life water distribution system.

METHODS

There are two approaches that can be adopted to estimate the overall and wall reaction rate parameters. These

approaches include actual chlorine decay studies on single pipe sections of a rehabilitated water distribution system and by calibration. These methods are discussed in the following subsections.

Pipe column studies

An overall reaction rate parameter can be determined by chlorine decay studies conducted on pipe sections obtained from a rehabilitated water distribution system. The combined effect of bulk and wall reactions is described by this parameter. In order to quantify the bulk and wall components separately, the chlorine decay studies have to be carried out in a glass bottle. Thus this part of the study involves simultaneous chlorine decay studies conducted in the glass bottle and pipe sections obtained from a distribution system. The wall reaction parameter can be determined by subtracting the value of the bulk reaction parameter from the overall reaction parameter.

Calibration approach

The prerequisite of the calibration approach is the requirement for a hydraulic model for determining flows in pipes, and a chlorine transport model for predicting the nodal chlorine concentrations. Also these models are used as forward simulation models in the parameter estimation model that is used to estimate the unknown wall reaction rate parameters. A brief description of the models is presented here for clarity.

Hydraulic analysis model

In the present study the hydraulic model developed by Niranjana Reddy (1994) is used to determine the flows in pipes under steady state conditions. The model is formulated in terms of conservation of flow (node continuity) and conservation of energy (loop/path continuity) equations. Since the loop/path equations are nonlinear, the complete set of linear (node continuity) and nonlinear (loop/path) equations cannot be solved directly. Hence in the model these equations are solved by the Tewarson–Chen adaptation of the Newton–Raphson iterative technique.

Chlorine transport model

The transport of chlorine down the length of a pipe is advection-dominated in most of the operating conditions. Longitudinal dispersion is neglected, which means that there is no intermixing of mass between adjacent parcels of water travelling down a pipe. The principle of mass conservation along with suitable bulk and wall chlorine reaction kinetics are used in formulating the chlorine transport model. The basic governing equation required to determine the steady state concentration of chlorine at any node j can be formulated as

$$\text{Cnc}_j = \frac{\sum_{i=1}^{\text{Ninp}_j} \text{Cnc}_{\text{nu}_i} \text{Rec}_i Q_i}{\sum_{i=1}^{\text{Ninp}_j} Q_i}; \quad j = 1, \text{Njn} \quad (1)$$

where Cnc_j = concentration at node j (mg/L); Cnc_{nu_i} = concentration at node nu_i (mg/L); Ninp_j = number of incoming pipes at node j ; nu_i = upstream node of incoming pipe i ; Q_i = flow in pipe i (m^3/s); Njn = number of nodes in the network and Rec_i = reaction coefficient for pipe i (dimensionless).

The reaction coefficient represents the combined effect of bulk and wall reactions as it is incorporated with the respective rate parameters and is a dimensionless coefficient. The expression for the reaction coefficient depends on the kinetics used for bulk and wall reactions. The details of the reaction coefficient are given in [Munavalli & Mohan Kumar \(2003\)](#). However, for clarity the expression for the first-order bulk reaction and first-order wall reaction is given by Equation (2):

$$\text{Rec}_i = \exp\left(-k_{\text{bi}} - \frac{k_{\text{wi}}k_{\text{fi}}}{r_{\text{hi}}(k_{\text{wi}} + k_{\text{fi}})}\right)t_i \quad (2)$$

where, t_i = travel time in pipe i (s); r_{hi} = hydraulic radius of pipe i (m); k_{wi} = first-order wall reaction parameter of pipe i (m/s); k_{bi} = first-order bulk reaction parameter of pipe i (s^{-1}); k_{fi} = mass transfer coefficient of pipe i (m/s) = $(D/d_i)S_{\text{hi}}$; d_i = diameter of pipe i (m); D = molecular diffusivity of chlorine (m^2/s); S_{hi} = Sherwood number of pipe i and is given by [Rossman \(2000\)](#).

For $R_{ei} > 2,300$ (turbulent flow)

$$S_{\text{hi}} = 0.023 R_{ei}^{0.83} S_c^{0.33} \quad (3)$$

For $R_{ei} \leq 2,300$ (laminar flow):

$$S_{\text{hi}} = 3.65 + \frac{0.0668(d_i/L_i)R_{ei}S_c}{1 + 0.04[(d_i/L_i)R_{ei}S_c]^{2/3}} \quad (4)$$

where R_{ei} = Reynolds number, S_c = Schmidt number = v/D and L_i = length of pipe i (m).

The reaction coefficient represents the kinetics of reactions occurring in bulk water and at the pipe wall. Bulk water reactions occur within the fluid volume. The consumption of chlorine by reaction with organic and inorganic chemicals in the bulk aqueous phase is reasonably well defined. The applicable reaction coefficient and the rate parameters involved in it can be determined by bottle tests followed by nonlinear least-squares analysis. The wall decay of chlorine involves the disappearance of chlorine due to reactions with the pipe walls. The apparent wall reaction rate can be influenced by the rate at which chlorine can be transported from the bulk flow to the wall. [Rossman et al. \(1994\)](#) suggested that this process can be represented by a film-resistant model of mass transfer along a pipe, the rate at which chlorine is hydrodynamically transported to the wall being proportional to the difference between bulk concentration and the concentration at the wall. An overall first-order reaction parameter represents the combined effect of bulk and wall reactions.

A steady state chlorine transport model was developed by incorporating the hydraulic model in it. If Nsn is the number of source nodes, then the above formulation (Equation (1)) with the appropriate reaction kinetics results in $(\text{Njn} - \text{Nsn})$ numbers of linear equations. An iterative procedure based on the Gauss–Siedel algorithm is adopted to solve the equations. The converged solution provides steady state chlorine concentrations at all the nodes for a given source chlorine concentration.

Parameter estimation model (inverse model)

The inverse problem involves estimating the unknown reaction parameters (wall reaction parameters), which are difficult to estimate by field procedure. It can be formulated as an unconstrained optimization problem where the objective is to minimize some function of the difference between observed and model predicted responses.

The global or grouped reaction rate parameters are to be determined so that the observed and computed chlorine concentrations are minimized in a least-squares sense. Thus the objective function is given by

$$\text{Minimize } E = \sum_{j=1}^M [Cno_j - Cnc_j]^2 \quad (5)$$

where M = number of monitoring nodes and Cno_j = observed chlorine concentration at monitoring node j (mg/L).

The global reaction parameter represents that all pipes in the system are assigned with a unique (wall reaction) parameter. Thus only a single parameter needs to be estimated to represent the reactions throughout the system. But for the case of the heterogeneity of pipes in terms of age, diameter and material it is not appropriate to use a global parameter. The system with heterogeneity should be divided into zones and the corresponding reaction parameters be estimated. Hence the pipes can be grouped so that the spatial variation in reaction rate can be appropriately represented and the number of groups is less than or equal to the number of available observations.

The parameter estimation problem formulated above is solved using the conventional inverse modelling approach which utilizes the steady state chlorine transport model as a routine in its simulation–optimization computational procedure. The optimization module used is the Gauss–Newton minimization technique (Munavalli & Mohan Kumar 2003).

It may be noted that the unit of the wall reaction parameter estimated by the pipe column approach is in terms of per unit time (d^{-1}). The difference between overall reaction parameter (d^{-1}) and bulk reaction parameter (d^{-1}) is taken to estimate the wall reaction parameter (d^{-1}) in the pipe column approach only. The wall reaction parameter in the pipe column approach is equivalent to the whole second term in the exponential function (Equation (2)) described above in the calibration approach. The first-order wall reaction parameter (k_{wi}) quantifies reactions at the wall in the calibration approach and is represented in terms of length per time units (m/d).

APPLICATION: RESULTS AND DISCUSSIONS

The approach of the pipe column studies was applied to the pipe sections obtained from the distribution system and the calibration approach was adopted for a portion of the real-life water distribution system.

Estimation of overall and wall reaction parameter by pipe column studies

The cast iron (CI) (125 mm \varnothing and 80 mm \varnothing , 60 cm long) and PVC (125 mm \varnothing , 45 cm long) pipe sections were procured from the rehabilitated water distribution system. The chlorine decay study in pipe sections was carried out as per the following procedure:

- The pipe sections were thoroughly cleaned and washed so that dust attached on the inner portion of the pipe was removed. Also one end of each pipe column was made watertight by fixing PVC caps at the bottom end.
- Sand-filtered water was used for the study. The water samples were brought from the Miraj water treatment plant. The water quality data of the sample water is given in column 2 of Table 1.
- The samples were chlorinated in the laboratory in order to have free residual chlorine in the range 1–4 mg/L by adding sodium hypochlorite. All the chlorine residuals were determined using a titrimetric procedure in which ferrous ammonium sulfate (FAS) was the titrant and N, N-diethyl-p-phenylene diamine (DPD) was used as an indicator.
- The chlorinated water was immediately poured into the pipe columns and amber-coloured glass bottles. Then

Table 1 | Water quality data

Water quality parameter	Raw water	Sand filtered water	Distribution system water
pH	7.90	7.07	7.20
Conductivity ($\mu\Omega^{-1}/\text{cm}$)	494	302	360
Dissolved oxygen (mg/L)	5.30	5.70	4.80
Temperature ($^{\circ}\text{C}$)	22	24	28
Chloride (mg/L)	110	50	95

the upper end of the pipe columns and glass bottles were also capped.

- (e) Thereafter, the residual chlorine concentration remaining in the pipe column and the glass bottles was determined regularly at one-hour intervals for a total duration of 6 hours.

The bulk and overall chlorine reaction parameters were estimated from the chlorine decay results. A programming code was written in Matlab and the Matlab function “lsqnonlin” was used to compute the parameter estimates. This function requires a user-defined expression. In order to determine the applicable reaction kinetics, the various reaction rate expressions were used in the present study. It was found that the first-order reaction kinetics yielded the best-fit results for both bulk and overall reactions. The best-fit results for the chlorine decay both for bottle and pipe column are shown in Figures 1 and 2. The bulk and overall reaction rate parameters were

determined for the best-fit results. The bulk, overall and wall decay parameters for CI and PVC pipes are given in Table 2.

The results indicate that wall reaction parameters for PVC pipes are lower than those of the CI pipes. The comparison of the wall reaction parameter for the CI pipes shows that, as the diameter of the pipe decreases, the wall reaction parameter increases. This is due to the fact that the mass transfer rate is higher for lower diameter pipes, thereby increasing the chlorine decay. The bulk reaction rates were found to be inversely proportional to the initial chlorine concentrations. Similar observations were reported previously by Hua *et al.* (1999), Powell *et al.* (2000) and Hallam *et al.* (2003) on the relationship between bulk reaction parameter and initial chlorine concentration. The variation in the relationship between water quality and bulk reaction rate parameter for the present and previous studies are given in Table 3.

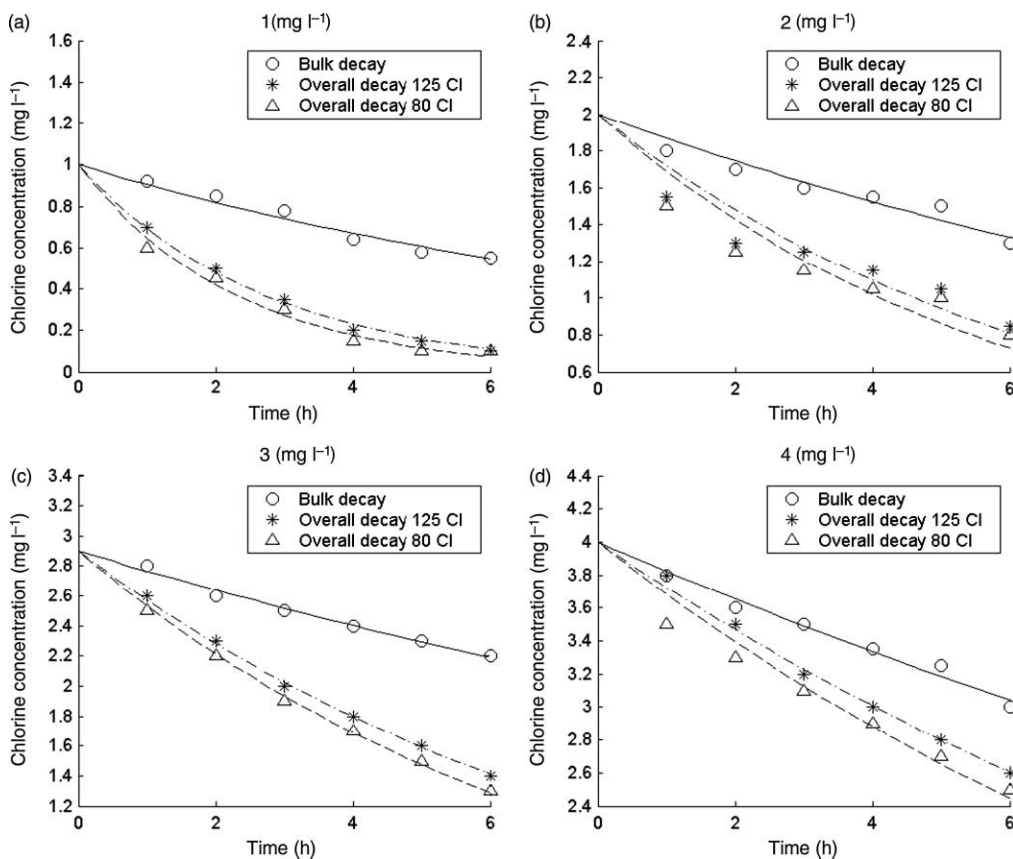


Figure 1 | Bulk and pipe column studies of chlorine decay in CI pipe.

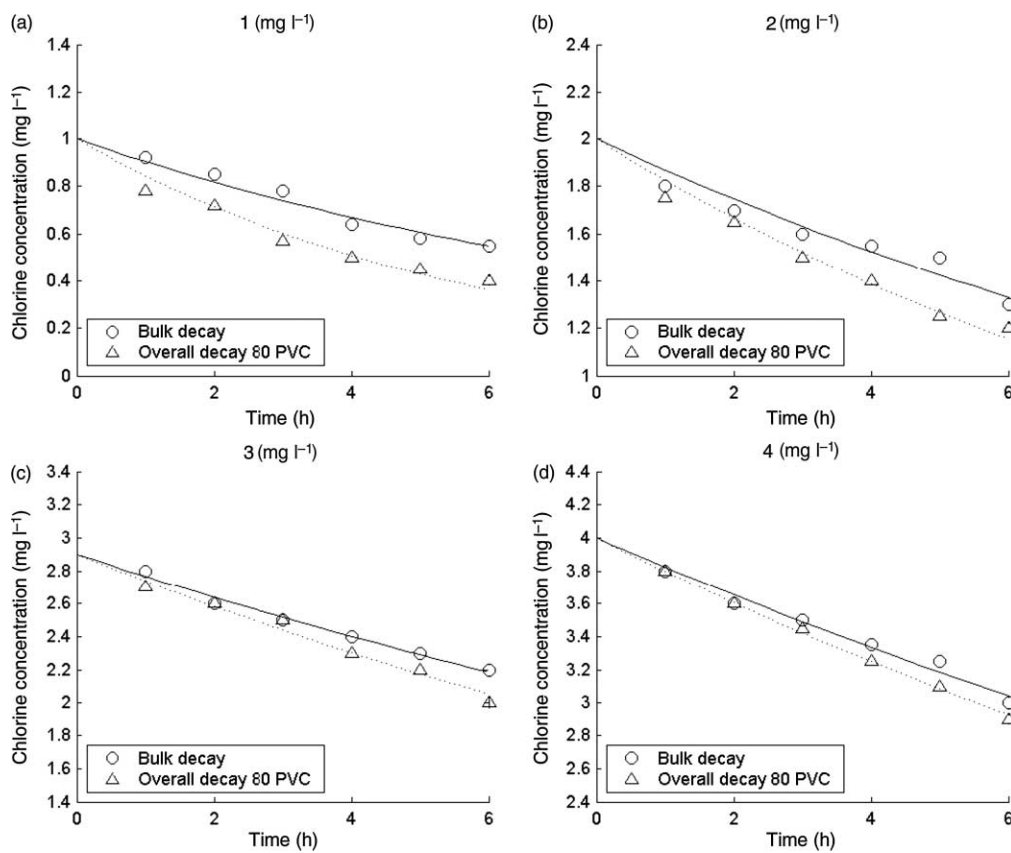


Figure 2 | Bulk and pipe column studies of chlorine decay in PVC pipe.

Estimation of wall reaction parameter by calibration

In the calibration approach the wall reaction parameter is estimated by back-fitting the field data to the computed results in a hydraulically calibrated network. A portion of the water distribution system from Miraj was selected for the determination of the wall reaction parameter. The study area consists of a number of residential colonies and apartments. The water distribution system of this area receives water from an elevated storage reservoir, which has

a capacity of 1,000,000 L and a full supply level of 587 m. The distribution network mainly consists of CI pipes of various diameters ranging from 80 mm to 400 mm. The schematic plan of the distribution system in the study area is shown in Figure 3. The other details of the network links and nodes are given in Tables 4 and 5, respectively. The chlorine input to the network has a constant value of 1.70 mg/L. The bulk first-order reaction parameter was computed using an expression given in Table 3 for

Table 2 | Results of pipe column study

Initial chlorine concentration (mg/L)	Bulk reaction parameter (d ⁻¹)	Reaction parameter for 125 mm CI pipe (d ⁻¹)		Reaction parameter for 80 mm CI pipe (d ⁻¹)		Reaction parameter for 125 mm PVC pipe (d ⁻¹)	
		Overall	Wall	Overall	Wall	Overall	Wall
1.0	2.40	8.81	6.41	10.40	7.99	4.05	1.65
2.0	1.63	3.61	1.98	4.04	2.41	2.20	0.56
3.0	1.13	2.88	1.75	3.24	2.11	1.38	0.25
4.0	1.09	1.71	0.62	1.97	0.88	1.25	0.16

Table 3 | Effect of water quality on bulk reaction parameter

	Best fit relationship between k_b and $1/Co$		
	Raw water	Sand-filtered water	Distributed water
Present study	$k_b = 5.373(1/Co) + 0.281$ $Cc = 0.48$	$k_b = 3.734(1/Co) - 0.210$ $Cc = 0.68$	$k_b = 2.846(1/Co) + 0.051$ $Cc = 0.78$
Hallam <i>et al.</i> (2003)	$k_b = 20.88(1/Co)$ $Cc = 0.67$	–	–
Powell <i>et al.</i> (2000)	–	$k_b = 0.336(1/Co)$ $Cc = 0.78$	–
Hua <i>et al.</i> (1999)	–	$k_b = 0.432(1/Co) - 0.576$ $Cc = 0.99$	–

Cc = correlation coefficient.

distributed water. It was determined to be 1.73 d^{-1} for an initial chlorine concentration of 1.70 mg/L . The system has a total of 6 h of supply and the system is considered to be under steady state hydraulically.

The first step in the estimation of the wall reaction parameter for any distribution system is to calibrate the system hydraulically. The hydraulic model of the network for generating the flow and pressure scenario is a prerequisite for hydraulic calibration. The objective of hydraulic calibration is to estimate accurately the nodal out flows, the head loss

characteristics of the pipes and heads supplied by reservoirs. In calibrating a water distribution system model hydraulically, it is customary to adjust the roughness coefficient for the pipes and consumption at the demand nodes so that the heads and flows predicted from the model agree with the values observed in the field. In the study area ten monitoring nodes 1–4, 8, 10, 13, 15, 16 and 18 were identified and extensive pressure measurements were carried out during the supply hours. A network model for analysis was developed. The trial-and-error procedure was adopted to adjust roughness parameter (Hazen–William coefficient) and nodal flows so that the field and simulated pressures were better matched. The statistical parameters, viz. mean error, root mean square (RMS) error and correlation coefficient, are used for assessing the best fit between observed and simulated pressures. The roughness parameters and nodal outflows, which are the results of hydraulic calibration, are given in Tables 4 and 5. The calibration statistics are represented in Table 6. A distribution system is considered to be calibrated hydraulically when the predicted nodal heads are satisfactorily close to the heads obtained from field gauge readings for several operating conditions and water consumptions. If a good dataset is available, a head difference in the range of 1.5–5.0 m is satisfactory; however, if the dataset is poor an accuracy in the range of 3–10 m is a reasonable target. For a satisfactory calibration, the predicted head at a node should be such that the head loss from the source to the node should be not more than 10% away from the head loss obtained from the field results

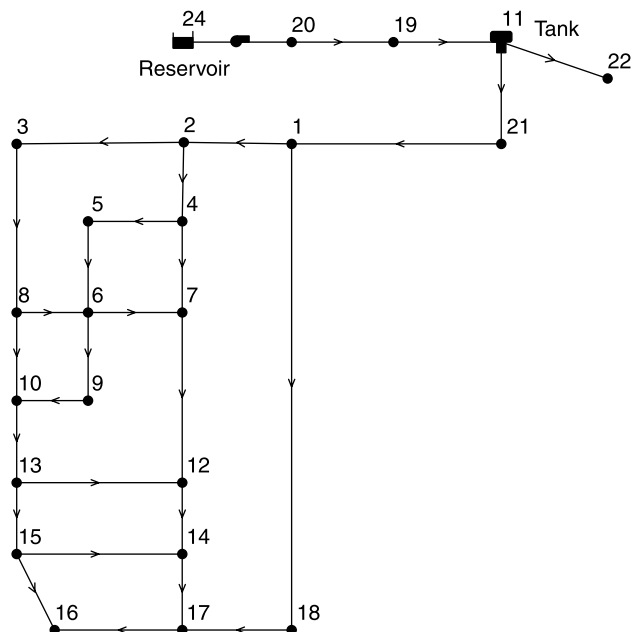
**Figure 3** | Distribution system of the study area.

Table 4 | Pipe data for the network

Link ID	Start node	End node	Length (m)	Diameter (mm)	Roughness	Flow (m ³ /d)	Velocity (m/s)
1	1	2	75	200	70	2854.41	1.05
2	2	3	200	200	90	1467.39	0.54
3	4	5	90	80	100	174.74	0.40
4	2	4	60	100	80	982.02	1.45
5	5	6	30	80	100	171.36	0.39
6	8	6	85	80	100	24.49	0.06
7	6	7	85	80	100	5.18	0.01
8	7	4	30	100	80	-529.18	0.78
9	9	10	60	80	100	181.23	0.42
10	9	6	120	80	100	-186.63	0.43
11	12	13	135	80	100	-25.00	0.06
12	3	8	130	100	100	792.39	1.17
13	8	10	60	100	100	605.22	0.89
14	10	13	30	100	100	713.55	1.05
15	7	12	150	100	80	391.26	0.58
16	14	15	130	80	110	-45.37	0.10
17	15	13	45	100	110	-475.24	0.70
18	12	14	30	80	80	247.51	0.57
19	15	16	60	100	110	348.87	0.51
20	14	17	100	80	80	90.39	0.21
21	16	17	120	100	80	-56.13	0.08
22	17	18	90	100	90	-505.74	0.75
23	1	18	450	100	100	573.24	0.84
24	11	21	250	250	75	4116.15	0.97
25	11	22	150	150	80	47.25	0.03
26	21	1	450	200	75	4116.15	1.52
27	11	19	200	200	70	-7597.29	2.80
28	19	20	2,000	400	70	-9014.79	0.83

(Walski *et al.* 2001). These results indicate that the network is well calibrated hydraulically.

The calibration of the water distribution system model for chlorine transport was carried out to estimate the wall chlorine reaction parameter. The *in situ* chlorine concentrations at nodes 1–18, 21 and 22 were measured during the supply hours. The water quality analysis for the distribution system water was also carried out and is presented in column 3 of Table 1. In order to calibrate the network model with reference to chlorine decay the inverse model developed by Munavalli & Mohan Kumar (2003) was used. The inverse model determines the wall reaction parameters,

which are associated with different reaction kinetics, either in single or in groups of pipes. The measured chlorine concentrations were used as input observations to the model. The system was calibrated for two cases of parameter estimation, viz. global and zoned. The global reaction rate parameter is a single wall rate parameter assigned to the entire network. All the pipes, irrespective of their heterogeneity in diameter, material and age, are assigned with this parameter. The zoned parameter is a wall reaction parameter assigned for groups of pipes. The pipes can be grouped according to their age, diameter and material. In the present study the pipes were grouped into

Table 5 | Node data for the network

Node	Elevation (m)	Demand (m ³ /d)
1	561.50	688.50
2	559.70	405.00
3	559.50	675.00
4	559.00	278.10
5	558.83	3.38
6	558.80	4.05
7	559.79	143.10
8	559.00	162.68
9	557.50	5.40
10	558.90	72.90
11	579.00	-
12	558.30	168.75
13	559.00	213.30
14	557.90	202.50
15	558.50	81.00
16	559.20	405.00
17	556.62	540.00
18	559.00	67.50
19	566.00	1417.50
20	555.00	0.00
21	567.00	0.00
22	569.00	47.25
Reservoir	555.00	-
Tank	579.00	-

Table 6 | Calibration statistics for pressure

Location	Pressure (m)		Error	
	Observed	Simulated	Mean	RMS
1	7.00	6.60	0.40	0.40
2	6.00	6.99	0.99	0.99
3	5.00	6.51	1.50	1.50
4	5.20	4.13	1.07	1.07
8	4.00	3.57	0.42	0.42
10	3.50	2.71	0.79	0.79
13	3.00	1.96	1.04	1.04
15	2.50	2.08	0.42	0.42
16	2.00	1.08	0.91	0.91
18	5.00	2.58	2.42	2.42
Network	4.32	3.82	1.00	1.15
Correlation between means		0.87		

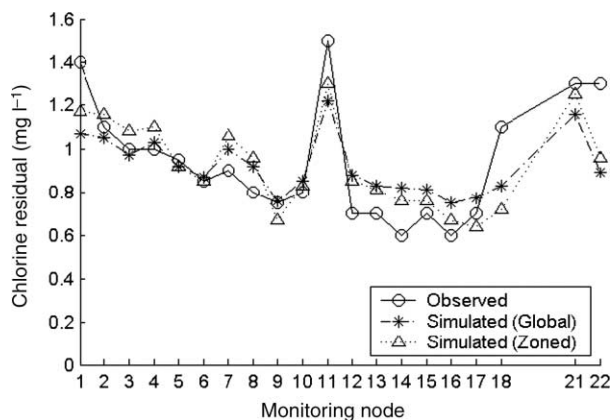


Figure 4 | Observed and simulated chlorine residuals at monitoring nodes.

three groups to study the variation of wall reaction parameters with respect to the diameter. The three groups consist of pipes having 80 mm, 100 mm and above 200 mm diameters, respectively. The inverse model was run using

Table 7 | Calibration statistics for chlorine global wall reaction parameter

Location	Chlorine (mg/L)		Error	
	Observed	Simulated	Mean	RMS
1	1.40	1.07	0.33	0.11
2	1.10	1.05	0.05	0.00
3	1.00	0.97	0.03	0.00
4	1.00	1.03	0.03	0.00
5	0.95	0.92	0.03	0.00
6	0.85	0.87	0.02	0.00
7	0.90	1.00	0.10	0.01
8	0.80	0.92	0.12	0.01
9	0.75	0.76	0.01	0.00
10	0.80	0.85	0.05	0.00
11	1.50	1.22	0.28	0.08
12	0.70	0.88	0.18	0.03
13	0.70	0.83	0.13	0.02
14	0.60	0.82	0.22	0.05
15	0.70	0.81	0.11	0.01
16	0.60	0.75	0.15	0.02
17	0.70	0.77	0.07	0.00
18	1.10	0.85	0.27	0.07
21	1.30	1.16	0.14	0.02
22	1.30	0.89	0.41	0.17
Network	0.94	0.89	0.14	0.17
Correlation between means		0.80		

the first-order bulk and first-order wall reaction kinetics for both global and zoned cases. The observed and simulated chlorine residuals for global and zoned wall reaction parameters are shown in Figure 4. The estimated value of the global wall reaction parameter was estimated to be 1.44 d^{-1} . The estimated values of the wall reaction parameter for the three groups of pipes are 7.17 m/d, 5.24 m/d and 1.00 m/d, respectively. The wall reaction parameters are found to be inversely proportional to the pipe diameter. The statistical parameters need to be computed to assess the accuracy of the fitting between observed and simulated concentrations. The parameters computed are the total number of observations, mean of observed values, mean of computed values, mean error, RMS error and correlation between means for each measurement location and for the network as a whole.

Table 8 | Calibration statistics for chlorine zoned wall reaction parameter

Location	Chlorine (mg/L)		Error	
	Observed	Simulated	Mean	RMS
1	1.40	1.17	0.23	0.05
2	1.10	1.16	0.06	0.00
3	1.00	1.08	0.08	0.01
4	1.00	1.10	0.10	0.01
5	0.95	0.92	0.03	0.00
6	0.85	0.85	0.00	0.00
7	0.90	1.06	0.16	0.03
8	0.80	0.96	0.16	0.03
9	0.75	0.67	0.08	0.01
10	0.80	0.83	0.03	0.00
11	1.50	1.30	0.20	0.04
12	0.70	0.85	0.15	0.02
13	0.70	0.81	0.11	0.01
14	0.60	0.76	0.16	0.03
15	0.70	0.76	0.06	0.00
16	0.60	0.67	0.07	0.01
17	0.70	0.64	0.06	0.00
18	1.10	0.72	0.38	0.15
21	1.30	1.25	0.05	0.00
22	1.30	0.96	0.34	0.12
Network	0.94	0.96	0.13	0.16
Correlation between means		0.79		

The calibration statistics is given in Tables 7 and 8 for the global and zoned parameters computed above, respectively. It can be seen from these tables that the statistical variation is marginal between the global and zoned wall reaction parameters. Generally, zoned wall reaction parameters predict the chlorine concentrations closer to the observed values of chlorine. But in the present case the zoning has not improved the nodal chlorine predictions significantly. It can be seen from columns 4 and 6 of Table 2 that the difference in wall reaction rates between pipes of 80 mm and 125 mm diameters is less. The difference shall be still lower between 80 mm and 100 mm pipes. Further, the majority of the pipes have diameters of 80 mm and 100 mm, hence zoning has not improved the predictions.

CONCLUSIONS

The process of modelling and calibration of a real-life water distribution system for the hydraulics and water quality was carried out. The quantification of the wall reaction parameter was also tried. The wall chlorine decay studies were carried out using pipe columns and on an actual real-life distribution system. The pipe column studies quantitatively showed that the wall reaction parameters are higher for CI pipes than PVC. The bulk reaction parameter varies inversely with initial chlorine concentration and the wall reaction parameter inversely varies with diameter.

The inverse model was found to be useful in estimating the global and zoned wall reaction parameters for a real-life distribution system. However, the qualitative field data consisting of pressure and chlorine residual measurements is a governing factor for calibration. Generally, zoned wall reaction parameters for a well-calibrated system simulate field conditions better than the global. But in the present study, there is a marginal variation between statistical parameters used for determining the best-fit models. The pipe material, diameter and initial chlorine concentrations were found to influence the wall reactions of chlorine decay. The hydraulic and water quality calibrations are essential for better predictions of pressures and chlorine residuals within the water distribution systems. Further, the calibrated distribution system is useful for the operation, maintenance and control of the system.

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