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MODELING RESIDUAL FREE CHLORINE IN DRINKING WATER DISTRIBUTION SYSTEMS

وصف الكلور الحر المتبقى فى شبكات توزيع مياه الشرب

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الملخص العربى

تخرج مياه الشرب من محطة التنقية فى أحسن جودة ممكنة لها. بمرور الوقت وباستمرار السريان فى شبكات التوزيع يقـــل تركيز الكلور الحر المتبقى وبذلك تقل مقدرة المياه على مقاومة التلوث البكتيرى. وهذا التغير فى جودة المياه قد يكون نتيجـة تحويلات كيميائية أو بيوكيميائية أو نتيجة لخلط المياه بمياه من مصدر أخر ليس بالجودة المطلوبة، وأخيرا قد يكون نتيجـــة لخلل فيزيائى بشبكة التوزيع نفسها. وحتى عهد قريب وخاصة فى مصر كانت الأبحاث قليلة فى مجال دراسة تغيـر جـودة المياه أثناء سريانها فى شبكات التوزيع.

فى هذا البحث تم دراسة العوامل التى تؤثر على تغير تركيز الكلور الحر المتبقى فى شبكة ميـــاه شـــركة الدلتـــا للأســـمدة وللصناعات الكيميائية بطلخا-محافظة الدقهلية.

لإجراء هذا البحث تم الأستعانة بأحدث البرمجيات المعتمدة من وكالة البيئة الأمريكية لنمذجة شبكات المياه وإيجاد الحلـــول الهيدروليكية لها – برنامج الوتركاد (WaterCAD). هذا البرنامج بالإضافة إلى انه ينفذ الحل الهيدروليكى تحـت مختلـف الظروف المطلوبة فإنه يستطيع إيجاد قيم مؤشرات جودة المياه فى شبكات التوزيع وذلك باستخدام الطـــرق العدديـة لحـل طريقة العناصر الحجمية المنفصلة لــ " أويلر". ومن ثم تم أستخدام البرنامج لحساب زمن بقاء المياه فـــى شـــبكة التوزيــع ومدى أنتشار الكلور الحر المتبقى وتعين تركيزه عند نقط المراقبة الحقلية بشبكة التوزيع. وبمقارنة القيــم المحســـوبة عــن طريق النموذج الرياضى بواسطة البرنامج عند مختلف الظروف الهيدروليكية بقيم التحليلات الحقلية أمكن تقيم حالة مواســـير الشبكة وتم إيجاد قيم المعاملات الكيناماتيكية اللازمة لنمذجة شبكة التوزيع.

وقد أوضح هذا البحث أهمية نمذجة شبكات توزيع مياه الشرب وتحليل النتائج الحقلية لإيجاد نماذج رياضية لوصف طبيعـة تغير الكلور الحر المتبقى كأحد مؤشرات جودة المياه واستخدام هذه النماذج فى متابعة التشـــغيل للوصـــول لجـودة المياه المطلوبة.

ABSTRACT

Water is at its peak quality when it leaves the treatment plant. With time, the disinfectant residual decreases, possibly with increase in microbial activity. Changes in quality may be caused by biological or chemical transformations, by mixing of waters from different sources, or by a loss of system safety. Until recently, no much research has been made to the problem of changes in water quality in distribution system especially in Egypt. This paper applies WaterCAD simulation model for modeling water quality in the distribution systems at El-Delta Co. for Fertilizer and Chemical Industries and compares the results to field data. This software implements the Eulerian Discrete Volume-Element Method (DVEM) to solve the numerical constituent transport problem for the system being analyzed. A model is used to predict the residence time and the propagation of chlorine residual in several points in the distribution system. Good correspondence with observed chlorine residuals is obtained at locations where the hydraulics is well characterized. It was found that using a wall decay constant in the range of 0.2 – 2.0 for pipes in a network might be suitable for all distribution systems. Field quality data is important in developing and understanding predictive models.

KEYWORDS

Drinking water, Distribution System, Disinfection, Chlorine Residual, Chlorine Decay.

INTRODUCTION

Treated water transported through the distribution systems from the purification plants to consumers may undergo substantial degradation in quality [8, 18]. There are growing interests in evaluating the factors that affect the variations of drinking water quality in distribution systems. Even the medium-sized water utilities may have hundreds of kilometers of pipes constructed from different materials at different ages. Over time, biofilm and tubercles attached to pipe walls can result in a significant loss of disinfectant residual and thereby adversely impact water quality.

Because of the complexity and size of most distribution systems, and the manual monitoring of distribution systems, it is very difficult to understand water-quality variation totally and in reasonable time [3, 4, 5]. So modern management of water-distribution systems needs simulation computer-based models that are able to accurately predict the dynamics of water-quality variations within the distribution systems [5, 12,13].

Several approaches have been taken to numerically model the transport and fate processes of dissolved substances in water-distribution systems. These methods can generally be grouped as either Eulerian or Lagrangain in nature, depending on the volumetric control approach, which is taken [15,9,10]. Both methods are based on dynamic formulations that relay on a system simulation approach to determine the movement and dispersion of constituents under time-varying conditions.

In Egypt chlorine is widely used as a disinfectant in drinking-water systems. Most water supplies attempt to maintain a detectable chlorine residual within the distribution system to minimize the potential for microbial growth. As chlorine travels through the pipes in a distribution system it can react with a variety of materials both within the water bulk and at the inner pipe surface.

The present paper describes the use of computational water quality models to study the chlorine decay within the drinking-water distribution system at El-Delta Co. for Fertilizer and Chemical Industries. In this study the WaterCAD software (Haestad Methods, Inc. 1997) has been used as computational aid.

CHLORINE DECAY MODELING

The important water quality measure relating to the drinking water is the residual chlorine. Chlorine is known to be consumed in the bulk liquid phase and at the distribution pipe wall [6,7]. Studies of chlorine decay rates in single lengths of pipe have revealed that the decay rate in the pipe is several times greater than the decay rate of the same water in a bulk [20]. Wable et al. [20] found that the chlorine consumption increased with increasing temperature. Studies by Clark et al. [7,8,9] yielded similar results to those of Wable et al. Comparing chlorine residual loss data in a network to chlorine loss in flask yielded ratios of 1.07 to 20.16. Sharp et al. [18] reported that, based on a field study for the Fort Monmouth, New Jersey,

USA, water-distribution system, unlined cast-iron pipe has a higher chlorine consumption than polyvinyl chloride (PVC) pipe and that the larger-diameter cast-iron pipe has a lower consumption than the smaller-diameter. Clark et al. [8] reported that, residual free chlorine of 6 mg/L disappeared within a few minutes in one galvanized pipe 30-40 years old, whereas it remained stable over a 24-hr period in a new pipe with the same type.

The physical, chemical and biological processes that control the fate (decay) of chlorine in water can be divided into transport and transformation processes. There are two basic transport processes: (1) advection, or transport of chlorine resulting from the flow of water in the distribution systems, and (2) diffusion, or transport due to turbulence in the water. Combing transport and transformation processes that occur along links of the distribution system yield the general classical one-dimensional differential equation [15, 16, 17]:

$$\frac{\partial C_i(x,t)}{\partial t} + u_i \frac{\partial C_i(x,t)}{\partial x} + R_{C_i(x,t)} = 0 \dots\dots\dots\dots\dots\dots\dots(1)$$

Where: C_i = free chlorine concentration in link i at location x and time t;

u_i = Mean flow velocity in link i; and

$R_{C_i(x,t)}$ = Reaction rate expression.

To obtain a general solution of the basic transport equation it is necessary to introduce an analytical time step, t, which serves as the interval of analysis over which substance concentrations are advected within link i (with this advection distance expressed as $u_i t$). This time step is referred to as the water quality time step.

Abdel-Gawad and Bewtra [1] studied the decay of total residual chlorine from chlorination of physical-chemical treatment effluent in natural river water. They found a first-order decay model to be suitable with the rate constant influenced by turbulence and temperature.

The expression for the general chlorine decay rate model for each link, i in the distribution system can be expressed as given below [6,7]:

$$R_{C_i(x,t)} = \frac{dC_i}{dt} = -k_b C_i - \frac{k_f}{R_h}(C_i - C_{wi}) \dots\dots\dots\dots\dots\dots\dots(2)$$

Where: k_b =   first order bulk rate constant,

k_f =   mass transfer coefficient between bulk flow and pipe wall,

R_h =   hydraulic radius of pipe, and

C_{wi} = chlorine concentration at the wall.

The first term in equation (2) is the bulk –flow reaction, the second term material is transported between the bulk flow and reaction sites at the pipe wall. The mass transfer coefficient k_f, which is used to model the chlorine transfer between the bulk fluid and pipe wall, is calculated internally by using the dimensionless Sherwood Number. Assuming that the rate of reaction at the wall is first order with respect to C_{wi} and it proceeds at the same rate as material is transported to the wall so that no net accumulation of material occurs over the time, the following mass-balance is for the wall reaction:

$$k_f(C_i - C_{wi}) = k_w C_{wi} \dotfill (3)$$

where k_w is the wall reaction constant. Solving for C_{wi} and substituting into (2) yield the following reaction-rate expression:

$$\frac{dC_i}{dt} = -k_b C_i - \frac{k_w k_f}{R_h(k_w + k_f)} \dotfill (4)$$

Under the assumption that the material entering a junction node mixes completely and instantaneously, an additional conservation equation for each junction can be written as [16, 17, 19]:

$$C_i\big|_{x=0} = \frac{\sum\limits_{j\in I_k} Q_j C_j\big|_{x=L_j} + Q_s C_s}{\sum\limits_{j\in I_k} Q_j + Q_s} \dotfill (5)$$

Where: i = link with flow leaving node k;
　　I_k = Set of links with flow into k;
　　L_j = Length of link j;
　　Q_j = Flow in link j;
　　Q_s = External source flow entering node k.

For variable-volume storage tanks, which are also assumed to be completely mixed, a mass balance across the tank yields [14]

$$\frac{\partial(V_T C_T)}{\partial t} = \sum\limits_{i\in I_T} \cdot Q_i C_i\big|_{x=L_i} - \sum\limits_{j\in o_T} Q_j C_T + R(C_T) \dotfill (6)$$

Where: V_T = volume of the tank at time t;
　　C_T = Concentration within the tank at time t;

I_r = Set of links providing flow into the tank; and

O_r = Set of links receiving flow from the tank. V_r

The same equations (1, 5, 6) can be used to model the age of water in the network. In this case C_i would be interpreted as the age of water in link i and C_T would be the average age of the blended water in the tank. The reaction term $R(C_T)$ would simply equal 1.0 and C_s for any source water entering the network would be zero.

When viewed over an entire network, the correlation of equation (1) with boundary conditions (5) and (6) results in a coupled set of partial differential/algebraic equations. An analytical solution becomes intractable for all but the simplest network arrangements. Consequently numerical methods must be relied upon [15].

NUMERICAL SOLUTION METHODS

There are several numerical approaches available for solution of water quality models. These methods can generally be grouped as either Eulerian or Lagrangian in nature depending on the volumetric control approach adopted. Each method assumes that a hydraulic model has determined the flow direction and velocity in each pipe at specific intervals over an extended period of time. These intervals are referred to hydraulic time steps and are typically an hour for most applications. Within a hydraulic time step the velocity within each pipe remains constant. Constituent transport and reaction proceeds at smaller intervals of time know as the water-quality time step (τ). Each method uses some forms of adjustment at the start of a new hydraulic time step to account for possible changes in flow velocity and direction.

Eulerian models divide the system into fixed pipe segments and then track the changes that occur as water flows through these segments. The Discrete Volume-Element Method (DVEM) is an example of Eulerian approach.

The discrete volume-element method is based on a plug-flow reactor assumption. The plug flow model accounts for advective transport and the kinetics of the constituent reactions within the plug. According to the physical plug flow reactor model, each reactor plug would be advected through the system and composted with incoming plug at flow-receiving nodes. In the Eulerian DVEM numerical modeling scheme this plug movement is simulated by transferring substance concentration state from one discrete volume-element (a "plug") to the next-adjacent volume-element along the direction of flow.

The DVEM proceeds by subdividing each link in the network into a number of equal sized elements at every hydraulic event in the simulation. To preserve accuracy the volumetric element for each link over the duration of every hydraulic event must be correctly computed. To ensure that fluid is not transported beyond the confines of any link within a single discharge and time step. It follows that τ cannot exceed the shortest travel time through any network link over the analysis interval.

The Time Driven Method (TDM) is an example of a Lagrangian approach. This method also breaks the system into segments, but rather than using fixed control volumes as in Eulerian methods, the concentration and size of the segments are tracked as they travel through the pipes. With each time step, the farthest upstream segment of each pipe elongates as water travels into the pipe, and the farthest downstream segment shortens as water exits the pipe.

Similarly to the DVM, the reactions of a constituent within each segment of the pipe are calculated, and the mass and flow entering each node are summed to determine the resulting concentration. If the resulting nodal concentration is significantly different than the concentration of the downstream pipe segment, a new segment will be created rather than elongating the existing one. These calculations are repeated for each water quality time step τ, until the next hydraulic change is encountered and the procedure begins again.

WATERCAD'S WATER QUALITY SOLUTION ALGORITHM

WaterCAD software was designed, developed and programmed by Haestad Methods'staff of Software Engineers and Civil Engineers [11,22]. WaterCAD is intended to represent the state of-the-art for stand alone, Windows based, Water Distribution Analysis and Design. WaterCAD's numerical computations are based on research conducted by the U.S. Environmental Protection Agency (EPA) Drinking Water Research Division, risk Reduction Engineering Laboratory, its employees and its consultants.

The WaterCAD implements the Eulerian Discrete Volume-Element Method (DVEM) to solve the numerical constituent transport problem for the system being analyzed. The method requires as basic input, the complete solution for the distribution of flows (magnitude and direction) for the network links and nodes at each discrete time step which occurs over an extended period simulation (EPS). The EPS results generate a sequence of hydraulic steps that are then reformulated into a distribution of hydraulic states encapsulated within discrete volume-elements by WaterCAD's DVEM algorithm. The constituent concentration is determined at each discrete volume-element in the system for every quality time step over the full duration of simulation.

WaterCAD implements a first-order reaction rate model that uses a composite reaction rate coefficient that effectively simulates reactions occurring in the bulk fluid as well as the fluid/pipe wall interface.

The model for solving the constituent transport by WaterCAD can be used to predict other water quality parameters including age. To accomplish this model makes the following assumptions. The concentration value, C_i, in the basic transport equation is set to age of water and the reaction term, $R(C_i)$, is set equal zero.

FIELD STUDY

The drinking-water distribution system at El-Delta Co. for Fertilizer and Chemical Industries was chosen as a case study to assess the WaterCAD dynamic water quality model described earlier and to evaluate the effect of the system operation on water quality. The El-Delta Co. is located on western bank of the Nile River and has both industrial and residential zones with about number of 560 family. The potable water produced by the treatment plant is used to cover many industrial purposes together with the existing residential zones. Potable water produced is conveyed via a network of pipes that covers the whole company. Potable water consumption fluctuates in the range of 70 – 80 l/s. This water is produced in the Company water treatment plant, which purifies the raw Nile River water through a conventional train of treatment (coagulation, sedimentation, filtration and disinfection). The distribution system has a total length of 10.235 km with 83 different diameters (250 – 100 mm) asbestos pipelines. These pipelines were constructed during the period between 1974 – 1979.

For modeling purposes, the service area was represented with the pipe network shown in Figure 1. It included all major and main loops. Pipe's lengths were scaled from maps and actual pipe's diameters were used. The Hazen-Williams roughness coefficient for each pipe was assigned based on the age and type of pipes. Final estimate of average water-use rates and the pattern of consumption throughout the service area were based on the type, density and number of building units surrounding each junction node in the distribution system.

Four sampling sites in the distribution system in addition to sampling sites at the pump station were identified as shown in Figure 1. The pump station was sampled on its discharge side. Free available chlorine for all samples was determined according to the Standard Methods [2] in the field with a portable DPD colorimetric test kit (Hach model 46700-05).

The free chlorine content of water introduced into the drinking water distribution system at the pump station was kept constant at 0.8 mg/L. The only remaining parameters to be specified in the chlorine decay model were the bulk and wall reaction constant.

The bulk decay constant (K_b) in all pipes was determined based on a laboratory beaker test of free chlorine decay in water taken from the service area. The test was conducted in the company chemical laboratories. Multiple 500-ml bottles were collected from the effluent of the water treatment plant and stored at constant temperature. Twice a day a bottle was examined for free available chlorine and then discarded. Figure 2. illustrates this behavior of the observed decay in chlorine residual and time. The best-fit first-order decay constant for these data was 0.60 d^{-1}. The wall decay constant (K_w) was adjusted over a range of values, and the simulated WaterCAD results were compared to the observed data at the 4 sampling locations out in the distribution system.
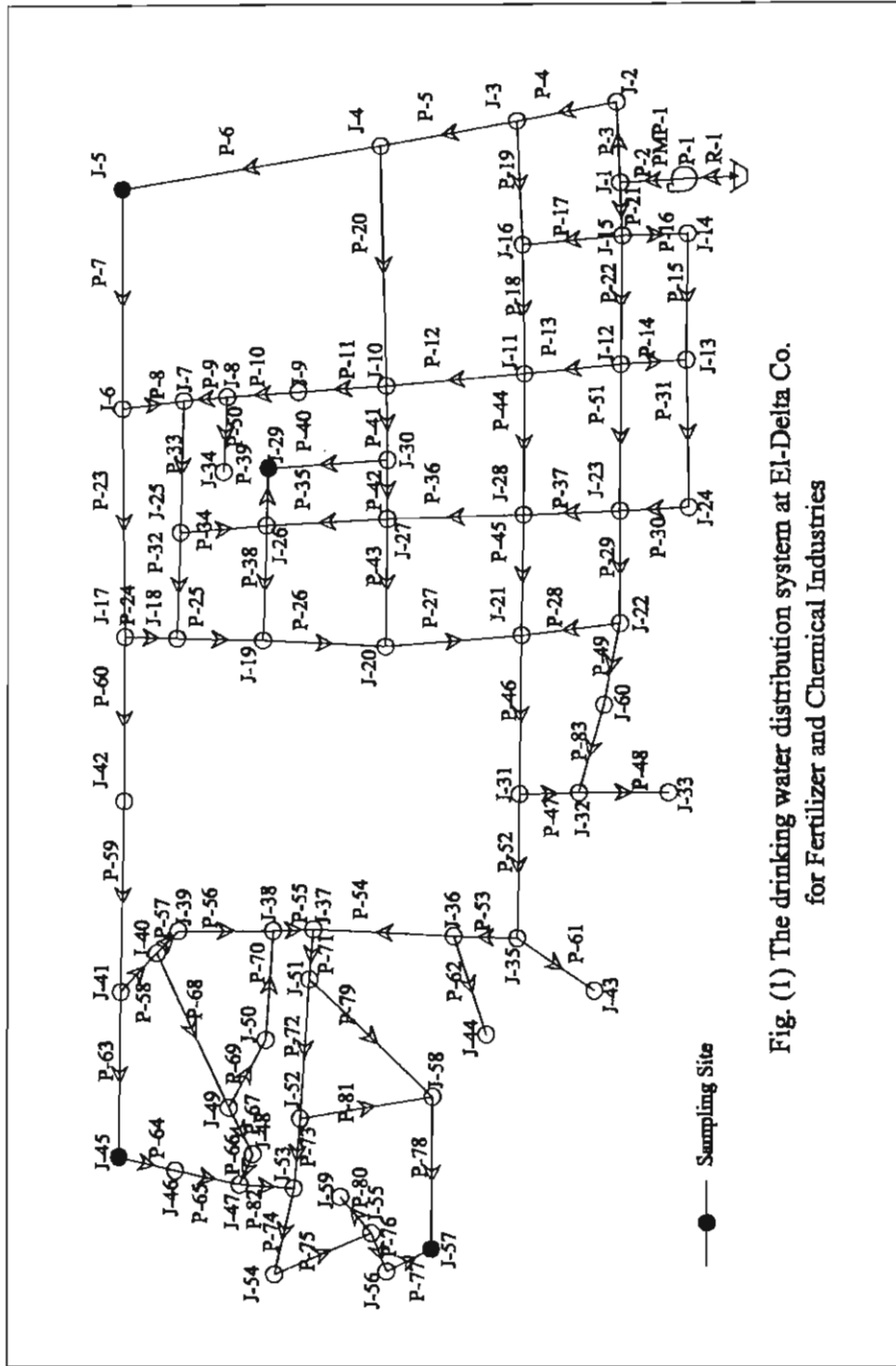
Fig. (1) The drinking water distribution system at El-Delta Co.
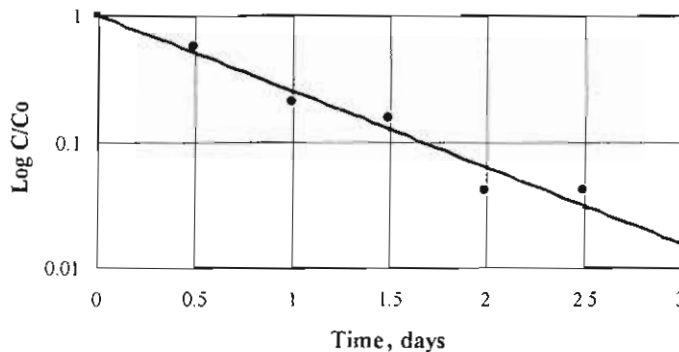for Fertilizer and Chemical Industries

Figure 2. Results of Free Chlorine Decay Bottle Test

Extended-period hydraulic simulation was used to compute flows, pressures and velocities for all pipes in the distribution system at one-hour intervals over the 48 hrs (2 days) sampling period. Using a trial-and-error approach for adjusting wall reaction constant (K_w), WaterCAD was used to simulate chlorine residual. It was assumed that K_w varied over the service. Although the model is not fully calibrated at this stage, the information gained from running the model is valuable in planing the chlorine study and assist in selecting both sampling sites (Nodes 5, 29, 45, 57) and frequency. After a numerous numbers of runs, K_w was adjusted over a range of values, and the simulated results were compared to the observed data.

Figures 3 - 6 show the comparison between the collected data at the observed nodes and that predicted by WaterCAD for a range of K_w values between 0.2 d^{-1} and 2.0 d^{-1}. Most of the observations at nodes 5, 29, 45 and 57 fall under the simulated range of these two K_w values. In the same figures 3-6, it's also shown the residence time of water that outflow from the observed nodes at the same time at which data is collected.

As can be seen from this simulation, the chlorine residual varies dramatically over time, depending on the time of day and the residence time. The comparison of data in figures 3-6 show that the free chlorine decreases as the residence time increases. That necessitates increasing the dose of chlorine through the period of low consumption (nighttime).

In spite of the fact that the network is old and contains small diameter pipes comparing with high water consumption, the prediction results from the simulating model gives high free chlorine at high consumption period. Explaining this phenomena results from the short traveling time in pipes and the absence of the elevated tank. The high level of decay within pipes may be even more serious than the long residence times in network pipe lines.
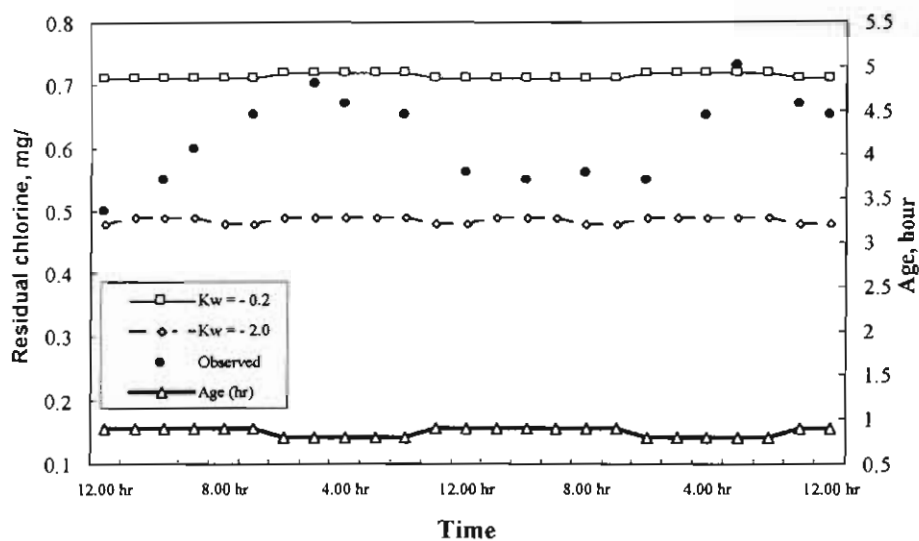
Figure   3. The residual predicted and observed free chlorine and the residence time   (age) of consumed water from Node 5 at different times during the day.
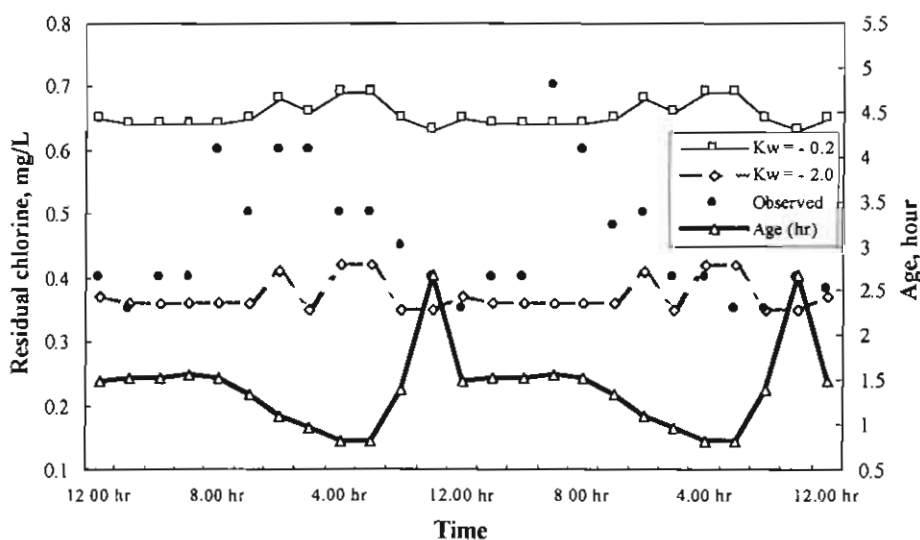

Figure 4. The residual predicted and observed free chlorine and the residence time (age) of consumed water from Node 29 at different times during the day.
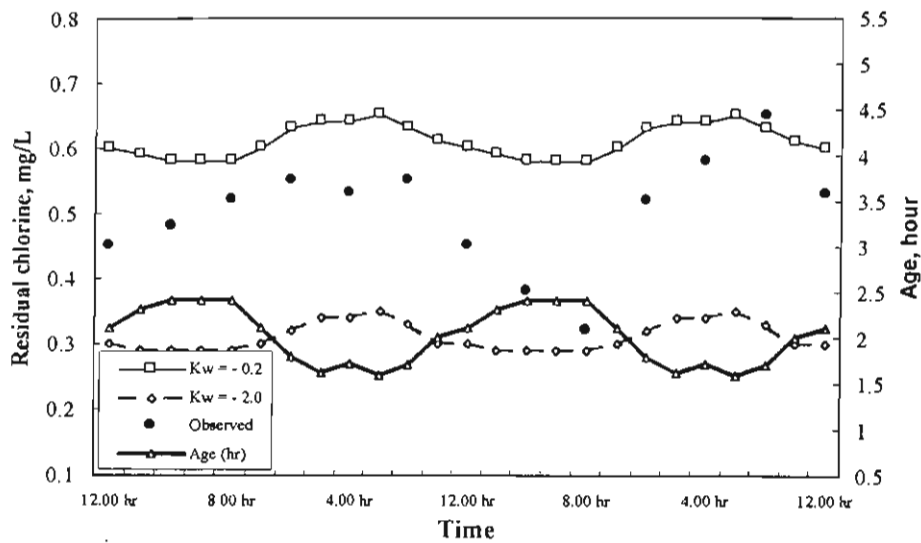
Figure   5. The residual predicted and observed free chlorine and the
residence time (age) of consumed water from Node 45 at
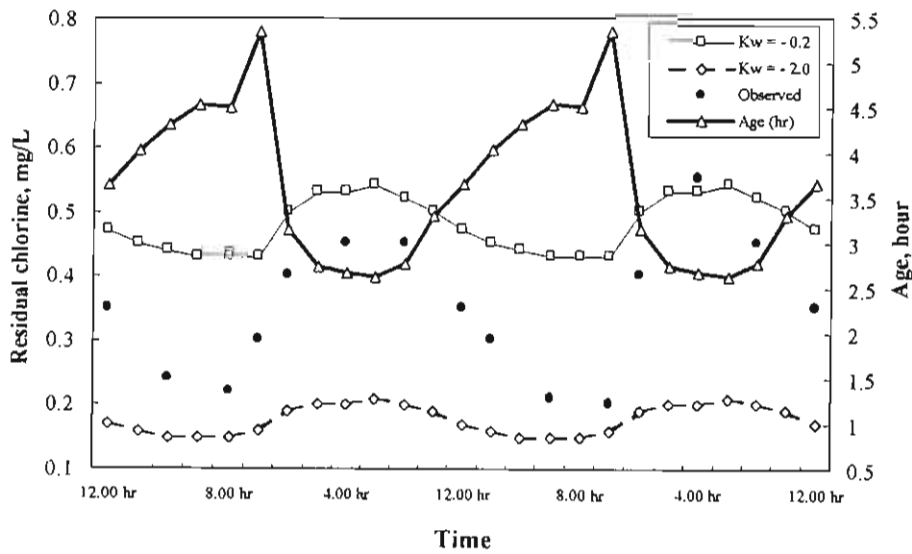different times during the day.

Figure 6. The residual predicted and observed free chlorine and the
residence time (age) of consumed water from Node 57 at
different times during the day.

SUMMARY AND CONCLUSIONS

During the last decade, emphasis has shifted from a fundamental concern on treating potable water to a basic concern to achieve quality of standards at the point of consumption. Because of the difficulty and size of most water distribution systems, understanding the factors that influence water quality between the treatment plant and consumer will be hard to determine. Water quality computer models are becoming increasingly useful to water utilities in evaluating these factors. These models provide water-supply managers a powerful and effective tool for understanding and enhancing the behavior of chlorine residuals throughout their systems under different hydraulic conditions.

The chlorine propagation model was applied to data collected over a 48 hr sampling period in the water distribution system at El-Delta Co. for Fertilizer and Chemical Industries. The bulk decay constant for the model was examined independently in the laboratory. Its wall decay constant was adjusted by trial-and-error.

The filed study emphasized that:

1. The distribution system can have a negative impact on water quality.
2. Chlorine residual loss is influenced by the pipe wall decay constant, the bulk decay constant ,and the residence time,
3. The wall decay constant for the asbestos pipe 20 years old and with diameter 250-100 mm may be in the range of $0.2 - 2.0 \, d^{-1}$.
4. To keep the free residual chlorine at the desired value, it is necessary to increase the dose of chlorine at periods of low consumption

ACKNOWLEDGMENTS

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