An event-driven method for modelling contaminant propagation in water networks

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An efficient computer-oriented methodology is presented for use in analyzing water quality variations in drinking-water distribution systems. The proposed method can be effectively used for modelling chemical, biological, and hydraulic changes that result from distribution system activities and to predict the transient distribution of contaminants throughout the pipe system. It is predicated on the material mass balance accounting for transport and kinetic reaction processes. Perfect advective one-dimensional displacement with complete mixing of material at the network nodes is assumed. The method is event-driven and determines the optimal pipe segmentation scheme with the smallest number of segments necessary to carry out the simulation process. The resulting approach allows for dynamic water quality modelling that is less sensitive to the structure of the network and to the length of the simulation than previously proposed methods. In addition, numerical dispersion of concentration profile resolution is eliminated. The applicability of the method is illustrated using an example water distribution network. Enhancement of distribution system water quality management is a principal benefit of the methodology.

Keywords: pipe networks, flow distribution, water quality, system simulation, dynamic analysis algorithms

Introduction

There is growing concern on the part of water utilities and governmental regulatory agencies regarding potential water quality problems in potable water distribution systems. Of principal concern is the problem of water quality variability within the distribution system. It is clear that the distribution itself may adversely affect the quality of treated water.[1–14] Water leaving the treatment plant may undergo substantial changes in quality while being transported through the distribution system before reaching the end consumers. These quality changes may be associated with complex physical, chemical, and biological activities that take place during the transport process. These activities can occur either in the bulk water column, the hydraulic infrastructure, or both.

Examples of such activities are numerous, including the loss of disinfectant residuals; reactions of disinfectants with organic and inorganic compounds that may result in aesthetic changes in taste, odor, and appearance; sudden disturbances in system boundaries (e.g., new construction, meter repairs, flushing program); system bacteriological failure resulting from insufficient disinfection of water mains after construction or repair, main breaks, loss of positive line pressure, or abrupt water pressure changes; back pressure (i.e., pressure on the consumer end is greater than the water system pressure) or back siphonage (i.e., the water system pressure creates a vacuum that sucks water from the consumer end);

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system design and operating scenarios; poor maintenance procedures; stagnation of water in dead-end mains and storage facility with long residence times; the blending of multiquality water that may result in chemical instability; contamination via cross-connections or leaky pipe joints; the depletion of dissolved oxygen; increase in turbidity; dissolution of lead; internal corrosion of pipes and the formation of corrosion by-products; generation of hydrogen sulfide; growth of bacteria or other microorganisms; accumulation of bacteria in unprotected (e.g., open) reservoirs; the formation of biofilms and tubercles on the pipe walls and in pipeline sediments, and other microbial colonizations; and the formation of disinfection by-products, some of which are suspected carcinogens such as trihalomethanes and haloacetic acids.

The Safe Drinking Water Act and its Amendments (SDWAA) will significantly challenge the waterworks industry in the United States.[15–16] Under this act, the United States Environmental Protection Agency (USEPA) is required to regulate the levels of pathogenic microorganisms in drinking water, specifically, *Giardia lamblia*, enteric viruses, and *Legionella*. These regulations establish maximum contaminant levels (MCLs) or action levels for many contaminants found in drinking water that are known or anticipated to induce adverse health effects. The current standard for trihalomethanes, the treatment technique regulation for dissolved lead and copper, the anticipated disinfectant/disinfection by-products rule, the Surface Water Treatment Rule requirement for maintaining a detectable residual disinfectant at representative locations in the distribution system to protect from microbial contamination or proliferation, the regulation of coliform bacteria under the Total Coliform Rule (TCR), and the inactivation of viruses under the Groundwater Disinfection Rule are examples of these regulations. Exceeding MCLs or action levels requires corrective actions to be taken by water utilities. The corrective actions may include the implementation of specified treatment techniques, replacement of lead service lines, looping of dead-end mains, and more frequent exercising of storage tanks. The regulations also contain significant monitoring requirements according to system size and vulnerability status and will apply primarily to 201,242 public water supply systems in the continental United States.[15–16] This includes all water distribution systems having at least fifteen service connections or regularly serving an average of at least twenty-five individuals daily at least sixty days out of the year. Because the SDWAA has been interpreted as requiring that the MCLs established under the act must be met at the consumer's tap,[16] it is imperative that sound yet efficient techniques for use in simulating and assessing the movement and transformation of contaminants in pipe distribution systems are available.

During the past decade, considerable attention has been focused on the development of algorithms for use in modelling water quality in pipe distribution systems. The various algorithms have been based on the use of steady-state and dynamic mathematical models. Steady-state models determine the ultimate spatial distribution of contaminants along with their travel paths and travel times throughout the piping system under a given set of loading and operational conditions. A set of linear algebraic equations is used to describe contaminant mass conservation at the network nodes. The contaminant nodal concentrations can be obtained using an iterative solution of the determinate nodal questions,[17–19] a direct sparse matrix solution,[20,21] an explicit marching-out solution scheme,[4] or an explicit graph-theoretical single-step substitution process.[22] Dynamic models simulate the movement and fate of contaminants under temporally varying conditions as the diurnal customer demands and other factors within the distribution system change. The other factors include changes in storage tank levels, valve settings, storage tanks and pumps going on- or off-line, flow reversal in pipes, and rapid demand changes (e.g., fire demands). The substance advection process is simulated numerically in a time-driven environment using the Lagrangian transport model,[23] the marching-out solution method,[5,6] or the discrete volume element method.[14] These algorithms are predicated on the assumptions of one-dimensional motion, single or successive steady-state (extended period simulation) network flow hydraulics, instantaneous and complete nodal mixing, ideal plug flow with negligible dispersion, and single constituent with one or more feed sources. Contaminants are normally treated as conservative or as simple first-order kinetic characteristic functions. A comprehensive review and bibliography of the various approaches was previously provided.[24,25]

This paper presents a computer-oriented methodology for analyzing water quality variations in drinking-water distribution systems. The method can be effectively used for modelling chemical, biological, and hydraulic changes that result from the system activities and to predict the spatial and temporal distribution of contaminants throughout the piping system. It is an explicit, event-driven, water quality modelling algorithm. Water distribution networks and the processes within them are usually categorized as *continuous systems* and hence suggest a *time-driven* simulation approach[26] by means of which contaminants are displaced along the pipes with the mean flow velocity by a finite time increment that is primarily influenced by the network structure and hydraulics. The proposed approach is, however, *event-driven* for reasons of space efficiency, computational effectiveness, and numerical accuracy. Under this environment, the contaminant advective movement is dictated by the system activities.

Although topological sorting of the network is not explicitly required by our algorithm, it is still performed in order to determine if the circulation problem exists,[22] which would make any reasonable simulation next to impossible to carry out without significant losses in accuracy. The primary advantage of the proposed approach is that it allows for dynamic water quality modelling that is computationally optimal. In addition, numerical dispersion of concentration front profile resolution is eliminated. The methods previously cited cannot make these claims.

The proposed algorithm will be referred to herein as the event-driven method (EDM). A one-dimensional transport model is assumed with instantaneous and complete cross-sectional mixing. Longitudinal dispersion is neglected. The algorithm is predicated on a mass balance equation that accounts for both advective transport and reaction kinetics. Input to the model consists of the topological portrait of the network, the temporal changes of the network flow hydraulics, the kinetic mechanism of contaminant formation and destruction, and the temporal definition of contaminant concentrations that are introduced at the network supply sources. The model output consists of a time history report of contaminant concentration at each node and within each pipe of the distribution network. The method is illustrated using an example water distribution network. Before the details of the method are examined, a short summary of the associated network model equations is provided.

Theoretical model

Network model

The general network model can be represented by a directed connected graph comprising a finite number of oriented unidimensional pipe segments interconnected by nodes in some specified configuration. Each pipe is of defined length, diameter, roughness, and material. Pipes may contain controllable elements such as pumps, regulators, and valves. The endpoints of each pipe are nodes with known energy grade (e.g., constant-pressure regions, elevated storage facilities, lakes, rivers, treatment plants, and well fields) or external consumption characteristics. Pipes and nodes are uniquely identified by labels allowing the network topology to be defined. The network model must obey the Euler relation:

$$e = n + l - 1 \tag{1}$$

where e, n, and l designate the numbers of pipes, nodes, and closed loops, respectively. When the network graph comprises m logically separated subnetworks, i.e., each subnetwork satisfying equation (1), then the Euler–Poincare relation

$$e = n + l - m \tag{2}$$

will hold.[27]

Steady-state model

Regardless of the network topological configuration, the steady-state mathematical model consists essentially of a set of quasilinear equations describing the physical laws governing the hydraulic behavior of the system. Continuity implies that at each node we have

$$\sum_{i=1}^{e} \lambda_{j,i} Q_i = 0;\ \lambda_{j,i} \in \{-1, 1, 0\} \text{ and } j = 1, \ldots, n \tag{3}$$

which asserts that at each node, the algebraic sum of inflows ($\lambda_{j,i} = -1$) and outflows ($\lambda_{j,i} = 1$) must be zero.

The balance of mechanical energy implies that along each closed loop, the algebraic sum of energy displacements must equal zero. That is

$$\sum_{i=1}^{e} \gamma_{m,i} \Psi_i = 0;\ \gamma_{m,i} \in \{-1, 0, 1\} \text{ and } m = 1, \ldots, l \tag{4}$$

where the energy displacement is considered positive ($\gamma_{m,i} = 1$) when the pipe orientation goes with the loop orientation. For each pipe, the energy displacement Ψ and volumetric flow rate Q are related by a characteristic function that can vary depending on the approximating flow resistance law selected and the type of controllable element present in the pipe.[28–34] This is a nonlinear function and can be expressed as

$$\psi = \zeta Q^2 + \xi Q^{\sigma} - \eta^2 \left(\alpha - \frac{\beta}{\eta^{\nu}} Q^{\nu} \right) \tag{5}$$

where ζ is the fittings constant given by

$$\zeta = \frac{8K}{g\pi^2 D^4} \tag{6}$$

ξ is the pipe resistance constant that can be defined by the Hazen–Williams expression as

$$\xi = \frac{\mu L}{R^{\sigma} D^{b}} \tag{7}$$

K is the sum of the minor loss coefficients for the fittings; g is the gravitational acceleration; L is the pipe length; D is the pipe diameter; R is the Hazen–Williams coefficient of roughness; μ is the constant that is dependent on the units used; α is the pump shutoff head at zero flow condition; β and ν are the regression coefficient and the exponent of the pump characteristic curve that represents actual pump operation in relation to its reference speed; η is the ratio of the pump rotational speed to the pump reference speed; and the exponents σ and b are 1.852 and 4.871, respectively. The pump operation can also be described by a quadratic characteristic function.[28,30,31]

The flow magnitude and direction associated with the pipes are determined by simultaneously satisfying equations (3) and (4) using methods as described by Jeppson,[35] Walski,[36] Osiadacz,[37,38] or Bhave.[39] Advantages and limitations of each technique have been discussed by Wood and Rayes,[40] Osiadacz,[37] Nielsen,[41] and Altman and Boulos.[42] Necessary and sufficient conditions for solution feasibility have been presented by Boulos et al. and Boulos and Altman.[27,28]

Dynamic model

The dynamic model involves a sequence of steady-state solutions linked by an integration scheme for the differential equation describing the storage tank dynamics. The model assumes that water usage patterns, external water supply rates, storage tank water levels, and pumping schedules remain constant over a fixed time period, but these quantities can change from one time period to another. Each such time-dependent change in the system boundary conditions is referred to as a *hydraulic event* and the duration of each event is referred to as the *hydraulic time step*. A hydraulic time step of 1 h is

normally used. Each individual hydraulic event uniquely defines some network flow distribution. The dynamic model thus consists essentially of solving a sequence of the steady-state model, described in equations (3) and (4), over a series of prespecified time steps to simulate the continuous dynamic phenomena. The dynamic characteristics of each event are used to update the inputs to the steady-state solution in every hydraulic time step.

The dynamics of the tank fill-up and depletion are modelled by a differential equation for the tank water level as a function of time. At each time step, the change in tank water level is computed from integrating the differential equation

$$\frac{dh}{dt} = \frac{1}{A_T}(Q_{in} - Q_{out}) \tag{8}$$

which expresses conservation of water volume at the variable-level storage tank. Here, h designates the tank water level; t is the time; A_T is the tank cross-sectional area; and Q_{in} and Q_{out} are the total inflows and outflows of the tank, respectively. This simulation approach is referred to as the extended period simulation model.[43–45] Although such an approach does not account for the pressure differences across individual pipes in the network that are required to accelerate or decelerate the water columns (i.e., it ignores the inertial effects of changing flow velocities), the model can be effectively applied to a large class of slowly varying transients where acceleration forces are insignificant. If greater accuracy is required, methods based on rigid water column theory for slow transients[46] or on elastic water column theory for rapid transients[37,47] can be applied. In either case, a sequence of network flow distribution between separate time-dependent hydraulic events can be determined for use as inputs to the contaminant propagation model.

Contaminant propagation model

Analytical model The propagation of contaminants in a distribution network consists essentially of three processes: advection in pipes, kinetic reaction mechanism, and mixing at nodes.

Advection in pipes. Steadily flowing contaminants in a pipe can be described by a one-dimensional mass conservation differential equation of the form

$$\frac{\partial C}{\partial t} = \frac{Q}{A}\frac{\partial C}{\partial x} + \theta(C) \tag{9}$$

where C denotes the contaminant concentration within the pipe; Q is the pipe volumetric flow rate; A is the pipe cross-sectional area; x is the distance (in the positive flow direction) along the pipe; and $\theta(C)$ is the rate of reaction of contaminant within the pipe.

Kinetic reaction mechanism. Changes in the contaminant concentration in the pipe can be described by a first-order kinetic rate expression of the form

$$\theta(C) = kC \tag{10}$$

where k is the first-order reaction rate coefficient and C is the contaminant concentration in bulk flow. The sign of the coefficient defines the kinetic reaction process. The coefficient is positive when modelling contaminant growth (e.g., trihalomethanes) and negative for decay (e.g., chlorine residual). Other kinetic rate expressions can also be used.[48–50]

Mixing at nodes. Assuming instantaneous and perfect mixing at the network nodes, the contaminant nodal concentrations can be obtained from the mass balance principle as

$$C_k = \frac{\sum_{j \in \{k\}}^{\beta_k} Q_j C_j}{\sum_{j \in \{k\}}^{\beta_k} Q_j} \tag{11}$$

where C_k denotes the contaminant concentration at node k; $\{k\}$ is the set of incoming pipes at node k; and β_k is the cardinality of $\{k\}$. For a variable-level tank, the change in concentration can be determined from the mass conservation relationship as

$$\frac{d(C_T V_T)}{dt} = Q_{in}C_{in} - Q_{out}C_T + \theta'(C_T) \tag{12}$$

where C_T and V_T are the fully mixed concentration and volume of the tank, respectively; C_{in} is the contaminant concentration of the incoming pipe; and $\theta'(C_T)$ is the reaction rate within the tank. Any outflow from the tank is assumed to carry the fully mixed concentration of the tank. The perfect mixing assumption within tanks may be loosened through the use of other mixing models, such as a multicompartment mixing model.[51]

For controllable elements such as pumps and valves, instantaneous contaminant advection across each element is assumed. That is, the incoming and outgoing contaminant concentrations for the element are identical.

Because the concentration profile along the pipes is dependent on upstream concentration fronts, the analytical solution to this problem becomes intractable for all but the simplest network configurations. Consequently, recourse to numerical solution techniques is required.

Numerical model

The proposed approach may appear to be similar to the time-driven procedure; however, the two methods are fundamentally different. Whereas the former operates on a time-driven modelling framework, our model is dictated by the system activities.

In the time-driven approach, the model is driven by the *water quality time step*,[14] a parameter determined by the network structure (e.g., pipe lengths) and hydraulics (e.g., pipe velocities). This works fine for the majority of water distribution networks; however, there do exist networks consisting of a number of relatively long pipes with small velocities. The number of pipe segmentations of long pipes in the time-driven methods could then become prohibitively high and cause memory problems not only for desktop, but even for mainframe computers. Ad hoc techniques can be used[6,14,23] but with a resulting loss of resolution. One way to avoid this problem is to use a more rigorous approach.

The EDM eliminates the above problem by segmenting the pipes into the smallest required number of segments necessary to carry out the simulation process. The segmentation of pipe(s) is performed only after a hydraulic or a subhydraulic event takes place. This is provably the least number of pipe segmentations that needs to be performed, eliminating the unnecessary segmentations of the time-driven methods. The following definitions are used:

Definition 1. A *hydraulic event* is an external (exogenous) event that causes a change in the flow and velocity patterns within the network.
Definition 2. A *hydraulic time step* takes place between two consecutive hydraulic events and is a time period during which all flow and velocity patterns remain constant.
Definition 3. A *subhydraulic event* is an internal (endogenous) event that causes a change in the contaminant concentration leaving (at least) one node.
Definition 4. A *subhydraulic time step* takes place between two consecutive subhydraulic events and is a time period during which contaminant concentrations (as well as flow and velocity patterns) remain constant.
Definition 5. A *semihydraulic time step* takes place between a subhydraulic and a hydraulic event.

Because we are modelling a dynamic system, no exact steady state will ever be achieved. The closest one gets is a pseudo steady state, that is, a time period occurring between any two hydraulic events that are sufficiently far apart so that no subhydraulic events (i.e., changes in nodal concentrations), take place anywhere in the network.

The EDM is implemented as a simulation system that uses the *next-event* scheduling method; that is, the clock time is advanced to the time of the next (or potential) event. The next-event approach requires that most events have a known time at which they are to occur. Moreover, the times of these events may change when the system is influenced by an exogenous event. This is true for our model, as all flow patterns, travel times, the network topology, and eventually the pipe and node concentrations are always known at any point in time during the simulation.

The simulational model is, therefore, reduced to a role of a smart scheduler that creates, identifies, and arranges activities (i.e., the hydraulic and subhydraulic events) in a chronological order. A simple linked list provides an elegant way of organizing records of future events by keeping them in a sorted order (with provisions for preemption and/or insertion of activities). The linked list approach is commonly used in the C and Pascal programming languages. Alternatively, a balanced binary search tree can be used to provide a more efficient data structure for the placement (retrieval) of events into (from) the activity list.

Initially, the known hydraulic events are placed into the activity list in chronological order. It is assumed that the initial contaminant concentration at every node is zero. Associated with each hydraulic event is a record indicating the specific network hydraulics (i.e., for all pipes, their flows and velocities are known). This information will eventually be used to determine not only the nodal concentrations, but also to create (and schedule) future subhydraulic events.

Observe that the only factors affecting the concentration at any node are the concentrations and flows in the pipes immediately upstream of the given node. In addition, in the prolonged absence of (sub)hydraulic events, no changes of concentrations at the junction nodes take place. Let us examine closely what causes subhydraulic events and how they are handled in our simulation model.

A subhydraulic event occurs when water with a different contaminant concentration reaches a node. Although we assume that no two subhydraulic events may take place at the same time, in case of ties, they are handled simultaneously as one compound subhydraulic event. To each pipe we dynamically assign pointers whose function is to serve as *separators* between volumes of water with different contaminant concentrations. They are used to define time-dependent contaminant displacement fronts. Each separator is a record containing four fields: *TC*, *DT*, *CC*, and *TA*. These indicate the time of creation, distance traveled so far, (current) contaminant concentration, and the projected time of arrival to the tail (downstream) node, respectively. As the injected contaminant moves through the system, the position of the separators defines the spatial location behind which contaminant concentrations exist at any given time. The life of a separator is limited by the time period required for it to travel through its pipe, i.e., to arrive at the tail node. When that happens, the separator serves no further purpose; it is disposed of and the memory is reclaimed for other separators.

For now let us ignore the kinetic reaction mechanism taking place in the system. We will explain how that is resolved in EDM shortly. The pipe segmentation procedure operates as follows. The arrival of a separator to its tail node in Δ time period signifies an occurrence of a subhydraulic event. This causes a number of actions to take place. First, the corresponding subhydraulic event is removed from the front of the activity list and the system simulation time is increased by Δ. Next, the *DT* fields of all the remaining separators in all of the pipes are updated accordingly, i.e.,

$$DT_{ij} = DT_{ij} + \Delta * v_i \tag{13}$$

where DT_{ij} is the distance between the ith pipe's jth separator and its source node, and v_i is the (current) flow velocity in pipe i. One might say that the separators "float" downstream toward their respective tail nodes for a time period equal to Δ. Note that the activity list does not have to be updated at this time as no reordering of subhydraulic events takes place. Next, a new nodal concentration at the tail node is computed. Finally, new separators are created, one for each outgoing pipe of the tail node under consideration, with the appropriate initial field values for the *TC*, *CC*, and the *DT*. Their estimated times of arrival (*TA*s) are determined according to the present flow pattern and the subhydraulic

events are placed, in chronological order, into the activity list.

Of course, if a (sub)hydraulic event were to take place before all of the separators had a chance to reach their tail nodes, the changes in the velocity distribution might necessitate the resorting of the activity list to keep it in chronological order. Also, special care is needed to handle cases of flow reversal in pipes as a result of a hydraulic event. Specifically, a flow direction vector for all pipes is maintained. If a hydraulic event causes flows of certain pipes to reverse, the *DT* and *TA* fields for every segment in these pipes are updated accordingly, and the source (head) and destination (tail) nodes are interchanged. It should be noted that any hydraulic event causes a change of the flow pattern in the network (and, eventually, contaminant concentration changes at the nodes). Hence, a new separator is introduced at the head of each pipe after every hydraulic event. Furthermore, observe that when a hydraulic event takes place, in general, it forces the majority of the subhydraulic time steps to be partitioned into two semihydraulic time steps. This situation can be easily accommodated by an appropriate replacement of the corresponding subhydraulic events with a pair of newly created subhydraulic events placed into the activity list.

Extension to nonconservative contaminants is straightforward and is modelled as follows. After each subhydraulic event takes place, the contaminant concentration is updated for all pipe segments given the appropriate kinetic reaction rate expression and with respect to the length of the subhydraulic time step. Under conditions of zero flow or flow reversal in pipes, the kinetic reaction mechanism continues with time. This is consistent with the approach described by others.[6,14,23]

Because the changes in contaminant nodal concentrations are reflected in the EDM immediately as they occur, the numerical accuracy losses that are introduced in any time-driven model are completely eliminated. The only parameter that significantly affects the performance of EDM is the total number of separators that are simultaneously active. Although the number of separators active at any point in time during the simulation is usually manageable, for certain networks it is theoretically possible to generate a sequence of events that will cause an exponential number (in the number of pipes) of separators to be created. In these cases, a "collapsing" of the separators may be carried out, that is the replacement of two or more separators by one if they are less than some (user specified) distance apart. Although this could introduce some computational inaccuracies, in practice these are sufficiently small to preserve the integrity of the simulation.

Illustrative example

As an example, we consider the simple water distribution network shown in *Figure 1*. A labelling scheme is shown for pipes and nodes. As can be seen from the figure, this network contains eight pipes, four junction nodes, and three source nodes. SI units and the Hazen–Williams head-loss expression are utilized for this example. *Tables 1* and *2* summarize the pertinent pipe and junction node characteristics, respectively. Supply sources A, B, and C represent pumping wells with total head of 50.0 m, 60.0 m, and 56.0 m, respectively. The three well pumps are identical and their operating data are shown in *Table 3*. The control valve in line 2 has a minor loss coefficient of 10. The network flow distribution was obtained using a widely used network analysis computer program.[34,52] The hydraulic results for pipes and junctions are also presented in *Tables 1* and *2*, respectively.

The sample network provides the means to illustrate the reliability and effectiveness of the proposed algorithm. Contaminant concentrations of 1000 mg/l, 800 mg/l, and 600 mg/l are injected at sources A, B, and C, respectively. The contaminant considered is assumed to be conservative and is initially absent throughout the

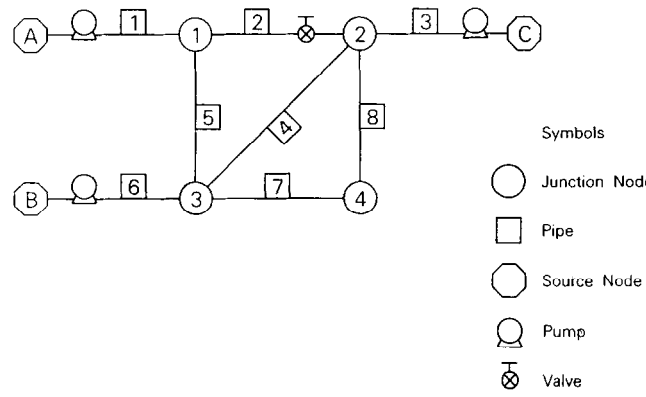

Figure 1. Example water distribution network.

Table 1. Pipe characteristics.

Pipe number	Head node	Tail node	Length (m)	Diameter (mm)	Roughness coefficient	Flow rate (l/s)	Velocity (m/s)
1	A	1	300.0	480.0	120.0	319.87	1.77
2	2	1	600.0	350.0	120.0	21.72	0.23
3	C	2	300.0	480.0	120.0	557.85	3.08
4	3	2	650.0	400.0	120.0	53.06	0.42
5	3	1	400.0	350.0	120.0	58.41	0.61
6	B	3	300.0	480.0	120.0	672.30	3.72
7	3	4	600.0	300.0	120.0	210.83	2.98
8	2	4	400.0	350.0	120.0	389.17	4.04

Table 2. Junction node characteristics.

Junction number	Demand (l/s)	Elevation (m)	Head (m)	Pressure (kPa)
1	400.0	120.0	176.40	552.93
2	200.0	120.0	176.55	554.41
3	350.0	120.0	176.92	558.03
4	600.0	120.0	159.10	383.36

Table 3. Pump characteristic data.

Head (m)	Flow rate (l/s)
130.0	0.0
120.0	1000.0
100.0	2000.0

system. *Figures 2, 3, 4,* and *5* compare the EDM solutions for contaminant propagation with the exact solutions for junction nodes 1, 2, 3, and 4, respectively. As shown in these figures, the EDM results are identical to the exact solutions. This exercise demonstrates the excellent predictive capability of EDM for tracking contaminant propagation in water distribution networks.

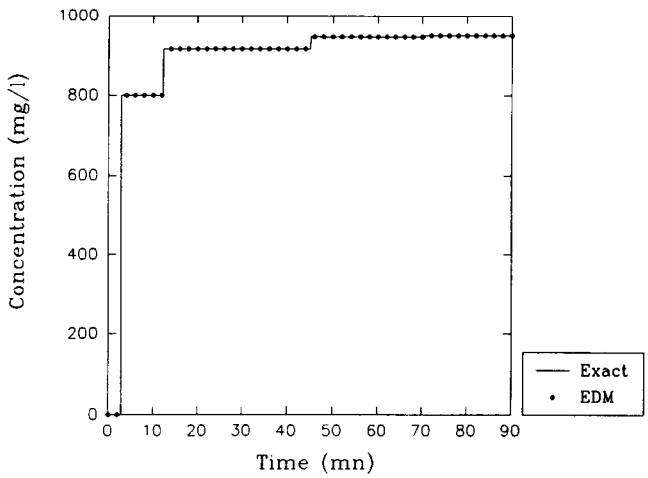

Figure 2. Exact vs. predicted concentrations at node 1.

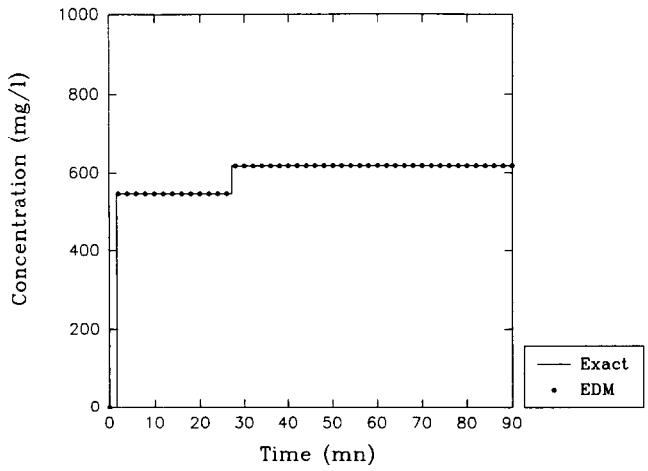

Figure 3. Exact vs. predicted concentrations at node 2.

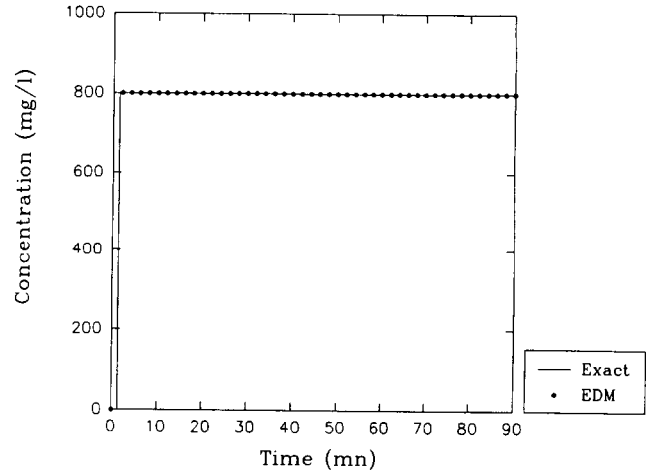

Figure 4. Exact vs. predicted concentrations at node 3.

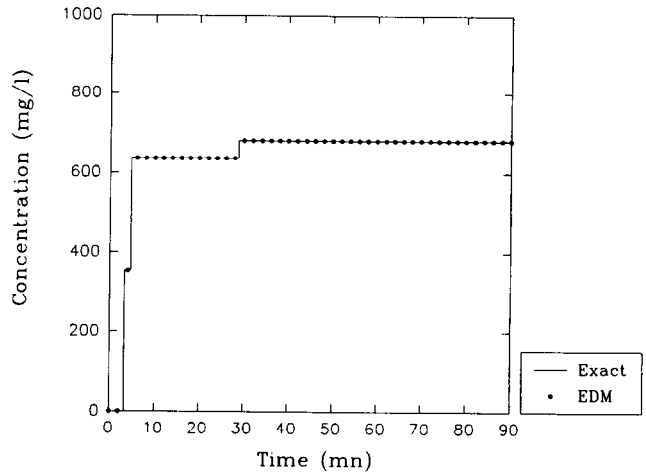

Figure 5. Exact vs. predicted concentrations at node 4.

Conclusion

Never before has the waterworks industry been as concerned about drinking-water quality as it is today. Of primary concern is the problem of water quality deterioration within the nation's water distribution systems. It is now well recognized that significant water quality changes may occur within water distribution systems. Many of these quality changes have been associated with complex physical, chemical, and biological activities that take place while finished water is being transported through the distribution system to the consumer. The threat of the distribution system to the maintenance of water quality had underscored the importance of understanding the processes of contaminant migration in pipe distribution systems.

The algorithm developed in this paper allows for the direct simulation of the transient distribution of contaminants throughout water distribution systems. The

algorithm is driven by the distribution system's endogenous and exogenous hydraulic activities. This allows for an effective and efficient computation of the contaminant concentration front profiles sought. Because the changes in contaminant nodal concentrations are simulated in the method as soon as they occur, the loss of resolution is eliminated. The only parameter that significantly affects the performance of the proposed approach is the overall number of separators during the lifetime of the simulation. Observe that the only time a pipe is segmented is when two volumes of water with different contaminant concentrations are present in that pipe or after a hydraulic event takes place. It follows that in the EDM, the number of separators is provably minimal, implying that the method is, in a sense, optimal.

The method provides a simple and flexible, yet very effective, tool for enhancing engineering insight into the dynamics of water quality variations and complex processes that take place in pipe distribution systems. Such capabilities will greatly enhance the ability of engineers to conceive and evaluate efficient and reliable water supply management decisions and realistic water quality monitoring strategies. It is understanding complexity through simplicity.

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