Recent water quality studies have emphasized the need for transient analysis of large pipe networks to properly assess the potential level of intrusion associated with negative pressure and the resulting effect on disinfectant residual efficiency. Transient analysis is computationally demanding even for simple pipe systems, and the computational effort for large pipe networks can be substantially high. Moreover, computational effort and accuracy of solution are interdependent. Therefore, understanding the computational efficiency and the accuracy of solution associated with the available transient analysis methods is essential for efficient handling of transients in large pipe distribution networks. This research investigated the numerical accuracy of solution and the computational efficiency of two popular methods for transient analysis—the wave characteristic method (WCM) and the method of characteristics—and elucidated their implications for practical applications. The authors offer a guideline for selecting the number of friction orifices for the WCM. In addition, this research demonstrated the superior performance of the WCM in both numerical accuracy of solution and computational effort for transient analysis of large water distribution networks.

Using the WCM for transient modeling of water distribution networks

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Transient modeling of liquid flow in large pipe networks has always been a difficult and tedious task. Many methods have been developed for transient analysis, and only a few have been successful in terms of acceptable level of accuracy of solution, programming ease, and computational efficiency. The wave characteristic method (WCM) is one such method that has been used with great success over the past quarter century by numerous modelers worldwide (Jung et al, 2007; Boulos et al, 2006, 2005; Wood et al, 2005a, 2005b, 1966). The fixed-grid method of characteristics (MOC) is another popular method that has been widely used (Wylie & Streeter, 1993, 1978; Streeter & Wylie, 1967). Although these two methods solve the same governing equations, make similar assumptions, and adopt a numerical procedure for time simulation, they differ significantly in their underlying approaches and computational requirements.

BACKGROUND

Historically, many of the transient modeling efforts were directed toward transmission mains and penstocks with little or no attention to complex water distribution networks. Recent studies by the National Research Council, the Water Research Foundation, and the US Environmental Protection Agency highlighted the potential for pathogen intrusion in drinking water distribution networks during transient-generated low-pressure events (Besner, 2007; Fleming et al, 2006; NRC, 2006; Friedman et al, 2004; LeChevallier et al, 2003, 2002; Kirmeyer et al, 2001). Findings of this nature have spurred the growth in transient modeling activities directed toward complex drinking water distribution networks.

Modeling methods compared and contrasted. The computational requirements of transient modeling are not trivial, even for small transmission mains. The computational requirements for transient modeling of large complex water distribution networks could be several orders of magnitude higher, ranging from several minutes to a few hours on modern personal computers. Despite the long computational time required to calculate transients in pipe networks, the final solution obtained still may not be accurate. This is attributable to topological and numerical simplifications (e.g., neglecting pipe branches, lumping consumption at main nodes, estimating the unknown pipe friction and effective diameter) that could dampen or completely distort the transient event.

In this context, therefore, the authors considered it prudent to compare and contrast the two popular transient modeling approaches—WCM and MOC—paying close attention to the computational efficiency and the numerical accuracy of solutions. Although marginal differences in computational effort may not influence the decision-making process, computational efforts that differ several orders of magnitude from one method to another to achieve similar accuracy would certainly influence the decision-making process. Computational time is also an important issue when a transient simulation model is used in an optimization framework. Popular optimization models (Jung & Karney, 2006; Kapelan et al, 2003; Lingireddy et al, 2000; Vitkowsky et al, 2000; Wang et al, 1997) run transient simulation models several hundred, if not thousands, of times to obtain the optimal solution.

A closer look at the two approaches found that the primary difference between the WCM and the MOC is the way the pressure wave is tracked between two boundaries of a pipe segment. The boundaries for pipe segment might include reservoirs, tanks, dead-end nodes, partially opened valves, pumps, junction nodes, surge-control devices, and vapor cavities. The MOC tracks a disturbance in the time–space grid using a numerical method based on characteristics (Wylie & Streeter, 1993; Streeter & Wylie, 1967) whereas the WCM tracks the disturbance on the basis of wave-propagation mechanics (Boulos et al, 2006; Wood et al, 2005, 1966). Although the two methods have several characteristics in common, they differ in certain respects that can influence the accuracy and computational effort of each method and therefore warrant an in-depth study. With regard to the accuracy of solution and the computational effort of modeling hydraulic transients in large pipe networks, two main issues are the selection of computational time step, Δt, and the adequacy of friction modeling (based on the steady-state friction factor).

Although no detailed analytical study has been reported for evaluating the numerical performance and computational efficiency of transient analysis methods for large pipe networks, some guidelines in terms of error analysis are available for first-order MOC for single pipeline systems. The MOC is classified by the order of integration used for the frictional term in its implementation. In the literature, the MOC generally means a first-order accurate integration scheme for the frictional term, and a second-order MOC implementation is also available. Other researchers have observed that in the MOC, a firm criterion for selecting the number of segments based on friction is not possible because any error produced is heavily dependent on the amplitude and frequency of the disturbance (Wylie & Streeter, 1993). The same argument applies to the WCM and any transient analysis method.

Wylie (1996) studied the accuracy and validity of the first-order MOC scheme by nondimensionalizing the basic equations of motion and continuity governing one-dimensional transient flow in prismatic pipe and exciter behavior. Exciter behavior describes the magnitude and effective duration of transient-initiating events, e.g., duration of a valve closure, valve opening, and pump shutdown; the rate of change of velocity of flow or pressure head at a point captures the exciter behavior (Wylie, 1996). Basic equations were first nondimensionalized to better characterize the pipeline using parameters most widely accepted in the literature; this representation was then combined with nondimensionalized system time constants to characterize a transient response (Wylie, 1996). Wylie presented an error study in terms of steady-state frictional losses, number of segments the pipeline is divided into for the analysis, and exciter behavior. He observed that the dimensionless numbers and time constants used in the study helped to generalize the characterization of different systems and can be used to evaluate the accuracy and range of validity of a solution procedure (Wylie, 1996).

Scope of current study. The current work uses the same parameters used by Wylie to evaluate the influence of steady-state frictional losses, the number of segments a pipeline is divided into for analysis, the exciter behavior, and the system time constants in modeling accuracy and then extends the study by applying these parameters to compare computational efficiency and accuracy of solution obtained by both first- and second-order MOC and the WCM for single pipelines. Guidelines for selecting the number of segments for the WCM were developed. The authors also provide a discussion and demonstration of the implications of these findings on transient modeling of large pipe networks.

Because both the MOC and WCM implement hydraulic components (e.g., pumps, valves, surge tanks, and air vessels) using the same mathematical equations describing the component, the authors assumed that the individual implementations of the hydraulic components in the two methods would result in comparable accuracy and computational effort. Therefore, the current work excluded modeling of hydraulic components from the discussion on computational efficiency. Similarly, computational issues involving cavitation, unsteady friction (Silva-Araya & Chaudhry, 2001; Pezzinga, 2000), nonlinear pipe behavior, dissolved air in fluid, and fluid structure interaction were not considered.

OVERVIEW OF THE MOC AND WCM

The following two equations govern the flow of fluid in prismatic closed conduits under transient conditions (Boulos et al, 2006; Wood et al, 2005a, 2005b; Wylie & Streeter, 1993; Almeida & Koelle, 1992). Eqs 1 and 2 show the continuity equation and momentum equation, respectively,

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \tag{1}$$

$$\frac{\partial H}{\partial x} = -\frac{1}{gA}\frac{\partial Q}{\partial t} + f(Q) \tag{2}$$

in which Q is the flow rate, H is the pressure head, $f(Q)$ is the friction slope expressed as a function of flow rate, A is the pipe flow area, a is the pipe celerity or wave speed, g is the gravitational acceleration, and x and t are the space–time coordinates. Advective terms are neglected in Eqs 1 and 2, which is justified in most cases.

Solution of Eqs 1 and 2 with appropriate boundary conditions yields head and flow values in both spatial and temporal coordinates for any transient analysis problem. The equations are first-order hyperbolic partial differential equations in two independent variables (space and time) and two dependent variables (head and flow). Because both methods have been discussed adequately in the literature (Boulos et al, 2006; Wood et al, 2005; Wylie & Streeter, 1993, 1978; Streeter & Wylie, 1967), only a brief account of each method is given in subsequent sections.

MOC. In the MOC, the governing partial differential equations are converted to ordinary differential equations and then to a finite difference form for solution by a numerical method. The solution space comprises two equations (termed characteristic equations) along with two compatibility equations for any point in a space–time grid. The compatibility equations are valid only when the characteristic equations are satisfied.

Figure 1 shows a typical space–time grid with characteristic equations. The MOC divides the entire pipeline into a predetermined number of segments, writes the characteristic and compatibility equations for every grid location, and then solves these equations for head and flow at all grid locations. The line friction of the entire pipeline is distributed in each of these segments. Various boundary conditions such as reservoirs, valves, pumps and other devices are handled by combining the appropriate characteristic equation with the equations defining the boundary. The first-order MOC uses only the known flow rates from the previous time step to compute the flow rate and head for the next time step. A second-order MOC scheme uses a nonlinear equation in the next time-step flow rate. The next time-step flow rate obtained by solving this nonlinear equation is then used to compute the next time-step head. Second-order MOC is more accurate than first-order MOC.

WCM. The WCM is based on the concept that transient pipe flow results from generation and propagation of pressure waves that occur as a result of a disturbance in the pipe system. A pressure wave, which represents a rapid pressure and associated flow change, travels at the sonic velocity of the liquid medium and is transmitted and reflected at all discontinuities in the pipe system. A pressure wave is also modified by pipe friction. The WCM essentially consists of two types of analyses: component analysis and junction analysis. Component analysis deals with the problem of transmission and reflection of pressure waves at a hydraulic device whereas junction analysis addresses the same problem at a pipe junction, a dead-end node, or a constant head reservoir. The entire line friction is modeled as an equivalent orifice situated at the midpoint of a pipeline or multiple orifices distributed uniformly throughout the pipeline.

Figure 2 provides a schematic representation of wave action at a friction orifice. D_1 and D_2 represent the magnitudes of pressure waves approaching the friction orifice, and D_3 and D_4 represent the magnitudes of pressure waves reflected off the friction orifice. H_1 and H_2 represent the pressure head at the corresponding locations before the pressure waves impinge on the friction orifice, and H_3 and H_4 represent the pressure head at the corresponding locations after the pressure waves impinge on the friction orifice. Similarly Q_i and Q_o represent flow through the friction orifice before and after, respectively, the pressure waves impinge on the friction orifice. Transmission and reflection at the friction orifice represent the effect of line friction on the pressure waves.

DIMENSIONLESS NUMBERS AND SYSTEM TIME CONSTANTS

Wylie (1996) nondimensionalized the basic equations using steady-state flow and friction parameters, potential surge, and wave reflection time of the pipeline. The parameters used are defined in the subsequent sections.

Steady-state frictional loss is defined in Eq 3

$$H_{fo} = \frac{fL}{D}\frac{(V_0)^2}{2g} \tag{3}$$

in which f is the Darcy–Weisbach friction factor, L is the length of the pipe, V_0 is the steady-state line velocity, D is the diameter of the pipeline, and g is the gravitational acceleration.

Algorithms used by each method and floating point operations involved in the solution procedure

The following sections detail the algorithms used by the wave characteristic method (WCM), first-order method of characteristics (MOC), and second-order MOC as well as the floating point operations (flops) involved in the solution procedures. The number shown in the square brackets for each statement is the number of flops involved in the statement. Only addition, subtraction, multiplication, division, and modulus operations were considered, and each operation was counted as one. Assignment operations were not counted.

COMPUTATIONAL EFFORTS ASSOCIATED WITH THE THREE METHODS

WCM computational effort of friction orifice analysis. The term "res" represents the resistance of the friction orifice.

$$F = a/(g \times A) \qquad [2]$$

$$Q_o = Q_i + (D_1 - D_2)/F \qquad [3]$$

in which a is the pipe celerity or speed, g is the gravitational acceleration, A is the pipe flow area, Q_i and Q_o represent flow through the friction orifice before and after, respectively, the pressure waves impinge on the friction orifice, and D_1 and D_2 represent the magnitudes of pressure waves approaching the friction orifice.

Solve

$$\{\, Q_f = Q_o$$

$$d_f = -\,\text{res} \times (Q_f \times |Q_f| - Q_i \times |Q_i|)/2 \qquad [7]$$

$$Q_o = Q_i + (D_1 - d_f - D_2)/F$$
$$\}\ \text{until } (Q_f - Q_o) \text{ is negligible} \qquad [4]$$

$$M = F \times (Q_o - Q_f) \qquad [2]$$

$$H_3 = H_1 + 2 \times D_1 - M \qquad [3]$$

$$H_4 = H_2 + 2 \times D_2 + M \qquad [3]$$

in which H_1 and H_2 represent the pressure head at the corresponding locations before the pressure waves impinge on the friction orifice, and H_3 and H_4 represent the pressure head at the corresponding locations after the pressure waves impinge on the friction orifice.

First-order MOC computational effort for solution of equations at a grid location. The term "res" represents the resistance of a single segment.

$$F = a/(g \times A) \qquad [2]$$

$$G = \text{res} \times g \times A \times \Delta t \qquad [3]$$

$$Q_{i,t} = 0.5 \times [(Q_{i-1,t-1} + Q_{i+1,t-1}) + 1/F \times (H_{i-1,t-1} - H_{i+1,t-1}) + Q_{i-1,t-1} \times |Q_{i-1,t-1}| + Q_{i+1,t-1} \times |Q_{i+1,t-1}|) \times G] \qquad [13]$$

$$H_{i,t} = 0.5 \times 1/F \times [(Q_{i-1,t-1} - Q_{i+1,t-1}) + 1/F \times (H_{i-1,t-1} + H_{i+1,t-1}) + (Q_{i-1,t-1} \times |Q_{i-1,t-1}| - Q_{i+1,t-1} \times |Q_{i+1,t-1}|) \times G] \qquad [15]$$

Second-order MOC computational effort for solution of equations at a grid location.

$$F = a/(g \times A) \qquad [2]$$

$$G = \text{res} \times g \times A \times \Delta t \qquad [3]$$

$$Q_2 = Q_{i,t-1}$$

$$\text{del}Q = 0$$

$$E = 0.5 \times [(Q_{i-1,t-1} + Q_{i+1,t-1}) + F \times (H_{i-1,t-1} - H_{i+1,t-1})] \qquad [5]$$

Solve

$$\{C_p = G/8 \times [|Q_{i-1,t-1} + Q_2| \times (Q_{i-1,t-1} + Q_2) + |Q_{i+1,t-1} + Q_2| \times (Q_{i+1,t-1} + Q_2)] \qquad [11]$$

$$C_{p\_der} = G/4 \times (|Q_{i-1,t-1} + Q_2| + |Q_{i+1,t-1} + Q_2|) \qquad [7]$$

$$\text{del}Q = -(C_p - Q_2 + E)/(C_{p\_der} - 1) \qquad [4]$$

$$Q_2 = Q_2 + \text{del}Q$$
$$\}\ \text{until del}Q \text{ is negligible} \qquad [1]$$

in which E is the percentage error

$$Q_{i,t} = Q_2$$

$$H_{i,t} = 0.5/F \times [(Q_{i-1,t-1} - Q_{i+1,t-1}) + 1/F \times (H_{i-1,t-1} + H_{i+1,t-1}) + G/4 \times (Q_{i-1,t-1} + Qi_{,t}) \times |(Q_{i-1,t-1} + Q_{i,t})| - (Q_{i+1,t-1} + Q_{i,t}) \times |(Q_{i+1,t-1} + Q_{i,t})|] \qquad [19]$$

Potential surge is represented by Eq 4

$$H_s = \frac{aV_0}{g} \tag{4}$$

in which a is the pipe celerity or wave speed.

The nondimensional factor is shown in Eq 5:

$$R = \frac{fL}{2D}\frac{V_0}{a} = \frac{H_{fo}}{H_s} \tag{5}$$

A value of $R \geq 1$ represents a case of attenuation and line packing in which the potential surge is less than the frictional head loss in the pipeline, and a value of $R < 1$ represents absence of attenuation and line packing. Use of H_s and R as defined here permits the characterization of pipelines into one of the comparing values of R (Liou, 1992; 1991). According to Wylie, this means that "pipelines with the same R value will offer the same response if equal, scaled, initial and boundary conditions are applied. This observation removes the specific values of diameter, length, wave speed, etcetera, in discussions comparing one system with another" (Wylie, 1996).

The evaluative index for friction in the MOC (Wylie & Streeter, 1993) is

$$\Psi = \frac{f\Delta x}{2D}\frac{V_0}{a} \tag{6}$$

which is represented in terms of R as

$$\Psi = \frac{f\Delta x}{2D}\frac{V_0}{a} = \frac{R}{N} \tag{7}$$

in which N is the number of segments in a pipeline and $\Delta x = L/N$ is the size of a single segment.

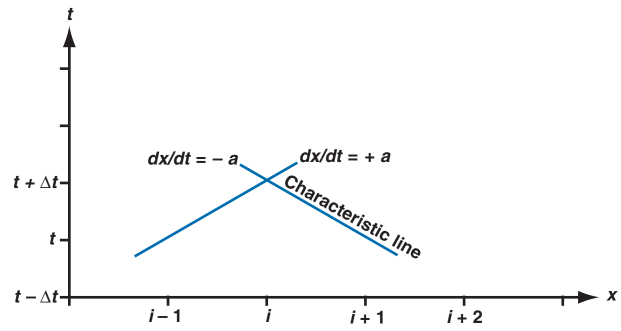
Wylie (1996) defined two dimensionless time constants—one based on the time, T_m, at which transient results are compared and another based on the time, T_e, over which a transient-initiating event or disturbance (such as a valve closure, valve opening, or pump rampdown) takes place. T_m and T_e are then nondimensionalized using wave travel time, L/a, to arrive at dimensionless time constants t_m and t_e. For example, for a pipeline with length L and wave speed a, the time for a transient pressure wave from the downstream end to travel to the upstream end is L/a. If the transient results are compared at time $T_m = 1.5 \times L/a$ after the initiation of transient pressure wave, then time constant t_m is $[1.5 \times (L/a)/(L/a)] = 1.5$. Similarly if the pressure transient was initiated by completely closing a valve in time $T_e = 0.2 \times (L/a)$, then t_e is $[0.2 \times (L/a)/(L/a)] = 0.2$.

Error is calculated in Eq 8 as

$$E = \frac{\Delta H}{H} = C_e \frac{R\frac{dv}{dt}}{N^z} \tag{8}$$

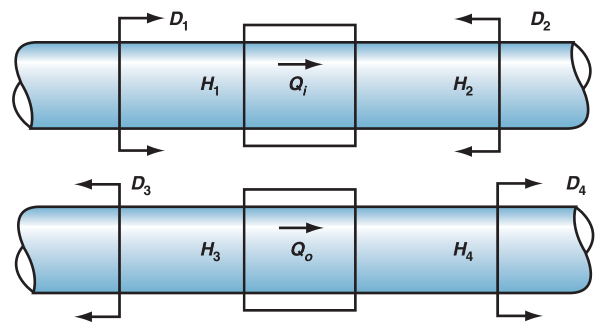
in which ΔH is the deviation in the computational results from the correct answer H obtained at a large value of N, dv/dt is the time rate of change of velocity and captures the exciter behavior, z is an exponent, and C_e corresponds to the percentage error E when $R\,(dv/dt)/N^z = 1$.

FIGURE 1 Space–time grid depicting characteristic lines



a—celerity or wave speed, t—time, x—space

FIGURE 2 Wave action at a friction orifice



D_1 and D_2—magnitudes of pressure waves approaching the friction orifice, D_3 and D_4—magnitudes of pressure waves reflected off the friction orifice, H_1 and H_2—pressure head at the corresponding locations before the pressure waves impinge on the friction orifice, H_3 and H_4—pressure head at the corresponding locations after the pressure waves impinge on the friction orifice, Q_i and Q_o—flow through the friction orifice before and after, respectively, the pressure waves impinge on the friction orifice

The exponent z is a function of R, dv/dt, time t_m at which comparison is made, and t_e, the dimensionless effective operator time. The exponent z is likely to vary differently when t_m and t_e are < 2 (T_m and T_e < 2 L/a are generally categorized as rapid transients) than when the same dimensionless time constants are > 2 (T_m and T_e > 2 L/a are generally categorized as slow transients).

Objectives of the current study. Eq 8 is a useful tool to study the combined effect of steady-state friction captured by R, exciter behavior represented by dv/dt, and the number of segments a pipeline is divided into for analysis, N, on the accuracy of a solution procedure. The error involved in a solution procedure can be compared by determining C_e and exponent z for that solution procedure. However, to facilitate comparison of the three solution procedures for this study, at least one of them must be fixed. Wylie (1996) reported that exponent z for first-order MOC is ~ 2 for $t_m = 2$ and $t_e < 2$. Therefore, if a value of 2 for z for the three methods is used, C_e for all three methods can be determined and compared. Conversely, C_e and z for first-order MOC can be determined, and this value of C_e can be used for second-order MOC and WCM, and the exponent value z can be solved and compared. In the current study, C_e and exponent z were determined for all three methods, and then the two approaches described previously were used to analyze the results for comparison.

The current study included the following objectives:

- Use these dimensionless parameters for first- and second-order MOC and WCM for evaluating the influence of friction modeling and system time constants on the modeling accuracy at a time, t_m, when the effect of line friction reflects completely on the computed results. Use a classic reservoir–pipeline–valve system with instantaneous valve closure as the transient-initiating event with $t_e < 2$. The time at which the effect of line friction influences the computed results most is clearly when t_m is < 2 ($T_m < 2\ L/a$) but close to 2. Thus, for each method, compute the head at the valve just before the end of one cycle (i.e., before the reflected wave from the reservoir impinges on the valve) for a different number of pipe segments, N.
- Conduct the previous error study for a long pipeline and short pipeline in which there is no attenuation and line packing (as is the case in large pipe networks), i.e., when R is < 1.
- Conduct the error study for a few cases to obtain an understanding of the difference in numerical performance of the three schemes when attenuation and line-pack effects are present, i.e., when R is > 1.
- Study the computational efficiency of each scheme for a specified level of accuracy.
- Discuss the implication of findings on the decision-making process for transient analysis of large pipe networks.

NUMERICAL EXPERIMENT

The effect of line friction and exciter behavior on modeling accuracy is studied by the classic reservoir–pipeline–valve problem. Figure 3 depicts the hydraulic system considered for this study. The pipeline connects a constant-head reservoir on the upstream end and a valve on the downstream end. The study considered two scenarios—one with a long pipeline (L = 6,583.7 m) and the other with a relatively short pipeline (L = 1,097.3 m), each with eight cases for various R values up to $R = 1$ ($R \leq 1$). The study also considered a third scenario with a long pipeline (L = 6,583.7 m) with six cases for R values ranging from 1 to 2 ($1 \leq R \geq 2$). The valve resistance, VR, is defined as $VR = \Delta H/Q^2$, in which ΔH is the head drop across the valve in m, Q is the flow rate in m^3/s, and VR = 19,006.2 s^2/m^5. Table 1 summarizes the hydraulic parameters of scenarios 1–3 and the steady-state results for all cases in each scenario.

The method of specified time intervals approach was used for the MOC (Wylie & Streeter, 1993). The Courant number, defined as $C_r = [a \times (\Delta t/\Delta x)]$, was kept at 1 in all cases by keeping the relation $\Delta t/\Delta x$ to wave speed a, thus avoiding interpolation errors. Because the transient-initiating event was an instantaneous valve closure, adjusting Δt to vary the number of segments while maintaining a Courant number of 1 was easily achieved. Instantaneous closure of the valve was the transient-initiating event (valve closes fully in 1 Δt) modeled in this example application. The percentage error of head at the valve just before the end of one cycle was calculated using the accurate solution obtained from using a large number of segments (1,200 when L = 6,583.7 m and 1,000 when L = 1,097.3 m). The number of segments in the long pipeline scenarios (L = 6,583.7 m) are 2, 3, 4, 6, 8, 12, 24, 60, 600, 1,200, and the associated Δt values (also the effective valve closure times) in seconds are 3.000, 2.000, 1.500, 1.000, 0.750, 0.500, 0.250, 0.100, 0.010, 0.005. The number of segments in the short pipeline scenario (L = 1,097.3 m) are 2, 4, 5, 10, 20, 100, 200, 1,000, and the associated Δt values (also the effective valve closure times) in seconds are 0.500, 0.250, 0.200, 0.100, 0.050, 0.010, 0.005, 0.001. Therefore scenario 1 has 80 configurations (8 × 10), scenario 2 has 64 (8 × 8) configurations, and scenario 3 has 60 (6 × 10) configurations. The dimensionless parameters R, dv/dt, C_e, and N are calculated for all configurations.

Effect of steady-state line friction on modeling accuracies. As discussed previously, in the MOC, both steady and unsteady friction approximations depend on the number of segments a pipeline is divided into. Frictional effects are computed by solving the compatibility equations at the intermediate points. For high line friction cases, Wylie and Streeter (1978) suggested the use of second-order MOC, i.e., use of a second-order accurate procedure for the friction term, resulting in compatibility equations that are nonlinear in flow rate.

The WCM handles line friction by introducing an orifice with an equivalent resistance within the pipeline. The orifice resistance is calculated using the total steady-state frictional head loss and the steady-state flow rate through the pipeline. Line friction is evenly distributed when multiple orifices are used. One set of computation is performed at every junction of adjoining segments in the MOC whereas in the WCM each segment has a friction orifice and therefore one set of computation is performed for every segment.

Figures 4, 5, and 6 show the percentage error in head at the valve for each method for varying numbers of segments and for each scenario for three values of R. The y-axis for Figures 4, 5, and 6 are logarithmic, and percent values < 0.001 were ignored for clarity. Figure 7 shows the percentage error of head versus the evaluative index for frictional accuracy Ψ defined by Eq 7.

Effect of exciter behavior on modeling accuracies. Analysis of results for exciter behavior on numerical accuracy was performed using a spreadsheet program. Because Eq 8 has two unknown variables, i.e., C_e and exponent z, three types of analysis were carried out. In the first case, both variables were solved for all methods. In the second case, C_e for second-order MOC and WCM were kept the same as that obtained for first-order MOC and the exponent was solved. In the third case, the exponent was kept at 2 for all cases, and C_e was solved for. Table 2 summarizes the results.

COMPUTATIONAL EFFICIENCY

Computational effort in both the MOC and WCM is associated with the calculation of heads and flows along the pipeline and at the boundaries. Elements or devices forming a boundary involve either simple equations or nonlinear quadratic equations. Because the techniques used by both methods to solve these nonlinear equations are similar, the computational effort needed at the boundaries in both methods is comparable. Therefore, it is sufficient to look into the computational effort needed in modeling the pipes by these methods. The sidebar on page 78 shows the algorithm used by each method and the floating point operations (flops) involved in the solution procedure.

WCM computational efficiency. Component analysis is a generic procedure used by the WCM to analyze the wave action at various discontinuities in the system (Boulos et al, 2006; Wood et al, 2005). It involves nonlinear equations solved iteratively by the Newton–Raphson method. Traditionally, the WCM made use of component analysis for friction orifice analysis as well.

The friction orifice problem is simple enough, however, that it can be handled more intuitively using the basic wave reflection mechanism. Equations involved

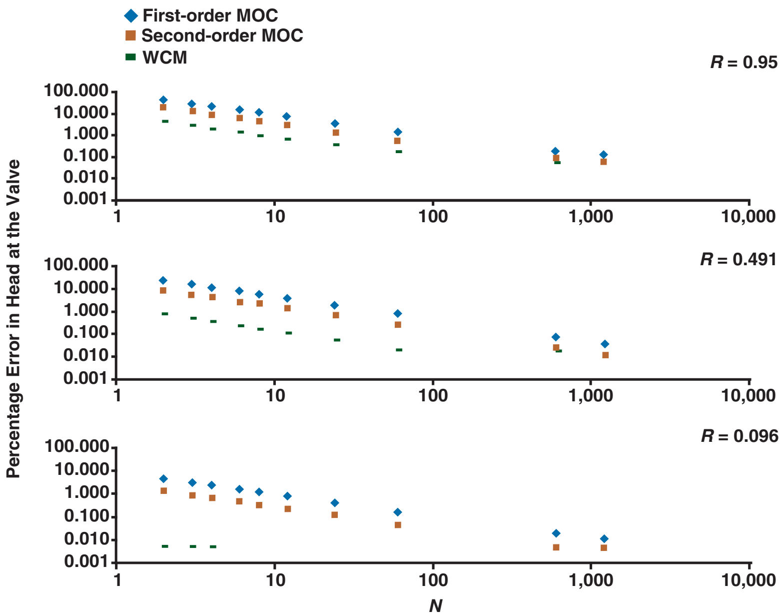
TABLE 1 Hydraulic parameters and steady-state results

Case	Hazen–Williams Roughness Coefficient	Diameter *mm*	$H_{reservoir}$ *m*	a *m/s*	V_0 *m/s*	H_{fo} *m*	H_s *m*	$R = H_{fo}/H_s$
Scenario 1: Pipeline length = 6,583.7 m, $R \leq 1.0$								
1	120	128.3	182.9	1,097.28	1.643	174.3	183.6	0.95
2	120	128.3	121.9	1,097.28	1.320	116.4	147.6	0.79
3	120	128.3	91.4	1,097.28	1.131	87.4	126.4	0.69
4	120	128.3	61.0	1,097.28	0.908	58.3	101.6	0.57
5	120	205.0	121.9	1,097.28	1.439	79.0	160.9	0.49
6	120	257.6	121.9	1,097.28	1.222	44.8	136.7	0.33
7	120	307.1	121.9	1,097.28	0.969	23.8	108.5	0.22
8	120	419.9	121.9	1,097.28	0.564	6.0	63.1	0.10
Scenario 2: Pipeline length = 1,097.3 m, $R \leq 1.0$								
1	75	78.0	259.1	1,097.28	2.432	271.8	256.5	1.06
2	90	78.0	228.6	1,097.28	2.722	225.4	304.2	0.74
3	100	78.0	213.4	1,097.28	2.908	209.7	325.1	0.65
4	120	78.0	121.9	1,097.28	2.569	119.1	287.4	0.41
5	120	205.0	121.9	1,097.28	2.137	27.4	238.9	0.11
6	120	257.6	121.9	1,097.28	1.469	10.5	164.3	0.06
7	120	307.1	121.9	1,097.28	1.061	4.7	113.9	0.04
8	120	419.9	121.9	1,097.28	0.576	1.0	64.4	0.02
Scenario 3: Pipeline length = 6,583.7 m, $R \geq 1.0$ and $R \leq 2.0$								
1	100	78.0	304.8	1,097.28	1.350	304.0	151.0	2.01
2	100	78.0	243.8	1,097.28	1.198	243.2	133.8	1.82
3	105	78.0	182.9	1,097.28	1.076	182.4	120.3	1.52
4	120	78.0	152.4	1,097.28	1.113	151.9	124.5	1.22
5	120	78.0	121.9	1,097.28	0.988	121.5	110.4	1.10
6	120	78.0	100.6	1,097.28	0.890	100.2	99.5	1.01

a—pipe celerity or wave speed, H_{fo}—frictional head loss, $H_{reservoir}$—head at reservoir, H_s—potential surge, R—nondimensional factor, V_0—steady-state line velocity

FIGURE 3 Schematic of the hydraulic system considered for the cast study

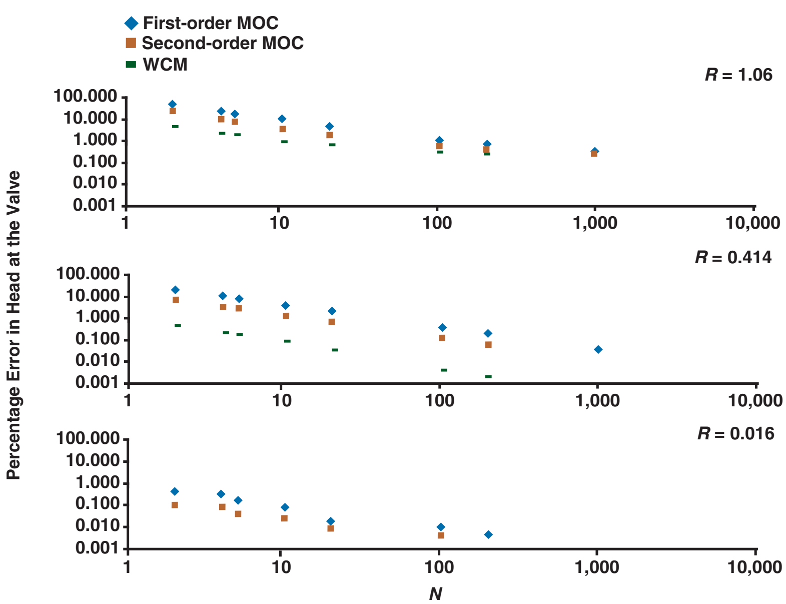
FIGURE 4 Percentage error versus number of segments for scenario 1



MOC—method of characteristics, R*—nondimensional factor,* N*—number of segments, WCM—wave characteristic method*

Pipeline length = 6,583.7 m, R *≤ 1.0*

FIGURE 5 Percentage error versus number of segments for scenario 2



MOC—method of characteristics, R*—nondimensional factor,* N*—number of segments, WCM—wave characteristic method*

Pipeline length = 1,097.3 m, R *≤ 1.0*

in the friction orifice analysis were cast differently and solved by a simple iterative technique. It was found that the new approach was computationally less expensive than the former approach. Both methods solved the same equations, but equations were set up differently and adopted two different iterative techniques.

The new procedure for handling the friction is shown in the first section of the sidebar. This method needed more iterations in the early phase of transient analysis but less iterations later on; on average, the method required two iterations. The computational effort involved was 5 + (2 × 11) + 8, or 35 flops.

First-order MOC computational efficiency. Because the entire pipeline is divided into a number of segments for calculation of heads and flows and similar equations are solved for each grid point, computational effort can be ascertained by determining the total number of computations associated with a grid location. The second section of the sidebar shows the flop calculations for first-order MOC, which needed 33 operations per segment per time increment.

Second-order MOC computational efficiency. Although mixed schemes used in other work (Streeter & Wylie, 1993; Almeida & Koelle, 1992) are more accurate than first-order MOC and less computationally expensive than second-order MOC, the current study used the second-order scheme reported by Wylie and Streeter (1978) for its accuracy. Second-order MOC differs from first-order MOC only in that it has a nonlinear equation in flow rate. The Newton–Raphson method was used to solve the nonlinear equation, and it was found that the second-order MOC scheme needed (on average) two iterations for convergence. As shown in the third section of the sidebar, the number of computations for a single segment was 10 + (2 × 23) + 19, or 75 flops.

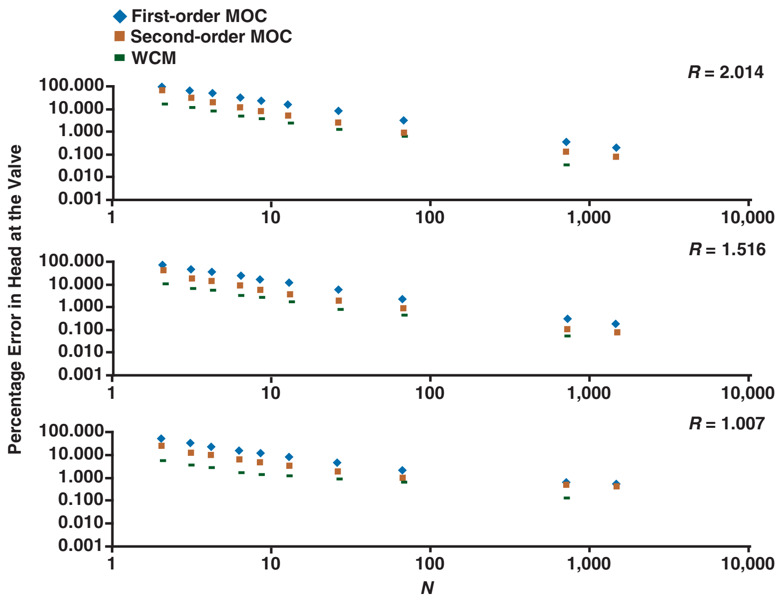
Chaudhry (1979) proposed a predictor–corrector scheme, which purportedly is more computationally efficient than second-order MOC. Results from this scheme were either similar or slightly inferior to second-order MOC and required 62 flops per segment per time increment.

INFERENCES AND DISCUSSION

The results shown in Figures 4, 5, and 6 support the following premises.

- All methods were accurate at a higher number of segments, regardless of the value of *R*.
- Results from the methods differed significantly when the number of segments was low.
- The WCM produced consistently more accurate results than both first- and second-order MOC schemes for lower segment cases.
- Results from the WCM were much closer to the accurate solution even with just two segments. The maximum percentage error for the WCM in cases with two segments was 4.5% for $R < 1$ and 16% for $R > 1$. The maximum percentage error for first- and second-order MOC schemes was 46.8% and 23.4%, respectively, for $R < 1$ and 89.5% and 69.2%, respectively, for $R > 1$.

FIGURE 6 Percentage error versus number of segments for scenario 3



MOC—method of characteristics, R—nondimensional factor, N—number of segments, WCM—wave characteristic method

Pipeline length = 6,583.7 m, R ≥ 1.0 and R ≤ 2.0

Figures 4, 5, and 6 show the performance for individual cases whereas Figure 7 shows the percentage error against the frictional evaluative index R/N for all configurations. The percentage error for the maximum value of $R/N = 0.53$ for $R < 1$ was < 5% for the WCM but 46.8% and 23.3% for the first- and second-order MOC schemes, respectively. For $R/N = 1.01$ for $R > 1$, the corresponding percentage error results for the WCM, first-order MOC, and second-order MOC were 16.3%, 89.5%, and 69.2%, respectively. The WCM was more resilient against the value of frictional index than were the MOC schemes.

As a general guidance for accurate solution, the evaluative index should be well below 0.15 for accuracy of solution by first-order MOC (Streeter & Wiley, 1978). Wylie (1996) reported that the first-order MOC scheme was accurate (1% error) for values < 0.01.

Table 2 shows the underlying relationship between percentage error and the dimensionless parameters.

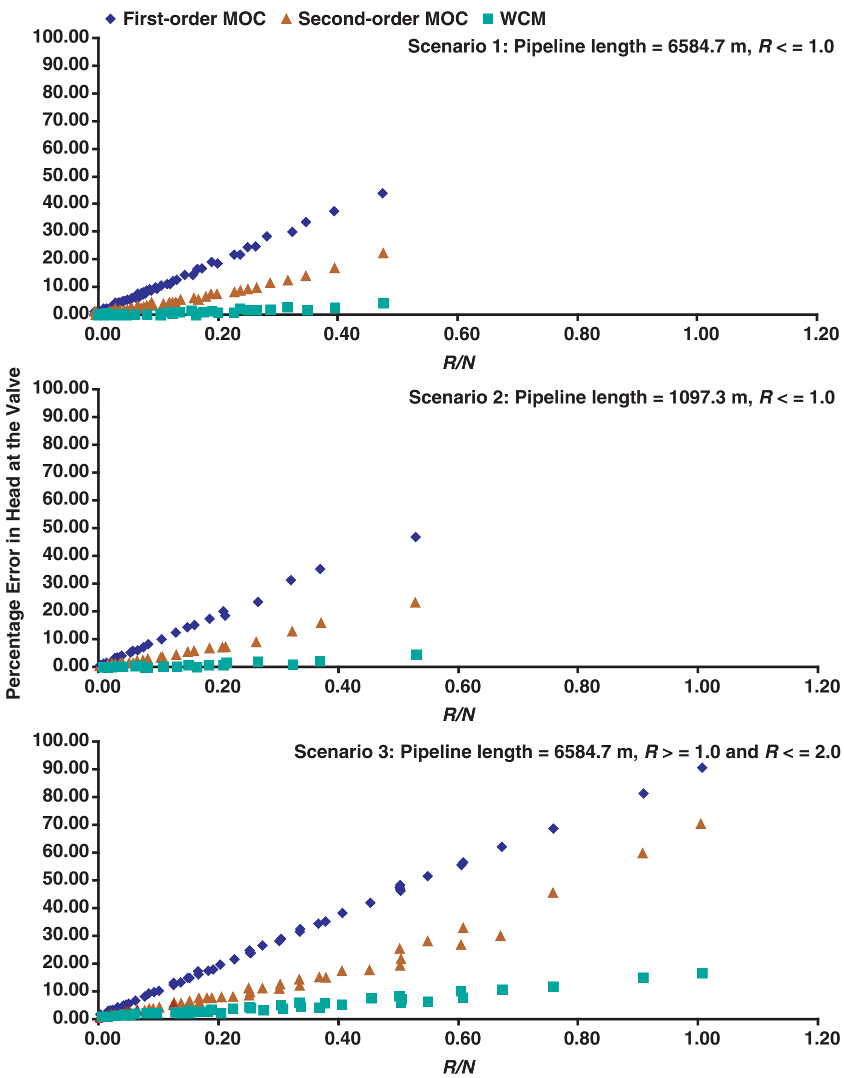
- Analysis types 1 and 3 indicated that for $R < 1$ and the same number of segments, the WCM produced results 14 times more accurate than the first-order MOC scheme and 7 times more accurate than the second-order MOC scheme.
- Analysis type 2 indicated that for $R < 1$ and the same level of accuracy, if N is the number of segments for first-order MOC, then the WCM required only $N^{(2/5.5)}$ (or $N^{(0.364)}$) segments, and if N is the number of segments for second-order MOC, then the WCM required only $N^{(2.9/5.5)}$ (or $N^{(0.527)}$) segments. For example, in a hypothetical case in which first-order MOC required 100 segments for a specified accuracy, the WCM would require only $100^{(0.364)} = 5.3$, or 6 segments.
- Analysis type 3 indicated that for $R > 1$ and the same number of segments, the WCM produced results 6 times more accurate than the first-order MOC scheme and 3 times more accurate than the second-order MOC scheme.

Table 3 summarizes the number of segments required for each method and associated computational effort required for < 2% error in the computed head. For the MOC schemes, only N–1 computations were needed for N segments. For the WCM, N frictional orifice computations needed to be made. The conclusions established previously can be numerically verified using values in the table.

Although computations can be performed with a single orifice (single segment case) for a system in the WCM, the single segment case was ignored in order to facilitate comparison across the three methods. For cases in which two orifices were suggested by the study to achieve a percentage error of < 2% in the computed head, one orifice would have been sufficient. As an example, Figure 8 shows the head at the valve for case 5 of scenario 3 for a two-segment case using first-order MOC, second-order MOC, and the WCM and compares these results with the accurate solution obtained with 1,200 segments for a total simulation period of 500 s. As shown in the figure, the WCM performed better than the two MOC schemes.

A similar argument can be made regarding the selection of number of segments for the systems studied. Had

FIGURE 7 Percentage error versus frictional evaluative index $\psi = \frac{f\Delta x}{2D}\frac{V_0}{a} = \frac{R}{N}$



a—celerity or wave speed, D—diameter of the pipeline, f—Darcy–Weisbach friction factor, MOC—method of characteristics, N—number of segments, R—nondimensional factor, V_0—steady-state line velocity, WCM—wave characteristic method, x—space coordinate

the variation of number of segments been smoother and evenly spaced in each system, the variation in number of segments for a particular accuracy across different systems would have been less, especially in the second-order MOC scheme and the WCM.

Table 3 yields the following findings:

• For a value of R up to 0.5, it is sufficient to use only two friction orifices in the WCM to ensure a percentage error of < 2%. The WCM in this case would be at least 20 times more computationally efficient than the first- and second-order MOC schemes.

• For $R > 0.5$ and $R < 1$, it is sufficient to use six friction orifices in the WCM to ensure a percentage error of < 2%. In this case, use of the WCM would be at least 10 times more computationally efficient than the first- and second-order MOC schemes.

TRANSIENT ANALYSIS OF LARGE PIPE NETWORKS

Analysis of large pipe networks is computationally intensive, and the computational effort is directly proportional to the time step, Δt, selected for the analysis. As is true for any numerical scheme, a smaller Δt results in better accuracy of solution. In addition, the time step determines the number of segments, N, that a pipeline segment is divided into and therefore the accuracy of the method.

Selection of the time increment. In general, selection of the computational time step Δt for the transient simulation of a complex pipe network has the following constraints:

• Δt should be less than or equal to the shortest wave travel time (length/celerity) in the network (in the pipes modeled);

• Δt should be less than or equal to the minimum time span of exciter behavior or boundary condition changes; and

• Δt should be the greatest common divisor (GCD) of travel times of all pipelines and the minimum time span of boundary condition change.

Accuracy and Courant stability criteria. As described previously, the MOC requires that the ratio of the distance step, Δx, to the time step, Δt, be equal to the wave speed, a, in the pipe. In other words, the Courant number, defined as $[a \times (\Delta t/\Delta x)]$, ideally should be equal to 1 and must not exceed 1 for stability reasons (Chaudhry, 1979). Because most pipeline systems have a variety of different pipes of various wave speeds and lengths, it might be difficult to satisfy the Courant stability criterion for all pipes with a reasonable (and common) value of Δt (Karney & Ghidaoui, 1997). This challenge can be overcome by either adjusting the lengths and/or wave speeds of the pipes or allowing the Courant number to be < 1. Allowing a Courant number < 1 requires a numerical interpolation that in turn leads to numerical damping and phase shift of the pressure wave, particularly for fast transients and steep wave fronts (Chaudhry, 1987). The errors resulting from interpolations can be reduced by adopting a greater number of segments, resulting in a smaller computational time step (Karney & Ghidaoui, 1997), which in turn increases the computational time requirements. Similar treatment of adjusting the wave speed or pipe lengths should also be performed in the WCM.

Advantage of the WCM. In the MOC, the time step directly determines the number of segments, N, for each pipeline and subsequently the accuracy of solution; for a Courant number, C_r, of 1, Δx can be calculated from the relation, $C_r = a \times (\Delta t/\Delta x)$ and then $N = L/\Delta x$. Thus any change in Δt results in a corresponding change in N, which is necessitated by the underlying computation mechanics of the MOC.

In the WCM, the time step does not directly determine the number of segments, N. Rather it requires only that the wave travel time of each segment length be a multiple of Δt. Therefore, for the same Δt, the WCM has the advantage of choosing a different number of segments, N. This makes it possible to choose a Δt required by constraints described previously in this section and then later choose a number of segments, N (thus, the number of orifices), required for a certain accuracy. This represents a significant advantage, and it stems from the underlying wave propagation mechanics of the WCM.

This can be easily explained using an example application. Consider a pipeline of length L with wave speed a and transient time step Δt. If the wave travel time (L/a) of the pipeline is $12 \times \Delta t$, then the MOC absolutely needs 12 pipe segments ($N = 12$). In the WCM, the number of segments, N, can be 1, 2, 3, 4, or 6. For example, using the inferences of this study, N can be selected, depending on R, i.e., $N = 2$ for values of $R < 0.5$ and $N = 6$ for values of R between 0.5 and 1.0.

Example application. To illustrate the effect of friction modeling, issues in selecting time increment for simulation, and computational effort associated with each method for a pipe network, the authors used a small, well-published network model (Streeter & Wylie, 1978). Figure 9 shows the schematic for this system, and Table 4 presents the pipe characteristics of the system. The reservoir grade = 191 m, and all nodal elevations = 0 m. Nodal demand at the dead end located in pipe P-7 = 30 cfs (0.85 m^3/s), and demand at all other nodes = 0. Minor loss in all pipes = 0.

The transient-initiating event is the demand change at the dead end located in pipe P-7 over a period of 0.6 s, i.e., demand of 0.85 m^3/s at time = 0 decreases to 0 in 0.6 s.

TABLE 2 Summary of pulse magnitude analysis

Scenario	First-order MOC			Second-order MOC			WCM		
	C_e	**Exponent z**	SSE	**C_e**	**Exponent z**	SSE	**C_e**	**Exponent z**	SSE
Both C_e and exponent z are solved for all.									
Scenario 1: Pipeline length = 6,583.7 m, $R \le 1.0$	124.52	1.99	520.48	62.33	2.18	60.39	9.61	2.06	3.68
Scenario 2: Pipeline length = 1,097.3 m, $R \le 1.0$	10.76	1.99	22.47	5.47	2.17	18.45	0.79	2.03	5.49
Scenario 3: Pipeline length = 6,583.7 m, $R \ge 1.0$ and $R \le 2.0$	135.86	1.98	896.74	148.45	2.67	161.68	22.95	2.06	8.19
C_e is kept constant and exponent z is solved for second-order MOC and WCM.									
Scenario 1: Pipeline length = 6,583.7 m, $R \le 1.0$	*124.52*	1.99	520.48	*124.52*	2.93	164.55	*124.52*	5.53	22.57
Scenario 2: Pipeline length = 1,097.3 m, $R \le 1.0$	*10.76*	1.99	22.47	*10.76*	2.95	91.56	*10.76*	5.72	14.66
Scenario 3: Pipeline length = 6,583.7 m, $R \ge 1.0$ and $R \le 2.0$	*135.86*	1.98	896.74	*135.86*	2.58	174.04	*135.86*	4.32	303.16
Exponent z is kept constant and C_e is solved for all.									
Scenario 1: Pipeline length = 6,583.7 m, $R \le 1.0$	125.21	*2.00*	520.55	51.88	*2.00*	71.13	9.06	*2.00*	3.71
Scenario 2: Pipeline length = 1,097.3 m, $R \le 1.0$	10.82	*2.00*	22.51	4.63	*2.00*	25.32	0.77	*2.00*	5.49
Scenario 3: Pipeline length = 6,583.7 m, $R \ge 1.0$ and $R \le 2.0$	138.84	*2.00*	901.39	77.60	*2.00*	1,008.03	21.57	*2.00*	9.05

C_e—percentage of error, MOC—method of characteristics, R—nondimensional factor, SSE—sum of squared error, WCM—wave characteristic method

Boldface indicates that the variable has been solved for all three methods. Italics indicate that the variable has been kept constant for all three methods.

TABLE 3 Number of segments and computational effort required for percentage error < 2%

Scenario	*R*	Number of Segments: First-order MOC	Number of Segments: Second-order MOC	Number of Segments: WCM	Computational Effort Per Time Increment—*flops*: First-order MOC	Computational Effort Per Time Increment—*flops*: Second-order MOC	Computational Effort Per Time Increment—*flops*: WCM
Scenario 1: Pipeline length = 6,583.7 m, $R \leq 1.0$							
1	0.95	60	24	6	1,947	1,725	210
2	0.79	60	24	3	1,947	1,725	105
3	0.69	60	24	2	1,947	1,725	70
4	0.57	60	24	2	1,947	1,725	70
5	0.49	24	12	2	759	825	70
6	0.33	24	4	2	759	225	70
7	0.22	12	4	2	363	225	70
8	0.10	6	2	2	165	75	70
Scenario 2: Pipeline length = 1,097.3 m, $R \leq 1.0$							
1	1.06	100	20	5	3,267	1,425	175
2	0.74	100	20	4	3,267	1,425	140
3	0.65	100	20	2	3,267	1,425	70
4	0.41	100	10	2	3,267	675	70
5	0.11	10	2	2	297	75	70
6	0.06	4	2	2	99	75	70
7	0.04	4	2	2	99	75	70
8	0.02	2	2	2	33	75	70
Scenario 3: Pipeline length = 6,583.7 m, $R \geq 1.0$ and $R \leq 2.0$							
1	2.01	600	60	24	19,767	4,425	840
2	1.82	600	60	24	19,767	4,425	840
3	1.52	600	24	12	19,767	1,725	420
4	1.22	60	24	6	1,947	1,725	210
5	1.10	60	24	6	1,947	1,725	210
6	1.01	60	24	6	1,947	1,725	210

flops—floating point operations, MOC—method of characteristics, *R*—nondimensional factor, SSE—sum of squared error, WCM—wave characteristic method

The velocity of flow in pipe P-7 = 4.24 fps (1.29 m/s). Using Eq 4, the potential surge H_s = 434.5 ft (132.5 m). Steady-state results indicated that the pipe frictional losses in the system varied from 1.4 to 10.9 ft. Frictional head loss in pipe P-7 = 4.4 ft. From Eq 3, H_{fo} = 4.4 ft (1.34 m). From Eq 5, R = 0.01.

Because R is < 0.5, one friction orifice would be sufficient for reasonable solution in the case of the WCM. However, the number of segments needed in MOC must be determined first from the stability criteria and then checked for adequacy of frictional modeling.

As described in the previous section, the selection of the time increment Δt has the following constraints:

- Δt should be less than or equal to the smallest travel time, i.e., $\Delta t \leq 0.4$ s (travel time of pipe P-4);
- Δt should be less than or equal to the time span of boundary condition changes, i.e., $\Delta t \leq 0.6$ s (demand decreases to 0 in 0.6 s); and
- Δt should be the GCD of all travel times and all time spans of boundary condition changes, i.e., Δt = GCD of (0.4, 0.5, 0.6, 0.606, 0.7, 0.8) = 0.002 s.

The travel time of 0.606 s for pipe P-7 skews the Δt selection from a much larger possible Δt value. Given the supposition that 0.606 s can be rounded to 0.6 s, then Δt can equal 0.1 s. However, the error in doing so is that pipes P-1 and P-7 are modeled as 1,980 ft in length rather than 2,000 ft. Alternatively, the wave speed could be adjusted to account for these changes.

Adjusting pipe lengths and/or wave speeds that result in a larger Δt does not appear to be a major issue for the example network under consideration. However, it may not always be possible to adjust the time increments to larger values. Consider a scenario in which one pipe in the network is significantly shorter than the rest. For example, if pipe P-1 in the example network were 50 ft long rather than 2,000 ft long, the resulting travel time would be 0.01515 s. As the shortest travel time, this would control the selection of Δt even when all other travel times are adjusted to meet the GCD requirement. However, rounding 0.01515 s to a significantly higher value might imply a large adjustment to pipe lengths and/or wave speeds, which could unduly affect the accuracy of results. Short pipes are common near pump stations when modeling large distribution networks. Because Δt controls the total number of segments for the MOC and thus the total computational effort, it is worthwhile to explore the computational efforts needed both with shorter and adjusted Δt.

Table 5 shows the procedure for calculating computational effort for a total simulation period of 50 s for the first-order MOC scheme. In comparison, using the WCM, cases 1 and 2 require 7.876×10^6 and 0.157×10^6 computations, respectively.

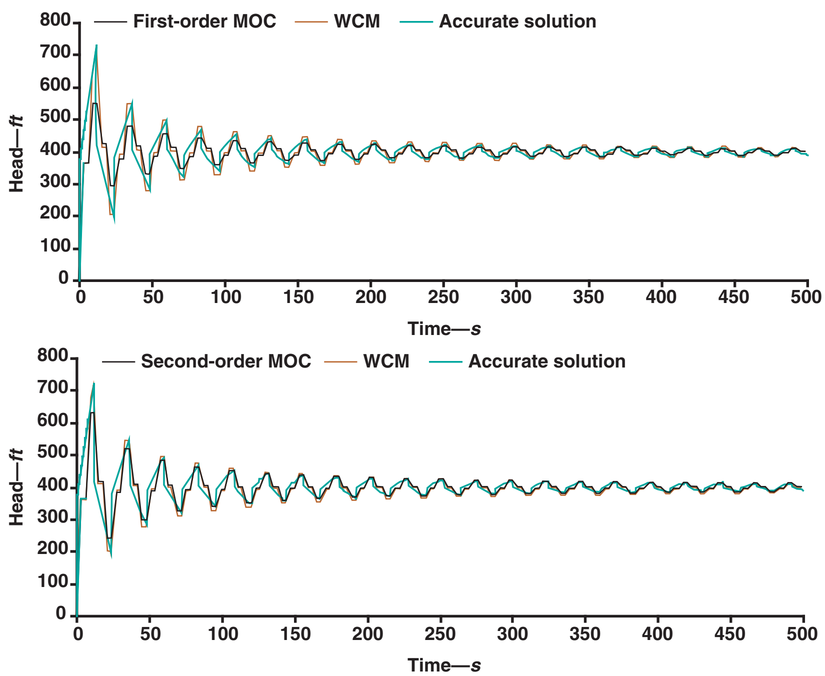
The computational effort of first-order MOC is 272 times greater than that of the WCM in case 1 and 4 times greater in case 2. Figure 10 shows the results of head at the junction of pipes P-1, P-2, and P-3 for case 2 for both methods.

SUMMARY AND CONCLUSIONS

This work examined the numerical accuracy and computational efficiency issues of the WCM and MOC in solving basic unsteady flow equations in closed conduits. Although both methods solve the same governing equations and make similar assumptions, they differ significantly in their approaches. Numerical accuracy of solution and computational effort (which are interdependent) were studied for both methods, and their implications for practical applications were investigated.

The current study used nondimensional parameters and time constants reported previously in the literature. Guidelines in the form of error study were developed for the number of friction orifices to be used in the WCM to ensure an acceptable

FIGURE 8 Head at the valve for 500-s simulation period



MOC—method of characteristics, WCM—wave characteristic method

FIGURE 9 Network example

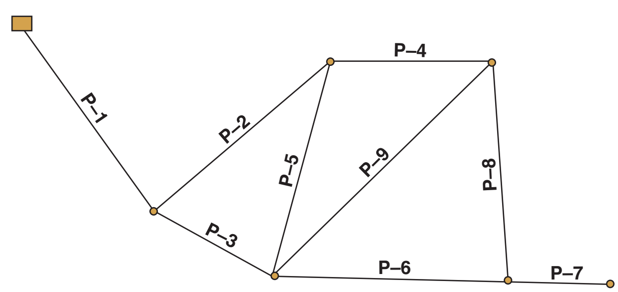


TABLE 4 Pipe characteristics for example application

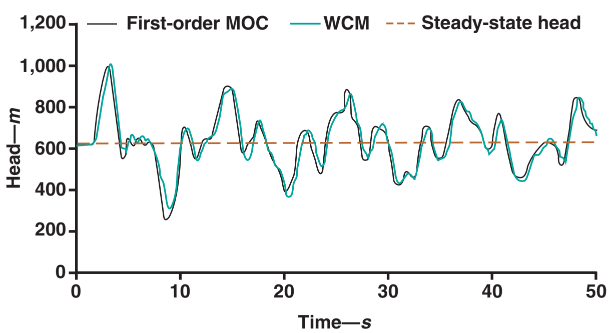
Pipe Number	Length *ft (m)*	Diameter *in. (mm)*	Hazen–Williams Roughness Coefficient	Wave Speed *ft/s (m/s)*
P-1	2,000 (610)	36 (914)	92	3,300 (1,006.1)
P-2	3,000 (914)	30 (762)	107	3,750 (1,143.3)
P-3	2,000 (610)	24 (610)	98	4,000 (1,219.5)
P-4	1,500 (457)	18 (457)	105	3,750 (1,143.3)
P-5	1,800 (549)	18 (457)	100	3,000 (914.6)
P-6	2,200 (671)	30 (762)	93	3,140 (957.3)
P-7	2,000 (610)	36 (914)	105	3,300 (1006.1)
P-8	1,500 (457)	24 (610)	105	3,000 (914.6)
P-9	1,600 (488)	18 (457)	140	3,200 (975.6)

TABLE 5 Computational effort of the MOC

Pipe Number	Case 1—Δ*t* = 0.002 *s*		Case 2—Δ*t* = 0.1 *s*	
	Number of Segments	Number of Computations	Number of Segments	Number of Computations
P-1	303	249,150,000	6	82,500
P-2	400	32,934,000	8	118,800
P-3	250	205,425,000	5	66,000
P-4	200	164,175,000	4	49,500
P-5	300	246,675,000	6	82,500
P-6	350	287,925,000	7	99,000
P-7	303	249,150,000	6	825,00
P-8	250	205,425,000	5	66,000
P-9	250	205,425,000	5	66,000
	Total number of computations = $2{,}143 \times 10^6$		Total number of computations = 0.713×10^6	

MOC—method of characteristics, *t*—time

FIGURE 10 Case 2 results for the WCM and first-order MOC



MOC—method of characteristics, WCM—wave characteristic method

level of accuracy. The number of segments required for a particular level of accuracy is governed by the twin issues of frictional losses and system time constants. The WCM was found to be more resilient against the value of frictional index than were MOC schemes. Study results indicated that compared with the WCM, first- and second-order MOC schemes needed a substantially greater number of segments within a pipeline for the same level of accuracy.

Computational efforts for short and long pipelines and for a network of pipes associated with first- and second-order MOC schemes and the WCM were explored, and the results highlighted the computational advantages of the WCM. Depending on the time step chosen, the difference in computational effort could be several orders of magnitude. Furthermore, in contrast to the MOC, with the WCM the transient analysis time step and the numbers of segments that a pipeline is divided into are not bound by the Courant number. This constitutes a key advantage of the WCM because small transient analysis time steps (often necessitated by the presence of short pipes in a network) can be accommodated by the WCM along with only the required number of segments needed for the accuracy of solution. Conversely, in cases needing small time steps, the MOC would require several segments, as required by Courant number conditions.

Results from the case study also suggested that with the WCM the use of two orifices for the entire pipeline is acceptable for values of nondimensional parameter $R < 0.5$ and the use of six orifices is acceptable for values of R between 0.5 and 1. This is not a very stringent requirement for most transient modeling studies, especially those dealing with large water distribution networks. This means that for larger systems, the WCM can substantially reduce the computational time while ensuring accurate results. The ability to efficiently handle large distribution systems is essential for transient-generated pathogen intrusion studies. The reduction of computational time could also be useful when a transient simulation is coupled with an optimization model in which hundreds, if not thousands, of repeated transient simulations are required.

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Date of submission: 04/26/08
Date of acceptance: 09/04/08

If you have a comment about this article, please contact us at journal@awwa.org.

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