This article explores and provides an overview of several important issues of uncertainty and error that arise in modeling water distribution systems. Initial emphasis is given to the ability and role of both the Hazen-Williams and Darcy-Weisbach friction models to describe hydraulic losses in a pipeline. Notwithstanding the suitability of these friction models, there exists a multitude of other uncertainties that can affect the accuracy of a hydraulic solution. A source of error often ignored during extended period simulation arises through the reservoir routing scheme used at storage elements. Other uncertainties stem from the way demands are represented (in both space and time), how the behavior of various hydraulic devices (such as valves and pumps) is emulated in simulation programs, and how the system's behavior is assumed to evolve in time. Persistent problems are also associated with aggregating demands, calibrating and skeletonizing systems, and gathering reliable field data. The problems associated with reservoir routing and system calibration are elucidated through more detailed numerical examples.

Sources of error in network modeling: a question of perspective

Modeling is a crucial planning, design, and operational activity. It is often through models that engineers and operators anticipate the consequences of their actions. Of course, no model is perfect; any model invariably distorts in some way the very system behavior it seeks to faithfully represent. Clearly then, if a model is to be used appropriately, it is essential that the approximations and limitations inherent in it be understood and appreciated. This is precisely the goal of this article. Yet before jumping into a detailed discussion of hydraulic modeling errors, it is helpful to place this activity into its historical context.

A chief goal of modeling water distribution systems has been to determine the proper size of hydraulic components so that a system will perform well under most conditions. The primary aim in design has been to conceive a robust system that will render an acceptable performance—that is, it will have adequate pressures and velocities—most of the time, even if it is conceived with little "hard" information about such things as pipe friction coefficients, water consumption magnitude, and patterns.

BY YVES R. FILION AND BRYAN W. KARNEY

Partly as a way of counteracting the inherent uncertainty in the design information, a looped-system configuration is usually adopted. This design is hydraulically robust and tends to be insensitive to the system details. Given the relative simplicity of early systems, the high level of uncertainty associated both with field estimates of parameters and with predicting their future values (problems that are still relevant), as well as the relative infancy of computing science, steady or nearly steady models have most often been used to analyze hydraulic networks. The sensible aim has been to design a system that performs reasonably well in the face of significant uncertainty. For this purpose, steady-state and extended-period models have been indispensable resources.

In recent years and in light of certain research developments, the original utility of steady-state and extended-period models has been augmented to include the functions of operational control, feedback, water quality modeling, and database management. Though accepting the internal logic of these extensions, the appearance of these "high-end" functions has raised some concerns among practitioners about the sometimes disappointing accuracy of the modeling approach.

It was, of course, easy to dismiss the poor predictive performance of the earliest network models. The first solutions of the loop and node equations were prone to numerical errors and convergence problems (Wood & Rayes, 1981). In addition, the power of computer systems was small, which forced the exclusion of all but the largest pipes. Data were scarce, and carefully documented field experience was rare.

However, although these obvious shortcomings have been progressively addressed, the persistence of model errors has encouraged a deeper look at their source. In particular, the friction model (e.g., Hazen-Williams versus Darcy-Weisbach) used in solvers to represent the hydraulic losses in a system is sometimes suspected as a possible source of significant error. Given that the friction model constitutes the central element of the steady-state solution and thus has important ramifications concerning the hydraulic capacity and serviceability of a system, these findings are not surprising.

Making an informed decision about which loss model to use is often a primary concern of analysts. However, the modeler who is ultimately faced with this decision needs to ponder two more general questions:

- What physical factors are most important in predicting the response of the real system?
- What are the main sources of uncertainty and error when a distribution system is modeled?

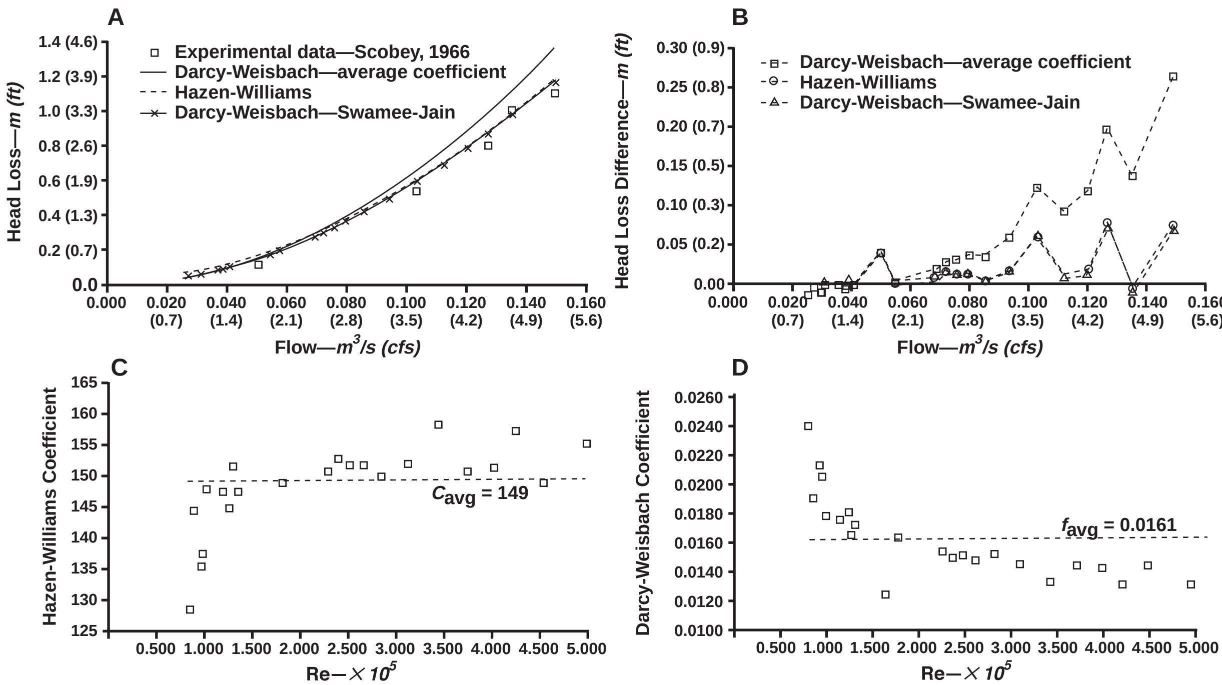
Historically, at least, the answers to these questions were more obvious. If the primary goal was to determine a suitable set of pipe diameters and system interconnections and the system was required to function for many years, then estimates of system demand were crucial, as were the basic relationships between head and flow. Other concerns were less important because operational flexibility could be established in the field as the system evolved. For obvious reasons, the experience of operators was at least as important as that of modelers and analysts. However, the situation has been evolving—cities have grown, systems have expanded and become operationally more complex, budgets have been stretched, and greater expectations have inevitably been associated with the outcomes of computer models. For all these reasons, it is useful to reflect again on what convention network models provide and what essential limitations they embody.

A chief goal of modeling water distribution systems has been to determine the proper size of hydraulic components so that a system will perform well under most conditions.

This article explores these issues and extends the context in which friction losses and the relative accuracy of two popular friction models are evaluated. The article contends that although the friction model should be chosen judiciously and does exert some influence over the accuracy of results, a plethora of other factors (e.g., unknown demands, unknown friction coefficients, and uncertainty of device behavior) can also introduce important errors into the hydraulic solution. Although many of the issues raised have been individually mentioned in the literature, the specific goal here is to provide some perspective by gathering together in one location a more comprehensive overview of modeling errors.

The article begins by discussing the ability of conventional friction models (Hazen-Williams and Darcy-Weisbach) to describe the complex process of turbulence in pipes. Following this, the article elaborates on possible inaccuracies when reservoir levels are tracked. Ancillary issues are then discussed, including uncertainty in the representation of demand and the validity of some rudimentary control structures that have recently been added to extended-period programs. The scope of the discussion is then broadened to include the general issues surrounding the assumption of steady flow and the complimentary issue of the unsteady behavior of water distribution systems. The discussion then shifts to issues regarding calibration and raises problems associated with the scarcity of field data, extended-period calibration, and distinguishing between roughness and diameter reduction in calibration studies. The uncertainty and reliability of field data and

FIGURE 1 Plots of models and experimental data: friction models and experimental data from Scobey, 1966 (A); difference between model and experimental data (B); and Hazen-Williams/Darcy-Weisbach coefficients calculated directly from experimental data (C) and (D)



measured demands in a system are examined, as are other sources of errors, such as system skeletonization and recordkeeping.

HYDRAULIC MODELING: IDEALIZATIONS AND REALITY

The first part of this article focuses on common errors in conventional hydraulic modeling, particularly associated with extended-period simulation (EPS) programs.

Friction models. The Hazen-Williams and Darcy-Weisbach friction models are often presumed to be excellent (or at least very good) descriptors of the turbulent phenomena in a pipeline. That is, given accurate demands and friction values, these equations are assumed to accurately and independently predict head loss in a pipe system. Yet the predictions of the equations are seldom identical. Not surprising, then, the decision concerning which model to use in a hydraulic modeling exercise typically carries a lot of weight with the designer. Thus, how well do the Hazen-Williams and Darcy-Weisbach models represent hydraulic conditions in a pipe? Are both models equally valid approximations?

Perhaps another question is even more basic. How should this issue of friction model accuracy be resolved? In this article, this issue is not addressed (as has been common) by the a priori assumption about which equation is more valid (invariably assumed to be Darcy-Weisbach). Rather, the authors' approach is to compare both friction models with experimental/field data. In this case, the authors focus on data reported by Scobey (1966). The anecdotal evidence gleaned clearly shows that both friction models are imperfect descriptors of the complex phenomenon of turbulence. The decision concerning which friction model to use, although perhaps difficult and even irresolvable, might actually be irrelevant in most practical cases.

Scobey (1966) reported experimental values of flow/head loss for new (smooth) pipes available in commercial- or standard-diameter sizes. In total, six individual data sets were chosen and pertain to pipes of varying length (from 10.1 m [33 ft] to 3,818.5 m [12,528 ft]), diameter sizes (from 143 mm [5.6 in.] to 487 mm [19.2 in.]), and lining materials, including asbestos cement (AC), welded steel, and wrought iron. All measurements in the data sets corresponded to turbulent-smooth or transitional-flow conditions in the pipelines tested. Unless otherwise noted, all tests were assumed to be performed at 15°C.

First, the Hazen-Williams and Darcy-Weisbach friction models were compared with the experimental data. Using the flow/head loss data, individual Hazen-Williams and Darcy-Weisbach friction coefficients were calculated and averaged. This value was deemed to represent the friction conditions in the pipe over the range of experimental data values found in Scobey (1966). However, a slightly different approach was taken to properly describe the dependency between the Reynolds number and friction factor inherent in the Darcy-Weisbach equation when turbulent-smooth or transitional-flow conditions prevailed. Here, a single data point, which correlated well with the Hazen-Williams prediction, was chosen.

With this flow/head loss pair, a value of friction factor was calculated with the Darcy-Weisbach equation. The friction factor and an appropriate Reynolds number were then substituted into the Swamee-Jain equation to calculate the roughness of the pipeline. (See the sidebar on page 124.) The Swamee-Jain equation is accepted to be an excellent approximation (accuracy is about ±1%) of the implicit Colebrook equations over an appropriate range of Reynolds number ($5{,}000 < R_e < 10^8$) and roughness ($10^{-6} < e/D < 10^{-2}$) (Swamee & Jain, 1976). The values of Reynolds number and pipe roughness calculated from the six data sets conform to these limits. With this fixed value of roughness, predictions of head loss were found with the Darcy-Weisbach equation.

In Figure 1, part A, a plot of the Darcy-Weisbach model was given and compared with both the Hazen-Williams model and the experimental data for a pipe lined with AC material from Scobey (1966). The difference between the model estimates and the experimental data was also plotted in Figure 1, part B. Using experimental data, individual coefficient values (Hazen-Williams and Darcy-Weisbach) were calculated with both models and were plotted in Figure 1, parts C and D. Similar comparisons between the two friction models and the experimental data found in Scobey (1966) are also included in Figure 2, parts A to F.

The plots clearly show discrepancies between the experimental data and the predictions of the two models. Although this may be attributable in part to experimental errors and imperfections in the laboratory conditions (e.g., turbulent wakes created at inlet section, buoyancy effects, nonuniform distribution of roughness elements along the pipe), it serves as a reminder—at least anecdotally—that the models are unlikely to perfectly reproduce the hydraulic conditions within the pipes tested. The discernible differences between model predictions and data should come as no surprise; after all, both the Hazen-Williams and Darcy-Weisbach equations are only convenient representations of the otherwise complex and largely intractable turbulent phenomena in pipe systems. The complex mass, momentum, and energy exchanges—as well as the turbulent shear stresses, velocity, and pressure fluctuations in a fluid—are actually "smoothed" over by these relatively simple algebraic equations (Karney, 1999a).

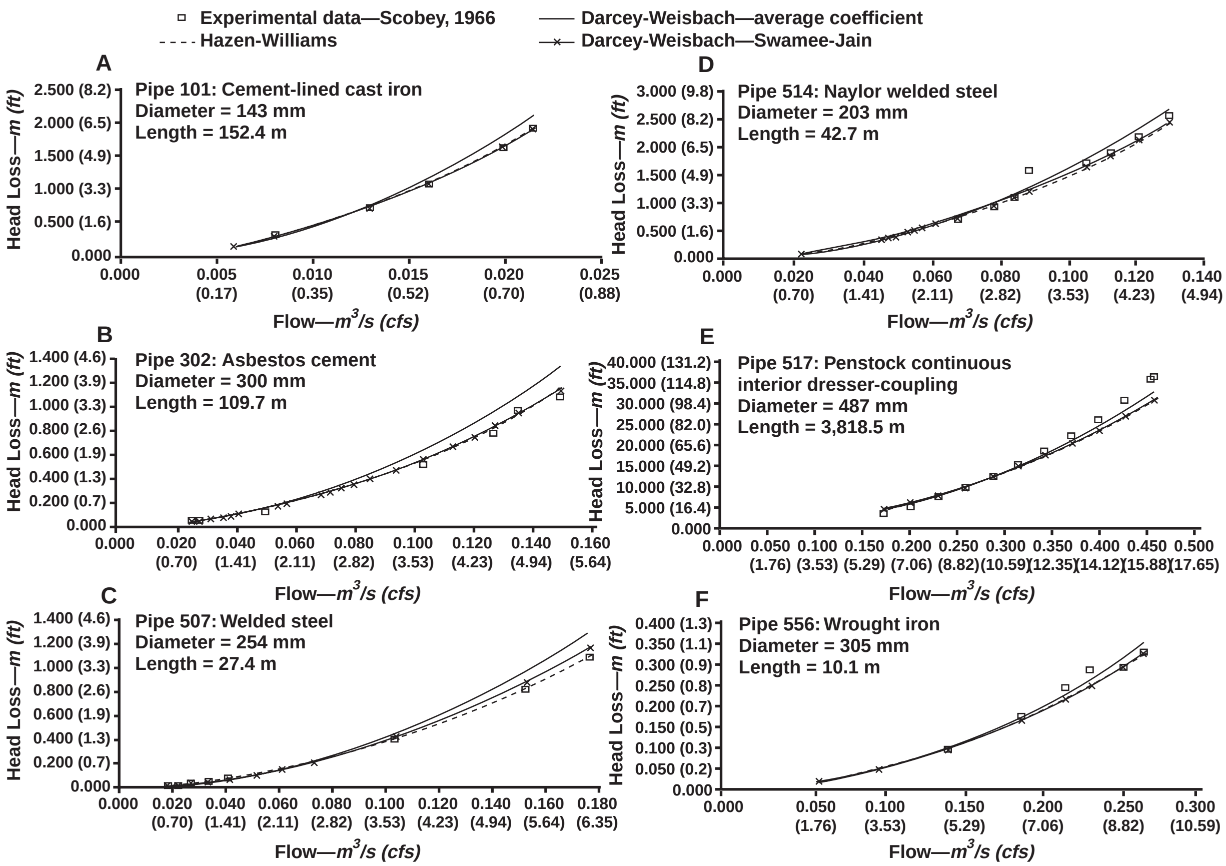
The models ignore the factors of background turbulence, recent levels of fluid transients in the system, and flow interactions between roughness elements. Instead, these algebraic models only track the mean flow characteristics (time-averaged velocity and flow) of a fluid in a pipeline and, at best, provide a rough account of the integrated effects of turbulence. While the prediction of both models seems to be reasonable in Figures 1 and 2, ignoring the details of turbulent flow may occasionally introduce significant errors into mean-flow calculations and the overall hydraulic solutions that depend on those estimates (Karney, 1999a).

Unsteady friction. A case of particular importance occurs when conditions in a system are unsteady and changing quickly. In fact, when hydraulic transients are introduced into a pipeline system, the estimates of the two steady-friction models (whether used in a steady-state or transient model) become even more unreliable. Because neither model explicitly describes the velocity profile across the diameter of a pipe but instead only reports the time-averaged, mean velocity at a pipe section, the shear stresses engendered by transient conditions in a system are consequently ignored. Through experimental studies, it has been shown that the behavior of unsteady velocity profiles—and, by extension, transient shear stresses in a pipe—can diverge quite significantly from steady-state profiles. For example, Brunone et al (1999) found that large differences in velocity gradients exist at the pipe wall under transient conditions. This fact suggests that the mechanism behind unsteady friction is somewhat different from its steady-state counterpart. Whatever the case may be, the modeler should recognize that the two friction models are mere simplifications of complex processes inside a pipe system and should not presume that the estimates they produce will always have a high level of accuracy. This is a large topic and one that is currently receiving active attention by researchers; however, it is generally beyond the scope of this article.

Model selection. Although there are some small differences between model predictions and the experimental data, for the most part, as shown in Figures 1 and 2, both models describe the experimental data reasonably well. Perhaps surprisingly, the predictions of the Hazen-Williams model are very similar to the predictions yielded by the Darcy-Weisbach model for turbulent-smooth and transitional-flow conditions. Under this range of conditions, the Darcy-Weisbach model is sometimes thought to be the more accurate model, given that it is dimensionally homogeneous, and it more rigorously accounts for the flow conditions near the wall (viscous sublayer) through the Colebrook-White equations. The Hazen-Williams equation, on the other hand, was formulated to give good approximations of head loss when flow conditions in a pipe can be classified as turbulent-rough. Certainly, the Hazen-Williams equation will sometimes break down at a high Reynolds number in very rough pipes (Walski, 1984). However, from Figures 1 and 2, a modicum of evidence suggests that this distinction is sometimes immaterial. This conclusion is consistent with the experience of many practitioners.

This, of course, provokes the following practical question: when is it appropriate to use the Darcy-Weisbach model, and when is it appropriate to use the

FIGURE 2 Comparison of two friction models with six experimental data sets from Scobey, 1966



Hazen-Williams model? Finding the complete answer would require an exhaustive set of experimental data or solving the full set of differential equations that describe the continuity and momentum conditions at a point (Navier-Stokes equations of fluid motion) over a finely discretized grid in all three dimensions. In addition, a detailed representation of each roughness element along a pipe would have to be provided. Even with the fastest supercomputer available today, it would take an inordinate amount of time to find a full solution that could be compared with the two friction models to determine which one is most suitable for a specific set of conditions. Luckily, this is not an issue to be concerned about. In most cases, both models will yield similar results that owing to the relative predictability of turbulent flow at the macroscopic level, are reasonably accurate for most purposes.

Errors in reservoir routing. A reservoir routing scheme is used in the majority of EPS models. The source of error in these schemes stems largely from the assumption of constancy in hydraulic conditions across a time step and the failure to use "grid-refinement" techniques. In a conventional EPS model, the rate at which water is exchanged with the reservoirs and tanks of a system is calculated at the beginning of the time step, whereby the remainder of the system is assumed to remain in the hydraulic state determined at the start of the time step. It is often presumed that using the Euler solution to solve the reservoir differential equation will accurately track the amount of water flowing in and out of a system's reservoirs and tanks when the system is operating under normal conditions. However, in a real system, demands are continually changing (sometimes quickly), as are the reservoir and tank levels and the operating points of pumps, even when a system operates under normal conditions. For these reasons, the numerical errors incurred by an EPS program can often be significant.

Recent research has investigated the significance of these routing errors. For example, in a study conducted by the authors (Filion & Karney, 2000), an EPS was performed on a system with the popular steady-state model EPANET (Rossman, 1993) and a transient (water hammer) model (McInnis et al, 1998).

The simulations were performed on the hypothetical looped network shown in Figure 3. At node 34 of this system, a pump station with three pumps in a parallel arrangement draws water from the source node S_1 (elevation 100 m [328 ft]). The system also includes two

DARCY-WEISBACH AND SWAMEE-JAIN EXPRESSIONS

The uncertainty analysis in this article is repeated here with the Darcy-Weisbach and Swamee-Jain (Swamee & Jain, 1976) expressions. When measurements of head loss and flow are entered into the Darcy-Weisbach equation, the friction factor can be easily calculated with Eq S-1:

$$f_1 = \frac{\pi^2 g H_1 D_1^5}{8 L Q_1^2} \tag{S-1}$$

The values D_1, Q_1, and H_1 designate nominal diameter, measured flow, and measured head loss, respectively. The length of the pipe L and the gravitational acceleration g are constants in the equation. Using the Swamee-Jain expression, the calibrated value of absolute roughness, which corresponds to the value of friction factor found with Eq S-2 and S-3, can be determined:

$$f_1 = \frac{0.25}{\left[\log\left(\frac{e_1}{3.7\,D_1} + \frac{5.74}{R_e^{0.9}}\right)\right]^2} \tag{S-2}$$

$$R_e = \frac{4\rho Q_1}{\pi\mu D_1} \tag{S-3}$$

The variable e_1 in Eq S-2 is the calibrated value of absolute roughness, which corresponds to the calibrated friction factor f_1. Also, the terms ρ and μ designate the density and dynamic viscosity of the fluid in the pipe.

To determine how a change in diameter affects the flow in the pipe, the diameter of the pipe—which figures in both the Darcy-Weisbach and Swamee-Jain equations—is varied from its nominal value D_1 to its real or field value D_2. This step is presented in Eq S-4:

$$|Q_1 - Q_2| = \sqrt{\frac{\pi^2 g(sH_1)}{8L}} \left| \left(\frac{D_1^5}{f_1}\right)^{0.5} - \left(\frac{D_2^5}{f_2}\right)^{0.5} \right| \tag{S-4}$$

The value of diameter D_2 in this general expression corresponds to the calculated flow of Q_2. The relationship between pipe diameter and flow is made clearer by substituting the Swamee-Jain expression into this general expression to produce Eq S-5:

$$|Q_1 - Q_2| = \sqrt{\frac{\pi^2 g(sH_1)}{2L}} \left| D_1^{2.5} \log\left\{\frac{e_1}{3.7 D_1} + \frac{5.74}{\left[\frac{4\rho Q_1}{\pi\mu D_1}\right]^{0.9}}\right\} - D_2^{2.5} \log\left\{\frac{e_1}{3.7\,D_2} + \frac{5.74}{\left[\frac{4\,\rho Q_2}{\pi\mu D_2}\right]^{0.9}}\right\} \right| \tag{S-5}$$

Once the value of diameter D_2 is chosen and entered into this convoluted equation, the value of flow Q_2 can be found with a suitable iterative scheme (e.g., Newton's method, Secant method, successive substitution method). The calculated difference in flows $Q_1 - Q_2$ is then equated to a Darcy-Weisbach difference expression, in which the value of absolute roughness is varied from its calibrated value e_1 to its real or actual value e_2. In this way, an equivalent uncertainty in pipe absolute roughness $e_1 - e_2$ is found, as shown in Eq S-6:

$$|Q_1 - Q_2| = \sqrt{\frac{\pi^2 g(sH_1)}{8L}}\, D_1^{2.5} \left| \left(\frac{1}{f_1}\right)^{0.5} - \left(\frac{1}{f_2}\right)^{0.5} \right| \tag{S-6}$$

To better appreciate the relationship between flow and absolute roughness, the Swamee-Jain equation is substituted in this expression to give Eq S-7:

$$|Q_1 - Q_2| = \sqrt{\frac{\pi^2 g(sH_1)}{2L}}\, D_1^{2.5} \left| \log\left\{\frac{e_1}{3.7 D_1} + \frac{5.74}{\left[\frac{4\rho Q_1}{\pi\mu D_1}\right]^{0.9}}\right\} - \log\left\{\frac{e_2}{3.7\,D_1} + \frac{5.74}{\left[\frac{4\rho Q_2}{\pi\mu D_1}\right]^{0.9}}\right\} \right| \tag{S-7}$$

In this last equation, the variable Q_2 figures as a known value. The values D_1, Q_1, and H_1 denote the nominal pipe diameter, the measured flow, and the measured head loss across the pipe. The value of absolute roughness e_2, which corresponds to the calculated flow Q_2, is determined with one of the iterative schemes mentioned earlier. Once the value of this term is found, the difference between values of pipe roughness $e_1 - e_2$ is easily calculated. This difference can be thought of as a measure of the error incurred when the pipe diameter is held at its nominal value D_1 and the total loss effects in a pipe are lumped into a single roughness parameter e_1.

Following these steps, the uncertainty in velocity that parallels the uncertainty in absolute roughness $e_1 - e_2$ is again calculated with Eq 4 (main article) in which the term A_1 denotes the cross-sectional area of a pipe with a nominal diameter D_1. As before, the error associated with the calibrated bulk reaction coefficient can be determined with Eq 5 (main article).

variable-head reservoirs (R_1 and R_2) at nodes 33 and 43 to help maintain adequate pressures in the system and to provide an emergency store of water. Both reservoirs have a cross-sectional area of approximately 50 m^2 (538 sq ft) and are perched at an elevation of 130 m (426 ft). Water is drawn from the system at 11 locations (nodes 30, 31, 32, 35, 36, 37, 38, 39, 40, 41, and 42).

The extended-period analysis performed on the test system consisted of varying the demands and controlling the operations of the three pumps during the course of a 12-h simulated period. The variation in system demands followed a diurnal cycle of highs and lows. During periods of low flows, with a single pump operating, the reservoirs in the system filled. During times of large demands, three pumps were used to supply water to the network, and the reservoirs maintained pressure within the system. Figure 4 shows the pump schedule and the variation in demand used in the 12-h simulation.

Both the EPANET and the transient models were used to track the water level variation in reservoir R_1 connected to node 33 (Figure 5). The curve labeled "transient model" was run with a 0.1-s time step over the 12-h extended period. Because of the small time step, this curve can be considered numerically precise. The steady-state model EPANET, which uses the simple Euler method to solve the reservoir differential equation, was used to generate solutions with a 1-h time step (labeled "EPANET/Euler—*1 h*") and a 15-min time step (labeled "EPANET/Euler—*15 min*"). The EPANET model was also run with the modified Euler method and a time step of 1 h (labeled "EPANET/Modified Euler—*1 h*").

The transient model curve makes it clear that conditions within the system are constantly changing with time. In the plot, the solutions generated with EPANET and the simple Euler method diverge from the transient model results, producing both a magnitude and a phase error. Both anomalies can be attributed to the fact that the Euler method in the EPANET model conducts its time "leaps" solely on the strength of a single set of conditions, which are taken to remain steady or constant during a time step. As a result, the details of change in a system during a time step are ignored in the Euler method; thus, the accuracy of its estimates is correspondingly poor. This routing error can be mitigated somewhat by either calculating flows at the end of each time step and extrapolating water levels with a modified Euler technique or shortening the time step. In Figure 5, the solutions labeled "EPANET/modified Euler—*1 h*" and "EPANET/Euler—*15 min*" both have a smaller phase error and better mimic the general shape of the transient model plot. Without reducing the time step, the accuracy of an extended-period analysis could be improved by replacing the widely used first-order Euler method with a higher-order numerical integration technique.

The errors outlined in this example are anecdotal only; their magnitude is probably not representative of the errors usually incurred in hydraulic modeling exercises. Results clearly depend on specific values of demand, pipe and reservoir sizes, and how quickly conditions change. The point is, however, that this type of error can sometimes be significant, and yet its very existence is often overlooked. It is sobering to reflect that Euler solutions are almost universally rejected by numerical analysts as inaccurate, inefficient, or both (e.g., Hoffman, 2001; Schilling & Harris, 2000). At the very least, "grid refinement" techniques should be routinely used by modelers. In this approach, the simulation time step is progressively reduced until the solution converges to a numerically accurate value.

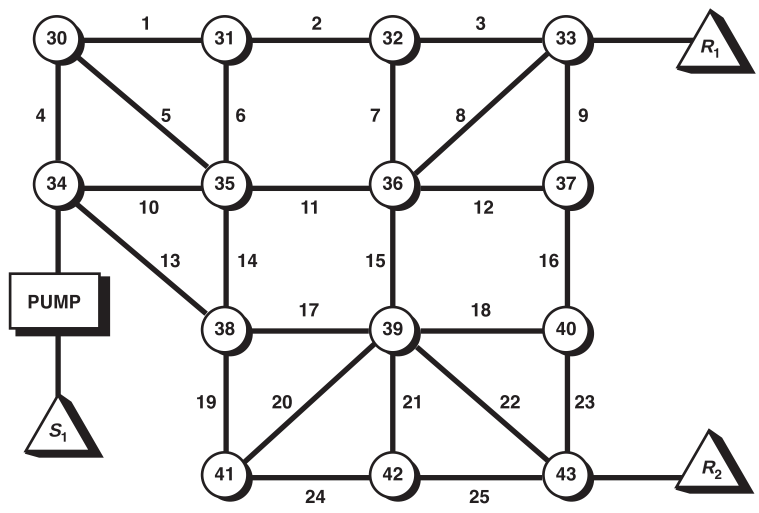
Future demands and demand representation. To design a system that will render an acceptable hydraulic performance throughout a period of time marked by changing consumption, model demands in a system are often set at artificial values that reflect the anticipated demand. This approach is difficult because future demands are almost never known with certainty. Thus, the assumed values of demand used in the model are seldom flows that could be measured in a real system. Clearly, the quality of hydraulic predictions will depend heavily on the quality of the demand estimates.

However, this problem of future demand estimation is not the only challenge. Most steady-state and EPS models assume that demands, whether representing leaks or household services, are independent of pressure (Karney, 1999b; Germanopolous, 1985). This assumption was no doubt originally justified by the imperfection of demographic estimates and by the simplicity of the hydraulic models. However, when the operation of a real system is being analyzed, a more accurate approach may be justified, because demands often depend on local pressure (e.g., sprinklers, domestic water devices, leaks, discharge from a hydrant). There is no doubt that the assumptions made about the representation of demand can influence the predicted solution.

Device behavior. A related issue is how conventional solvers represent the behavior of devices in a system. Most EPS programs use control algorithms that vary the settings of pumps and valves during the course of an EPS. In these solvers, when the settings of a hydraulic device (e.g., pump, pipe, control, or modulating valve) are changed suddenly, it is assumed that all parts of the system fall into equilibrium instantaneously with the new hydraulic state established at the device.

In actual fact, hydraulic unsteadiness is created whenever hydraulic conditions are changed. Although the results from the simplified analyses may be perfectly acceptable when a system's overall response is assessed or when general guidelines for system control are devised (Orr et al, 1999), they may give misleading information when used in more sophisticated analyses (e.g., opti-

FIGURE 3 Topology of the test network



mization, water quality, comprehensive system control). Perhaps more alarmingly, extended-period simulators with these control structures are sometimes being coupled with supervisory control and data acquisition (SCADA) systems to "optimize" the performance of systems, as well as to support the decisions pertaining to their day-to-day operations. Because no account of dynamic conditions is typically made in these approaches, the control strategies and actions they recommend to the system operators could actually worsen the performance of the system, instead of improving it (Karney, 1999b).

STEADY-STATE ASSUMPTION

In steady-state or EPS models, the primary modeling assumption is one of equilibrium: the flows and pressures are in balance, total inflow balances total outflow, and friction losses are compensated by external energy sources. This modeling idealization is often justified by arguing that hydraulic conditions at the boundaries of a system change slowly with time. However, if a sensitive pressure probe is connected at virtually any point in a system and readings are taken at almost any time of day, steady pressures will not be recorded. Instead, a series of short-lived fluctuations in pressures and flows will be observed as the system continually adjusts itself in a "herky-jerky" manner to the changing requirements of the users. The near steady-state representation of most modern distribution systems should be taken to be an approximate rendering of the largely unsteady behavior of such systems.

This raises an important issue about the behavior of most modern systems. The once-simple distribution systems fed by perched reservoirs and simple networks have been replaced with automated and highly complex systems, whose behavior often exhibits a dynamic character (Karney et al, 1994). These complicated networks usually comprise long, large pipes that often carry large flows and significant amounts of momentum. To control the pressures and flows in different zones of a system, an intricate system of pumps and valves (both control and modulating) is frequently used and operated. In fact, in most cases, these devices are continuously changing the hydraulic conditions at the boundaries of a system, even when it is operating under "normal" circumstances. Inevitably, with activity constantly afoot in a system, conditions will seldom be in a static state.

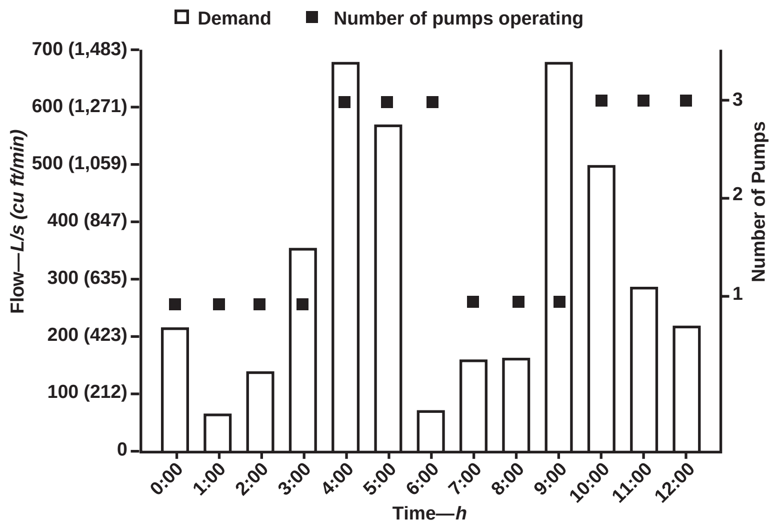
There are many examples of day-to-day sources of unsteadiness in a system. Perhaps the most common is the routine stopping and starting of pumps during the course of a typical service day, which often creates transient effects in a system and can degrade its performance. The regular opening and closing of control valves in a system are other good examples of a fairly commonplace exercise that routinely introduces unsteadiness in a modern system. When a valve is opened or closed (either slowly or quickly), pressure waves travel in upstream and downstream directions to "tell" the rest of the system of the new hydraulic conditions established at the valve. This hydraulic "communication" between components of a system accounts for the majority of unsteady flows and pressures that arise in a system during "normal" operations. Notwithstanding these routine transient occurrences, mishaps such as pump failures, sudden valve closures, or pipe breaks are added sources of unsteadiness that in some instances can have more serious consequences. Although this is obviously an abridged list of possible sources, it nevertheless shows the important role of unsteady conditions in most modern distribution systems. The assumption of steady-state conditions, however useful and pragmatic, is largely a fiction in the operation of real systems.

ERRORS IN MEASUREMENT AND CALIBRATION

Other complications occur when steady-state and EPS models are calibrated. The relatively small amount of information collected in calibration studies and the usual numerical practices can introduce significant errors in model parameters.

Steady-state calibration. A common approach in calibration work is to attempt to bring the system to a known steady state and then to measure the flow and pressure at select locations. These measurements are then used to calibrate a steady-state model by varying the friction coefficient of pipes—typically for groups of pipes assumed to have the same friction factor (only rarely is demand varied). The steady-state model is adjusted until the calculated values of pressure and head correlate well with the values obtained in the field. Mathematically, the problem is underdetermined; there are fewer equations than unknowns, and the "answer" or solution is not unique. In most cases, a large number of permutations of friction factors exist that can closely reproduce the typically small record of steady-state flow/pressure field observations. Thus, there is often no way to determine the "correct" or "real" permutation that accurately describes the system. As a result, the calibrated friction factors obtained from most calibration studies invariably contain errors and may introduce significant inaccuracies into the hydraulic solution, particularly for conditions markedly different from those recorded during the field test.

FIGURE 4 Schedule of pump operation and demand variation over the simulated 12-h period



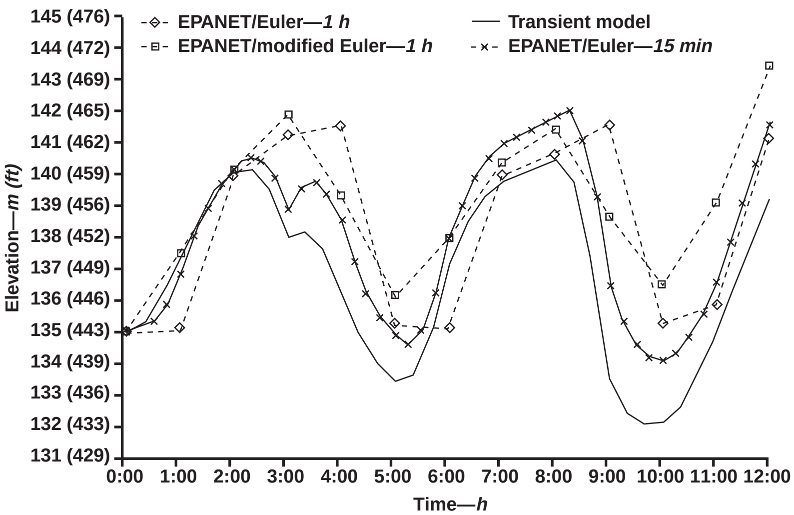
Extended-period calibration. To circumvent the underdetermination problem, field data are often collected over a length of time (ranging from a few hours to a few days) and over a range of operating conditions in the system. The friction coefficient of pipes and sometimes demands are varied by trial and error or by means of a computer generated optimization routine until the results of an extended simulation closely match the set of pressure/flow data (or trace of reservoir levels) recorded in the field. The output of this procedure is the calibrated values of friction and demand.

There are two problems with this approach. First, even if the apportioned demands in the system and the hydraulic conditions of its pumps and valves are perfectly known at each extended step, the errors incurred through the reservoir routing performed in the simulation might distort the distribution of flow. By matching the field data (measured pressures and flows) to the "erroneous" pressures and flows predicted by the model, the calibrated friction coefficients are likely to contain errors. The second problem relates to the amount of information needed to conduct such calibration experiments. Although taking a finite number of measurements of pressure/flow in the system at various instances in time may help narrow the possible range of friction coefficients in certain groups of pipes in a system, these limited data cannot, and should not, be expected to yield a unique solution of pipe friction coefficients. In fact, to obtain a unique solution, the distribution of demand in a system would have to be known at each time step of the extended solution. In trying to match the measured data to the results of an EPS, the analyst may turn an already difficult problem into an intractable one.

Pipe roughness and tuberculation. Another important problem is distinguishing between pipe roughness and tuberculation effects when a system is calibrated under steady-state conditions. The question distills down to this: does the recorded friction loss reflect a change in wall resistance, diameter, or some combination of these effects? Uncovering this distinction in a calibration study is complicated by the generic nature of steady-state conditions in a system and the scarcity of information extracted from these studies. In looped systems, the challenge is even greater because their high level of interrelatedness makes it difficult to extract the individual behavior of components from their overall response (Tang et al, 1999).

In most cases, an attempt is made to circumvent this problem by holding the diameter of a pipe constant at its nominal value and varying only its friction factor until the simulated data correspond reasonably well to the measured data. Lumping the total effects of head loss in the friction coefficient distorts the actual problem and often will accrue errors in the hydraulic solution. The nature and magnitude of these errors are elucidated here in analytical expressions that describe the hydraulic conditions in a single pipe connected to an upstream and downstream reservoir.

FIGURE 5 Variation of level in tank 1: results from four modeling runs



In Eq 2, the term s is a sign operator that has a value of 1 for flows with a positive direction and a value of –1 for reverse flows. The calibrated value of friction coefficient C_1 is held constant so that the difference in flow is caused only by varying the diameter from its nominal value D_1 to its real or field value of D_2. Absolute values are used in these expressions to emphasize the difference between nominal and field quantities.

With this result, the difference between friction coefficients C_1 and C_2 that produces the calculated difference in flow $Q_1 - Q_2$ is calculated in Eq 3.

$$|C_1 - C_2| = C_1 \left| 1 - \left(\frac{D_2}{D_1}\right)^{\beta} \right| \tag{3}$$

The difference between resistance coefficients calculated in Eq 3 is the type of error that arises in a hydraulic solution when a system is calibrated for changes in roughness C when diameter D varies. More specifically, it is a measure of the error incurred when the effects of roughness and a reduced diameter are lumped into a single resistance parameter C_1 while holding the pipe diameter at its nominal value D_1.

To determine the friction coefficient of pipes in a system, head loss and flow measurements are usually taken at various locations in a distribution system. In the small example given here, values of head loss and flow were measured in a pipe connected to an upstream and downstream reservoir. The calibrated value of resistance C_1 in a pipe was found by entering measured values of head loss and flow into the Hazen-Williams equation while holding the diameter of the pipe fixed at its nominal value of D_1. Equation 1 shows the Hazen-Williams calibrated resistance coefficient

$$C_1 = \frac{L^{\alpha} Q_1}{C_u D_1^{\beta} H_1^{\alpha}} \tag{1}$$

in which the variables D_1, Q_1, and H_1 denote the nominal diameter, measured flow, and measured head loss, respectively. The length of the pipe L is assumed to be perfectly known. The coefficients have values $\alpha = 0.54$ and $\beta = 2.63$, respectively, and the unit coefficient for metric (SI) units $C_u = 0.278$ (0.314).

As pipes age, their diameters are often gradually reduced, in large part because sediments and chemicals are deposited along their walls, and bacterial growth and tuberculation set in. To investigate the effects of a reduced diameter on the flow in this simple system, the Hazen-Williams equation is used to relate a difference of flows to a difference of diameters.

$$|Q_1 - Q_2| = \frac{C_u C_1 (sH_1)^{\alpha}}{L^{\alpha}} |D_1^{\beta} - D_2^{\beta}| \tag{2}$$

Calibration errors are deemed important insofar as they produce errors in hydraulic and water quality parameters that directly depend on them, such as velocity, residence time and bulk reaction coefficient. In this case, if the difference that exists between the calibrated and real values of friction coefficients C_1 and C_2 is known, the difference or uncertainty associated with the hydraulic parameters of velocity, residence time, and bulk reaction coefficient can be determined. For example, the velocity difference associated with the difference $C_1 - C_2$ calculated in Eq 3 is determined in Eq 4:

$$|V_1 - V_2| = \left| \frac{Q_1}{A_1} - \frac{Q_2}{A_1} \right| \tag{4}$$

The term A_1 here denotes the cross-sectional area of a pipe with a nominal diameter measuring D_1. Using this velocity difference, the sensitivity of a bulk reaction coefficient for a single pipe can be calculated with Eq 5:

$$|K_1 - K_2| = \left| \ln \frac{C(x, t + \Delta t)}{C(x - L, t)} \right| \frac{|V_1 - V_2|}{L} \tag{5}$$

The term $C(x - L,t)$ denotes the measured concentration of a constituent at an upstream section of a pipe at time t. The term $C(x, t + \Delta t)$ designates the concentration of the constituent after some time Δt, once it has been advected at distance $V\Delta t = L$ from the upstream section. The difference between both terms depends on the rate at which the constituent decays—or is produced—and is advected across the pipe.

Errors in calibrated values of pipe roughness can engender other errors (sometimes significant ones) in hydraulic and water quality parameters such as velocity, water age, bulk reaction coefficient, and concentration. The arbitrary approach of holding one parameter constant (usually the diameter) while varying the other (roughness coefficient) will almost certainly create distortions. More important, the errors incurred in the hydraulic solution can propagate to other calculations (e.g., simulation of water quality) that depend directly on that hydraulic solution. Although hydraulic errors of this sort may be tolerable in a "first-cut" hydraulic analysis, they may produce results that are wildly misleading in more detailed investigations.

Uncertainty in field measurements. In most calibration studies, the water distribution system is brought to a "steady state" before field measurements are taken (verified either through data or simply assumed). However, because users are continually changing their water requirements, pumps are changing their operating points, and reservoirs are filling and emptying, the state of the system is seldom truly steady (Walski, 1983). In most cases, whatever measurements of pressure and flow are gathered in the field will relate to a system in a state of change. Even if the settings of pumps, valves, and demands are held fixed in a system, the hydrant flow tests themselves inevitably induce transient conditions. In addition to the legitimate concerns surrounding the suitability of head loss and velocity data and the relative errors in their measurement (Walski, 2000), the engineer must still decide whether the collected data pertain to a system in a steady or transient state.

Even without these problems, field measurements presumed to correspond to "steady" conditions may sometimes produce misleading information. Take, for example, the measurement of head loss across the length of a new pipe connected to a much older one having a large friction factor. As the fluid passes from the old pipe to the newer one, the turbulence created by the roughness elements in the old pipe will be attenuated only well downstream of the junction, whereas a reversed flow may experience a different loss. Without knowledge of the disparity in roughness between the two pipes, the analyst may accept a friction factor that is not representative of other flow conditions. A partially closed valve may produce similar errors. Such valves often produce large losses, which may be incorrectly attributed to roughness conditions inside the pipe.

Uncertainty in demands. In large systems, water consumption is often estimated by taking the difference between the average pumping rate and the average inflow/outflow rate of the reservoirs. Given that the temporal (short term) and spatial distributions of demand in the system are generally unknown, the calculated bulk demand is usually apportioned throughout the system in accordance with available statistical water consumption data. However, because the hydraulic response (flow and pressure distributions) directly depends on both the absolute magnitude and distribution (both in time and space) of consumption, the assumed demands are apt to diverge from field values. The problem is complicated even further by the fact that diurnal patterns in some systems can vary widely from day to day (Walski et al, 2000). As a result, the friction coefficient of pipes is likely to be calibrated incorrectly with a model that predicts erroneous distributions of flows and pressures in the system. Unfortunately, the problem of apportioning demands in a system is not easily resolved and almost always presents an impediment in hydraulic modeling studies—whether they be steady-state or water hammer investigations.

System skeletonization. In some cases, calibration problems are attributable to excessive skeletonization. Sometimes, the head loss/flow field data will seem to diverge from the corresponding model predictions simply because the computer model (steady state, surge, or transient) has been overly simplified. This situation arises when a significant number of pipes (typically small diameter) are cut out of the hydraulic analysis, while the total demand measured in the system—often with a SCADA system—is retained and used in the model. The corresponding reduction in hydraulic capacity often engenders substantive losses in the idealized system (computer model) and may cause the predicted pressures to dip well below those measured in the field (Walski, 1990). Using this model to find the friction coefficient of pipes in the system is likely to produce errors in the calibrated values.

Although taking a finite number of measurements of pressure/flow in the system at various instances in time may help narrow the possible range of friction coefficients in certain groups of pipes in a system, these limited data cannot, and should not, be expected to yield a unique solution of pipe friction coefficients.

Poor recordkeeping. Another common source of error in calibration stems from poor recordkeeping. For example, if key elements such as pressure-reducing valves or pipe connections between contiguous pressure zones are for whatever reasons excluded from the analysis (i.e., hydraulic elements are not marked on system maps), the hydraulic behavior of the modeled system will likely be radically different from that of the real system (Walski, 1990). Again, using such a model to calibrate friction coefficients is likely to produce errors in the calibrated solution.

CONCLUSION

This article seeks to broaden the usual context in which decisions about the Hazen-Williams and Darcy-Weisbach steady-state friction models are regularly being made in practice. Despite the obvious importance of choosing an appropriate friction model, it is incumbent on the modeler or engineer to consider the great multitude of other factors that might come to bear on the accuracy of the hydraulic solution. In this article, many common sources of errors and uncertainties in hydraulic modeling were discussed. More specifically, the fundamental limitations of current modeling and calibration practices were discussed point by point. These arguments served to reinforce the contention that the accuracy of the friction model used in the hydraulic solution is only a relative concern when the array of other factors that can introduce significant errors and uncertainties in the hydraulic solution is seriously considered.

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FOOTNOTE

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