Calibrating hydraulic network models

To a novice, careful calibration of a hydraulic network model may be as daunting a task as climbing Mt. Everest.

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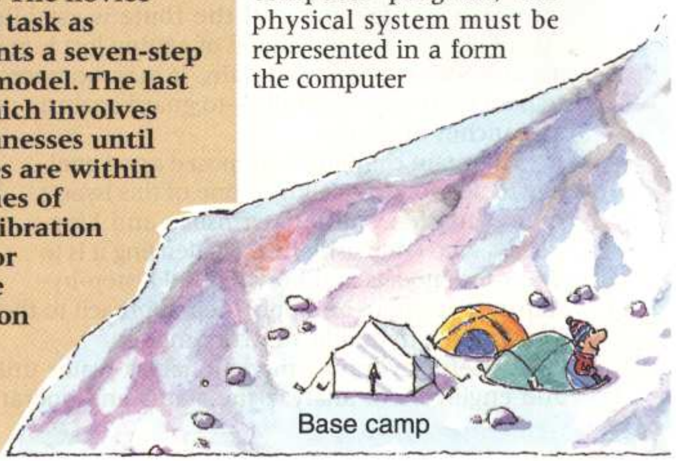
Although calibration should always be included in any hydraulic analysis, it is often neglected or done haphazardly. As a result, inappropriate data may be used or data errors may be overlooked, so the resulting hydraulic model is of limited value. The novice may see calibrating a hydraulic network model as a task as daunting as climbing Mt. Everest. This article presents a seven-step method for use in calibrating a hydraulic network model. The last and most difficult step is microlevel calibration, which involves the adjustment of demand loadings and pipe roughnesses until computed and observed field pressures or flow rates are within reasonable agreement for various levels and extremes of demand, pumping, and storage. Various explicit calibration algorithms have reduced the need for trial-and-error procedures and have improved the reliability of the resulting calibration. There remains little justification for failing to develop good calibrated network models prior to network analysis.

Computer models for analyzing and designing water distribution systems have existed for several decades. During this time, many advances have been made in their sophistication and applications. The availability and widespread use of microcomputer technology have enabled water utilities and engineers to analyze the status and operations of existing systems and to investigate the effects of proposed changes.[1] The validity of these models, however, depends largely on the accuracy of the input data.

Before an actual distribution system may be modeled or simulated with a computer program, the physical system must be represented in a form the computer



can analyze. This requires that the water distribution system first be represented by a node–link database (Figure 1). In this case, the links represent individual pipe sections, and the nodes represent points in the system where two or more pipes (links) join or where water is being input or withdrawn.

Data associated with each link include pipe identification number, pipe length, pipe diameter, and pipe roughness. Data associated with each junction node include junction identification number, junction elevation, and junction demand. Although it is recognized that water leaves the system in a time-varying fashion through various service connections along the length of a pipe segment, it is generally acceptable in modeling to lump half of the demands along a line to the upstream node and the other half of the demands to the downstream node.

In addition to the network pipe and node data, physical data must be obtained that describe all tanks, reservoirs, pumps, and valves. Physical data for tanks and reservoirs include information about tank geometry and initial water levels. Physical data for pumps include either the value of the average useful horsepower or data for use in describing the pump flow–head characteristics curve. Data should be entered into the computer in a format compatible with the selected computer model.

After data have been assembled and encoded, the associated model parameters should then be estimated prior to actual model application. In general, the most uncertain model parameters include pipe roughness and nodal demands. Because of the difficulty of obtaining economic and reliable measurements of these two parameters, final model values are normally determined via model calibration—i.e., adjusting those model parameters needed to produce results that closely approximate actual observed conditions as measured from field data. In general, a network model calibration effort should encompass seven basic steps (illustrated at left):

(1) Identify the intended use of the model.

(2) Determine initial estimates of the model parameters.

(3) Collect calibration data.

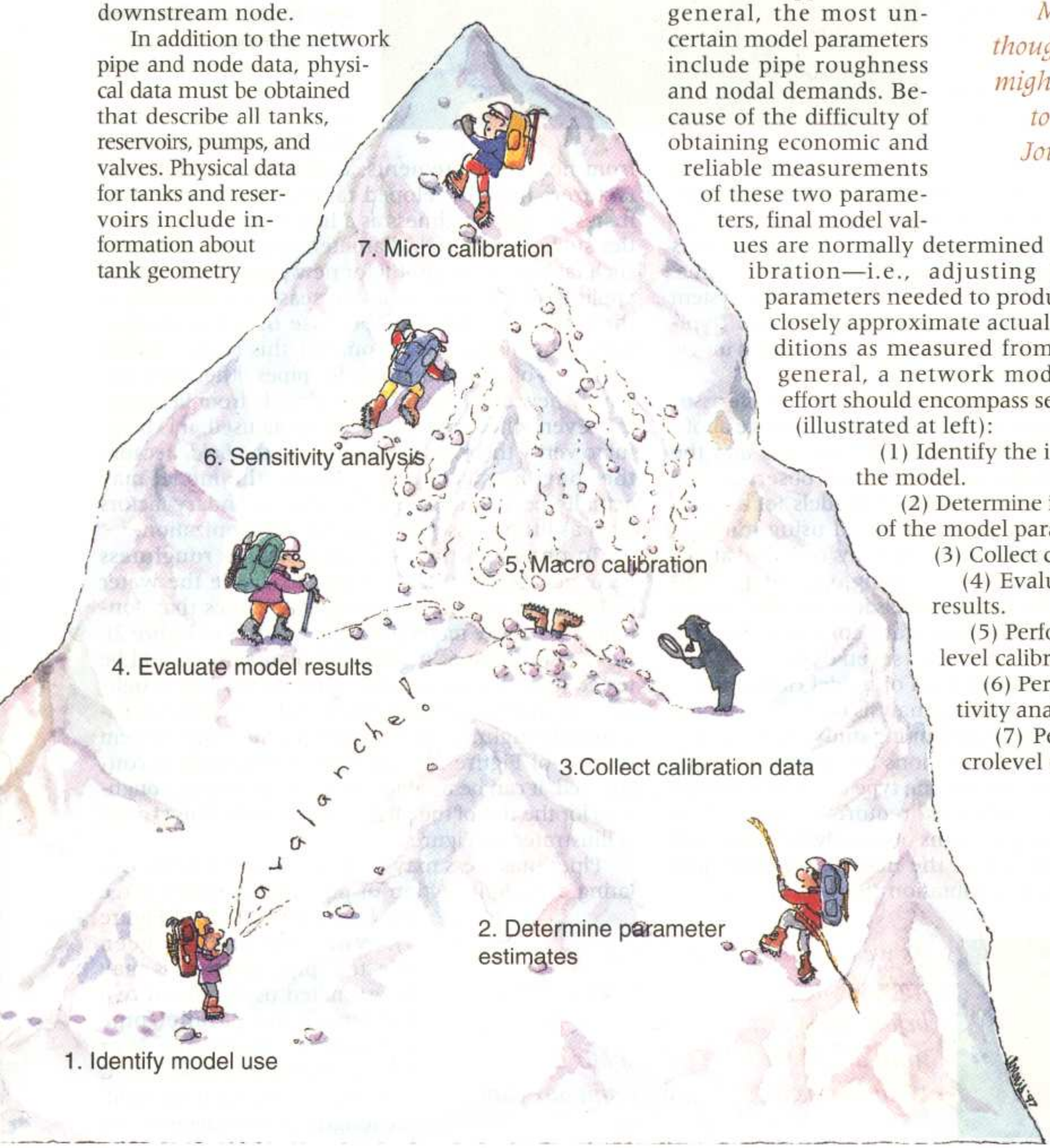
(4) Evaluate the model results.

(5) Perform the macrolevel calibration.

(6) Perform the sensitivity analysis.

(7) Perform the microlevel calibration.

On a recent trip to India, my colleague came across fragments of a diary from a recent expedition to the Himalaya Mountains. We thought its contents might be of interest to the readers of Journal AWWA.



Identify intended use of the model

Before calibrating a hydraulic network model, it is important to first identify its intended use (e.g., pipe sizing for master planning, operational studies, design projects, rehabilitation studies, water quality studies) and the associated type of hydraulic analysis (steady-state versus extended-period). Usually the type of analysis is directly related to the intended use. For example, water quality and operational studies require an extended-period analysis, whereas some planning or design studies may be performed using a steady-state analysis. In the latter, the model predicts system pressures and flows at an instant in time under a specific set of operating conditions and demands (e.g., average or maximum daily demands). This is analogous to photographing the system at a specific point in time. In extended-period analysis, the model predicts system pressures and flows over an extended period (typically 24 hours). This is analogous to developing a movie of the system performance.

Both the intended use of the model and the associated type of analysis provide some guidance about the type and quality of collected field data and the desired level of agreement between observed and predicted flows and pressures.[2] Models for steady-state applications can be calibrated using multiple static flow and pressure observations collected at different times of day under varying operating conditions. On the other hand, models for extended-period applications require field data collected over an extended period (e.g., one to seven days).

In general, a higher level of model calibration is required for water quality analysis or an operational study than for a general planning study. For example, determining ground elevations using a topographic map may be adequate for one type of study, whereas another type of study may require an actual field survey. Such considerations obviously influence the methods used to collect the necessary model data and the subsequent calibration steps.

Once we arrive at base camp, we immediately set about the task of organizing and inventorying our equipment. At this point we determine whether we have everything we need to begin our journey.

Determine model parameter estimates

The second step in calibrating a hydraulic network model is to determine initial estimates of the primary model parameters. In most models, some degree of uncertainty is associated with several parameters—most notably pipe roughness coefficients and the demands to be assigned to each junction node.

Pipe roughness values may be estimated in two ways. Initial estimates of pipe roughness values may be obtained using average values from literature or directly from field measurements. Researchers and manufacturers have developed tables that provide estimates of pipe roughness as a function of characteristics such as material, diameter, and age. Although such tables may be useful for new pipes, their specific applicability to older pipes decreases significantly as the pipes age—possibly because of tuberculation, water chemistry, and so on. For this reason, initial estimates of pipe roughness for pipes other than relatively new ones should come directly from field testing. Even when new pipes are being used, it is helpful to verify the roughness values in the field, because the roughness coefficient used in the model may actually be a composite of several secondary factors such as fitting losses and system skeletonization.

To obtain initial estimates of pipe roughness through field testing, it is best to divide the water distribution system into composite zones that contain pipes of like material and age (part A of Figure 2). Next, several pipes of different diameters should be tested in each zone to obtain individual pipe roughness estimates (part B of Figure 2) to construct a customized roughness nomograph for the entire system (part C of Figure 2). After the nomograph is constructed, it can be used to assign values of pipe roughness for the rest of the pipes in the system. This process is illustrated in Figure 2.

Pipe roughness may be tested in the field by isolating a straight section of pipe that contains three fire hydrants (part A of Figure 3). When the line has been selected, pipe roughness may be estimated using one of two methods:[3] the parallel-pipe method (part B of Figure 3) or the two-hydrant method (part C of Figure 3). In each method, the length and diameter of the

As we assemble at base camp, our eyes shift from the map in front of us to the range before us. We carefully examine the features until at last we have located our objective. With our bearings set, we begin our climb.

test pipe are first determined. Then the pipe is isolated, and the flow and pressure drop are measured either through the use of a differential pressure gauge or by using two separate pressure gauges. Pipe roughness can then be approximated by a direct application of either the Hazen-Williams equation or the Darcy-Weisbach equation.

Nodal demand distribution must be assigned. The second major parameter determined in calibration analysis is the average (steady-state analysis) or temporally varying (extended-period analysis) demand to be assigned to each junction node. Initial average estimates of nodal demands can be obtained by identifying a region of influence associated with each junction node, identifying the types of demand units in the service area, and multiplying the number of each type by an associated demand factor. Alternatively, the estimate can be obtained by first identifying the area associated with each type of land use in the service area and then multiplying the area of each type by an associated demand factor.

In either case, the sum of these products is an estimate of the demand at the junction node. Although in theory the first approach should be more accurate, the latter approach is more expedient. Estimates of unit demand factors are available from water resource handbooks and textbooks.[4]

Time-varying estimates of model demands for use in extended-period analysis can be made in one of two ways, depending on the structure of the hydraulic model. Some models allow the user to subdivide the demands at each junction node into different use categories, which can then be modified separately over time using demand factors for water use categories. Other models require an aggregate-use category for each node. In the latter case, spatial–temporal variations of nodal demands are obtained by lumping nodes of a given type into separate groups, which can then be modified uniformly using nodal demand factors. Initial estimates of either water use category demand factors or nodal demand factors can be obtained by examining historical meter records for various water use categories and by performing incremental mass balance calculations for the distribution system. The resulting set of temporal demand factors can then be fine-tuned through subsequent model calibration.

Collect calibration data

After model parameters have been estimated, the accuracy of the model parameters can be assessed. This is done by executing the model using the estimated parameter values and observed boundary conditions and then comparing the model results with the results from actual field observations. Data from fire flow tests, pump station flowmeter readings, or tank telemetry data are most commonly used in such tests.

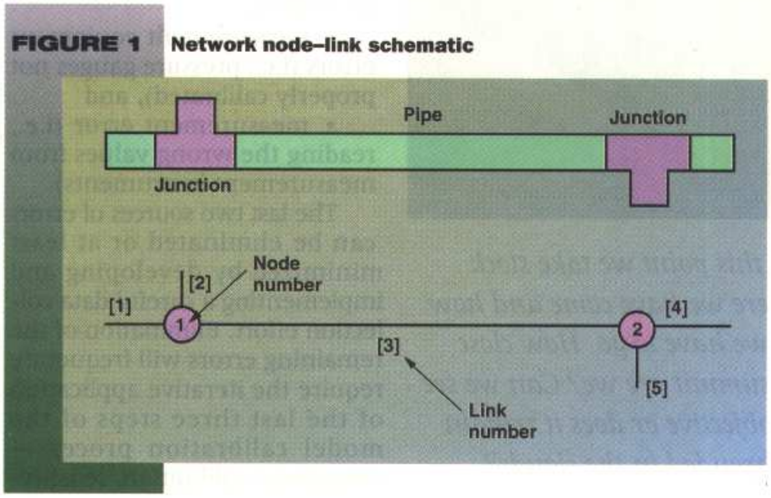
As we begin our ascent, we attempt to estimate the best route to reach our immediate objective. In so doing we must remain flexible in order to adapt to changing conditions.

Fire flow tests are useful for collecting discharge and pressure data. Such tests are conducted using both a normal pressure gauge (for measuring static and dynamic heads) and a pitot gauge (for calculating discharge). For a fire flow test, at least two hydrants are first selected. One is identified as the pressure or residual hydrant, and the other is the flow hydrant.

To obtain sufficient data for a model calibration, it is important that data from several fire flow tests be collected. It is also important that the associated system boundary condition data be collected before each test is conducted. This includes information on tank levels, pump status, and so on. For adequate model calibration, the difference between the static and dynamic pressure readings as measured from the residual hydrant should be at least 5 psi (10.2 in. Hg) with a preferable drop of 20 psi (40.7 in. Hg).[5] If the discharge hydrant does not allow sufficient discharge to cause such a drop, it may be necessary to identify, instrument, and open additional discharge hydrants.

In addition to static test data, data collected over an extended period of time (at least 24 hours and up to seven days) can be useful for calibrating network models. The most common type of data are those for flow rate, tank water level, and pressure. Depending on

FIGURE 1 Network node–link schematic

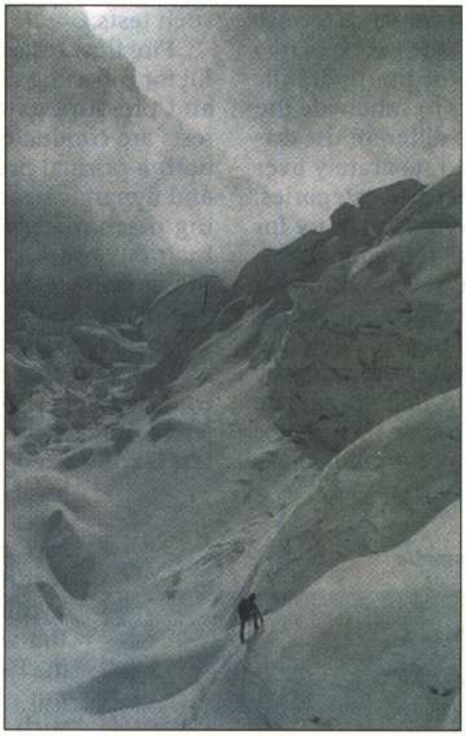


As we continue our climb up the mountain, we take care to secure our lifeline with each few steps. At this point the success or failure of our journey can hinge on the reliability of each pin we place.

the level of instrumentation and telemetry, much of the data may already be collected as part of normal operations. For example, many systems collect and record tank levels and average pump station discharges on an hourly basis.

These data are especially useful in verifying the distribution of demands among the various junction nodes. If such data are available, they should be checked for accuracy before they are used for calibration. If such data are not readily available, the modeler may have to install temporary pressure gauges or flowmeters to obtain them. In the absence of flowmeters in lines to tanks, inflow or discharge flow rates can be inferred from incremental readings of the tank level.

In recent years, both conservative and nonconservative constituents have been used as tracers to determine the travel time through various parts of a water distribution system.[6] The most common type of tracer for such applications is fluoride. By controlling the injection rate at a source (typically the water treatment plant), a pulse can be induced into the flow and monitored elsewhere in the system. The relative travel time of the pulse from the source to the sampling point can be measured. The measured travel time provides another data point for use in calibrating a hydraulic network model.



At this point we take stock of where we have come and how far we have to go. How close to the summit are we? Can we see our objective or does it remain shrouded in the clouds?

Evaluate model results

Using fire flow data, the model simulates the discharge from one or more fire hydrants by assigning the observed hydrant flows as nodal demands in the model. Predicted flows and pressures are then compared with the corresponding observed values in an attempt to assess model accuracy. Using telemetry data, the model simulates operating conditions (i.e., the variation of tank water levels and system pressures) for the day the field data were collected. The predicted tank water levels are then compared with the observed values in an attempt to assess model accuracy. Using water quality data, the travel times predicted by the model are compared with the corresponding observed values in an attempt to assess model accuracy.

Model accuracy may be evaluated using various criteria. The most common criteria are absolute pressure difference (measured in pounds per square inch [inches of mercury]) or relative pressure difference (measured as the ratio of the absolute pressure difference to the average pressure difference across the system). A relative pressure difference criterion is usually preferred. For simulations over extended periods, comparisons are made between the predicted and observed flow rates, pressures, and tank water levels. Depending on the application, a maximum-state variable (i.e., pressure grade, water level, flow rate) deviation between 5 and 10 percent is generally regarded as satisfactory.

Deviations between results of the model application and the field observations may be caused by several factors, including:

- erroneous model parameters (pipe roughness values and nodal demand distribution),
- erroneous network data (pipe diameters, lengths, and so on),
- incorrect network geometry (pipes connected to the wrong nodes),
- incorrect pressure zone boundary definitions,
- errors in boundary conditions (i.e., incorrect pressure-regulating valve settings, tank water levels, pump curves, and so on),
- errors in historical operating records (i.e., pumps starting and stopping at incorrect times),
- measurement equipment errors (i.e., pressure gauges not properly calibrated), and
- measurement error (i.e., reading the wrong values from measurement instruments).

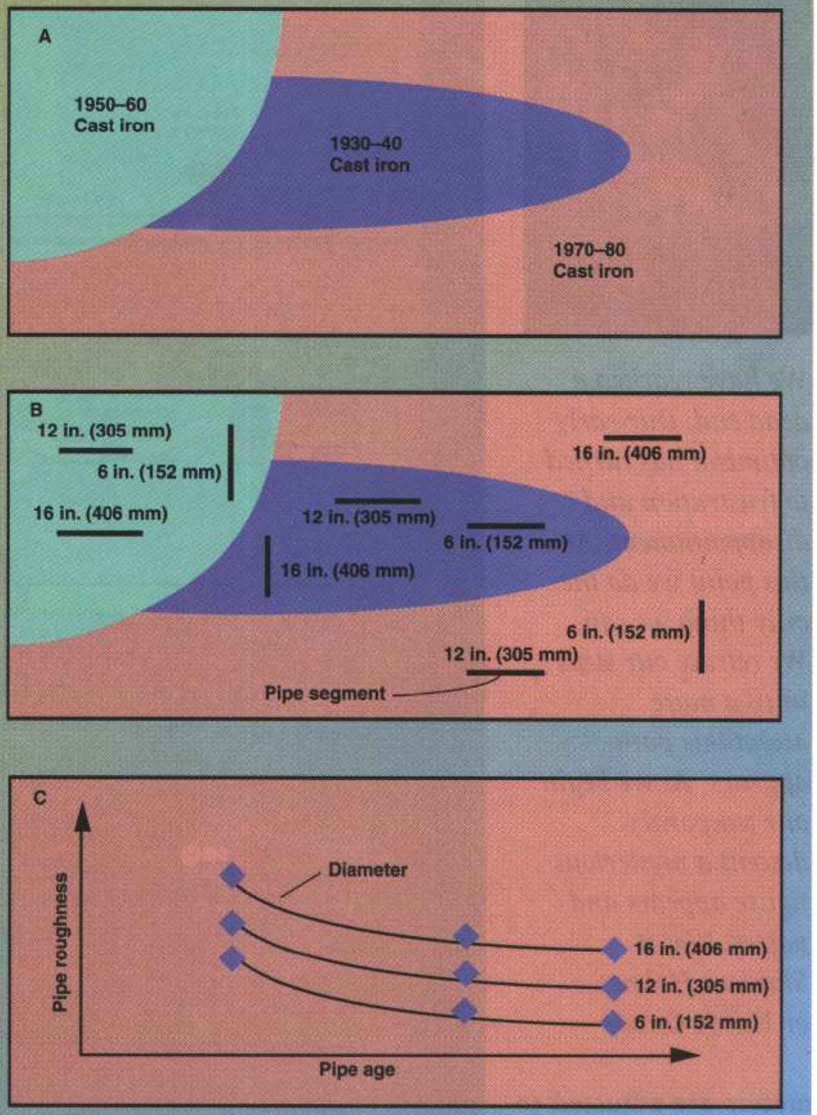
The last two sources of errors can be eliminated or at least minimized by developing and implementing a careful data collection effort. Elimination of the remaining errors will frequently require the iterative application of the last three steps of the model calibration process—macrolevel calibration, sensitivity analysis, and microlevel calibration. Each of these steps is described in the following sections.

Perform macrolevel calibration

If one (or more) of the measured state variable values is different from the modeled values by an amount deemed excessive (i.e, greater than 30 percent), the cause for the difference probably extends beyond errors in the estimates for either pipe roughness values or nodal demands. Possible causes for such differences are many but may include closed or partly closed valves, inaccurate pump curves or tank telemetry data, incorrect pipe diameters or lengths, incorrect network geometry, and incorrect pressure zone boundaries.[7]

The only way to adequately address such macrolevel errors is to systematically review the data associated with the model and compare them with the field data to ensure accuracy. In most cases, some data will be less reliable than other data. This observation provides a logical place to start in an attempt to identify the problem. Model sensitivity analysis provides another means of identifying the source of discrepancy. Potential errors in pump curves can sometimes be minimized by simulating the pumps with negative inflows set equal to observed pump discharges.[8]

FIGURE 2 Estimating pipe roughness through field testing: divide system into composite zones (part A), test representative pipes from each zone (part B), and construct customized roughness nomograph (part C)



Perform sensitivity analysis

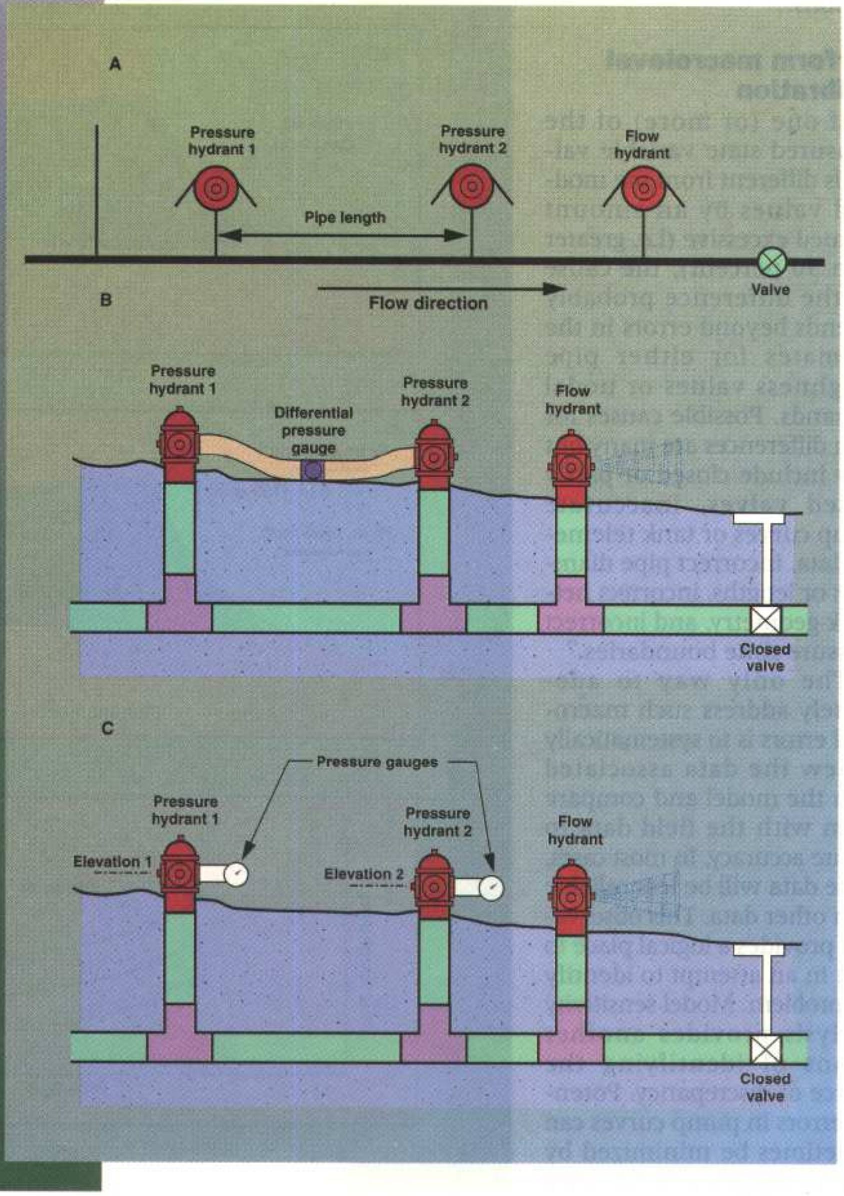
Before attempting a microlevel calibration, it is helpful to perform a sensitivity analysis of the model to help identify the most likely source of model error. This can be accomplished by varying the model parameters by different amounts and then measuring the associated effect. For example, many current network models have as an analysis option the capability to make multiple simulations, in which global adjustment factors can be applied to pipe roughness values or nodal demand values. By examining such results, the user can begin to identify which parameters have the most significant impact on the model results and thereby identify potential parameters for subsequent fine-tuning through microlevel calibration.

Perform microlevel model calibration

After model results and field observations are in reasonable agreement, a microlevel model calibration should be performed. The parameters to be adjusted during this final phase of calibration are pipe roughness and nodal demands. In many cases it may be useful to break the microlevel calibration into two steps: steady-state calibration and extended-period calibration. In a steady-state calibration, the model parameters are adjusted to match pressures and flow rates associated with multiple static observations. Fire flow tests are the normal source for such data. In an extended-period calibration, the model para-

We have reached a dead end. Our early optimism has turned to frustration and disappointment. At this point we do the only thing we can. We retrace our steps until a more acceptable path appears. As we begin our temporary descent a mysterious figure appears and passes. Was it Sherlock Holmes or Hardy Cross?

FIGURE 3 **Testing pipe roughness in the field: isolate straight section of pipe that contains three fire hydrants (A); estimate roughness using the parallel-pipe method (B) or the two-hydrant method (C)**



meters are adjusted to match time-varying pressures and flows as well as tank water level trajectories. In most cases, the steady-state calibration is more sensitive to changes in pipe roughness, whereas the extended-period calibration is more sensitive to changes in the distribution of demands. One potential calibration strategy would be to first fine-tune the pipe roughness parameter values using the results from fire flow tests and then try to fine-tune the distribution of demands using data about flow, pressure, and water-level telemetry.

Historically, most attempts at model calibration have employed an empirical or trial-and-error approach, which can prove to be extremely time-consuming and frustrating for most water systems. The level of frustration will, of course, depend somewhat on the expertise of the modeler, the size of the system, and the quantity and quality of the field data. Some of the frustration can be minimized by breaking complicated systems into smaller parts and then calibrating the model parameters using an incremental approach. Calibration of multitank systems can sometimes be facilitated by collecting multiple data sets with all but one of the tanks closed.[8]

Several researchers have proposed different algorithms for use in automatically calibrating hydraulic network models. Most of these techniques have been restricted to steady-state calibration. These techniques have been based on the use of analytical equations,[9] simulation models,[10–13] and optimization methods.[14–18]

Analytical approaches require simplification. Techniques based on analytical equations generally require significant simplification of the network through skeletonization and the use of equivalent pipes; thus the techniques may only elicit approximately correct results. Conversely, both simulation and optimization approaches take advantage of using a complete model and thus can be expected to yield better results.

Simulation approaches add equations. Simulation techniques are based on the idea of solving for one or more calibration factors by adding one or more network equations. The additional equations are used to define an additional observed boundary condition (such as a fire flow discharge head). By adding an extra equation, the researcher can explicitly determine an additional unknown.

The primary disadvantage of the simulation approaches is that they can only handle one set of boundary conditions at a time. For example, applying a simulation approach to a system with three different sets of observations (all obtained under different boundary conditions—i.e., tank levels, pump status, and so on) elicits three different results. Attempts to obtain a single calibration result will require one of two application strategies: a sequential approach or an average approach.

In the sequential approach, the system is subdivided into multiple zones whose number will correspond to the number of sets of boundary conditions. In this case, the first set of observations is used to obtain calibration factors for the first zone. These factors are then fixed, another set of factors is determined for the second zone, and so on. In the average approach, final calibration factors are obtained by averaging the calibration factors for each of the individual calibration applications.

Optimization approach is alternative to simulation. The primary alternative to the simulation approach is the optimization approach. In this approach, the calibration problem is formulated as a nonlinear optimization problem consisting of a nonlinear objective function subject to both linear and nonlinear equality and inequality constraints.[16]

Recently, researchers have begun to investigate the use of genetic optimization for solving such complex nonlinear optimization problems.[18] Genetic optimization offers a significant advantage over more traditional optimization approaches in that it attempts to obtain an optimal solution by continuing to evaluate multiple solution vectors simultaneously. In addition, genetic optimization methods do not require gradient information. Finally, genetic optimization methods employ probabilistic transition rules as opposed to deterministic rules, which has the advantage of ensuring a robust solution methodology.

Our confidence has increased along with our altitude. However, our ultimate goal remains hidden in the clouds. At this point we look for solid footing among the icy terraces. Which path will bring us closest to our final goal?

Future trends noted

With the advent and use of nonlinear optimization, it is possible to achieve some success in microlevel calibration. Of course, the level of success depends greatly on the degree to which sources of macrolevel calibration errors have first been eliminated or at least significantly reduced. Although these later sources of errors may not be as readily identified with conventional optimization techniques, it may be possible to develop prescriptive tools for these problems using expert system technology. In this case, general calibration rules could be developed from an experiential database that could then be used by other modelers in an attempt to identify the most likely source of model error for a given set of system characteristics and operating conditions. Such a system could also be linked with a graphical interface and a network model to provide an interactive environment for use in model calibration.

In recent years, advocacy has increased for the use of both geographic information system (GIS) technology and supervisory control and data acquisition (SCADA) system data based in model calibration. GIS technology provides an efficient way to link customer billing records with network model components for use in assigning initial estimates of nodal demands.[19] Such technology also provides a graph-

We establish our last camp. Our goal is within reach. What tactic shall we employ in the final assault on the summit—a more methodical approach around the southern face or a rapid ascent up the unfamiliar northern slope? For a moment our thoughts race back in time before the availability of modern equipment and bottled oxygen when inexperienced climbers could be found wandering near the summit with a glazed look of total confusion. How did anyone ever make it?

So, what are you waiting for? Climb that mountain!

ical environment for examining the network database for errors.

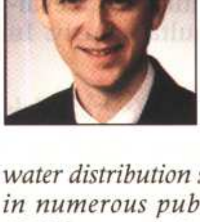
One of the more interesting possibilities with regard to network model calibration is the development and implementation of an on-line network model through linkage of the model with an on-line SCADA system. Such a configuration provides the possibility for a continuing calibration effort, in which the model is continually updated as additional data are collected through the SCADA system.[20]

Summary and conclusion

Network model calibration should always be performed before any network analysis planning and design study. A seven-step methodology for network model calibration has been proposed. Historically, one of the most difficult steps in the process has been the final adjustment of pipe roughness values and nodal demands through the process of microlevel calibration. With the advent of recent computer technology it is now possible to achieve good model calibration with a reasonable level of success. As a result, there remains little justification for failing to develop good calibrated network models before conducting network analysis. It is expected that future developments and applications of both GIS and SCADA technology will lead to even more efficient tools.

References

1. Ormsbee, L.E.; Chase, D.V.; & Grayman, W. Network Modeling for Small Water Distribution Systems. Proc. 1992 AWWA Computer Conf., Nashville, Tenn.
2. Walski, T.M. Standards for Model Calibration. Proc. 1995 AWWA Computer Conf., Norfolk, Va.
3. Walski, T.M. *Analysis of Water Distribution Systems.* Van Nostrand Reinhold, New York (1984).
4. Cesario, L. Modeling, Analysis, and Design of Water Distribution Systems. AWWA, Denver (1995).
5. Walski, T.M. Case Study: Pipe Network Calibration Issues. *ASCE Jour.—Water Resources Planning and Mgmt.,* 112:2:238 (1986).
6. Kennedy, M.; Sarikelle, S.; & Suravallop, K. Travel-Time Calibrations in Water Distribution Systems. Proc. 1991 AWWARF–USEPA Conf. on Water Quality Modeling in Water Distribution Systems, Cincinnati.
7. Walski, T.M. Sherlock Holmes Meets Hardy–Cross, or Model Calibration in Austin, Texas. *Jour. AWWA,* 82:3:34 (1990).
8. Cruickshank, J.R. & Long, S.J. Calibrating Computer Model of Distribution Systems. Proc. 1992 AWWA Computer Conf., Nashville, Tenn.
9. Walski, T.M. Technique for Calibrating Network Models. *Jour. ASCE—Water Resources Planning & Mgmt.,* 109:4:360 (1983).
10. Rahal, C.M.; Sterling, M.J.H; & Coulbeck, B. Parameter Tuning for Simulation Models of Water Distribution Networks. Proc. 1980 Institution of Civil Engrs., London.
11. Gofman, E. & Rodeh, M. Loop Equations With Unknown Pipe Characteristics. *ASCE Jour.—Hydraulics Div.,* 107:9:1047 (1981).
12. Ormsbee, L.E. & Wood, D.J. Explicit Pipe Network Calibration. *Jour. ASCE—Water Resources Planning & Mgmt.,* 112:2:166 (1986).
13. Boulos, P. & Ormsbee, L. Explicit Network Calibration for Multiple Loading Conditions. *Civil Engrg. Systems,* 8:153 (1991).
14. Meredith, D.D. Use of Optimization in Calibrating Water Distribution Models. Proc. 1983 ASCE Spring Convention, Philadelphia.
15. Coulbeck, B. An Application of Hierarchial Optimization in Calibration of Large-scale Water Networks. *Optimal Control Applications and Methods,* 6:31 (1984).
16. Ormsbee, L.E. Implicit Pipe Network Calibration. *Jour. ASCE—Water Resources Planning & Mgmt.,* 115:2:243 (1989).
17. Lansey, K. & Basnet, C. Parameter Estimation for Water Distribution Networks. *Jour. ASCE—Water Resources Planning & Mgmt.,* 117:1:126 (1991).
18. Lingireddy, S. & Ormsbee, L.E. Hydraulic Network Calibration Using Genetic Optimization. (Unpubl.)
19. Basford, C. & Sevier, C. Automating the Maintenance of a Hydraulic Network Model Demand Database Utilizing GIS and Customer Billing Records. Proc. 1995 AWWA Computer Conf., Norfolk, Va.
20. Schulte, A.M. & Malm, A.P. Integrating Hydraulic Modeling and SCADA Systems for System Planning and Control. *Jour. AWWA,* 85:7:62 (1993).



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