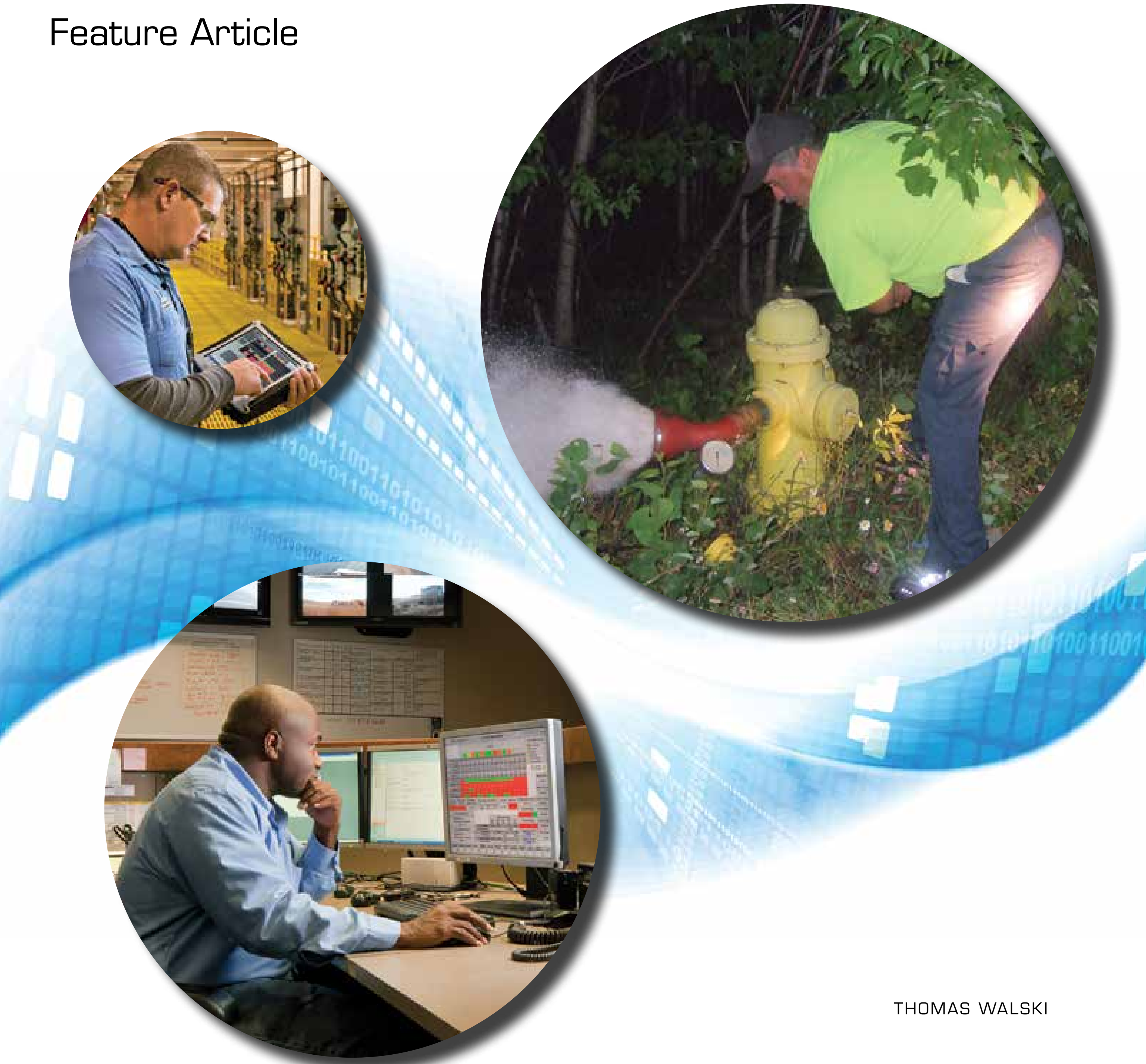
Feature Article



THOMAS WALSKI

Procedure for Hydraulic Model Calibration

CALIBRATING A MODEL CAN APPEAR TO BE A DAUNTING TASK, BUT BY USING AN ORGANIZED APPROACH, THE MODELER CAN MAKE THE RIGHT ADJUSTMENTS AND UNDERSTAND WHY.

Virtually every hydraulic water distribution model requires some level of calibration adjustment so that the model accurately represents the behavior of the real water system. The modeler is faced with an overwhelming number of potential adjustments to achieve good calibration. The procedure presented in this article provides a logical way to determine what parameters need adjustment so that modelers can calibrate their models without being trapped by compensation errors.

Layout imagery: Havey Productions, saicle/Shutterstock.com

BACKGROUND

Hydraulic models of water distribution systems are widely used to help solve engineering and operational problems. To ensure that a model accurately represents a real system, model results are compared with physical measurements over a range of conditions. If the model predictions agree with the data, the model can be used with confidence for the conditions it was calibrated to. Differences between a model and field observations could stem from poor field data that need to be corrected. Field data can include manual measurements, supervisory control and data acquisition (SCADA) system values, downloads from data loggers, and records from customer information systems. However, if the data are considered valid, the model inputs must be modified to minimize or at least understand any differences. This process has been discussed by the AWWA Model Calibration Subcommittee (2013a).

Most hydraulic models require some calibration for even basic uses, and numerous model adjustments are often required (Walski 1986). However, model developers and users must understand that adjusting the wrong parameters in order to achieve better model agreement results in compensating errors (Walski 1983). In addition, guidance in determining the source of model errors is scarce. Walski (1990) gives examples of some of the unusual reasons for models to require further calibration.

Since numerous adjustments can be made, the modeler is often faced with too many choices of what to adjust. Adjusting the wrong parameter in order to achieve agreement may align the model with the observed data, but it is really the result of compensating errors (Walski 1986). The number of possible adjustments often overwhelms the modeler.

There is extensive guidance in the literature on model calibration (Tomic 2015; AWWA 2012; Speight et al. 2010; Walski 2010, 1983; Hirrel 2008; Edwards, Cole & Brandt 2006; Walski et al. 2003; Ormsbee & Lingireddy 1997). A literature review by the AWWA Model Calibration Subcommittee (2013b) found over 200 papers published on the subject of calibration. While these papers all provide useful information, many of the solution methods include the hidden assumption that the modeler knows the source of error in the model. In reality, there are two steps in the model calibration process: (1) determining why the model is not in calibration and (2) making the necessary adjustments to reconcile the model with the system. The first step is by far the most difficult and important; however, it is the second step that receives the most attention in the literature.

A significant problem facing modelers during calibration is figuring out where to start, because the number of changes can be daunting. What a modeler would like to do is pick a manageable subset of parameters to adjust, verify them, and then move on to test another subset. This article provides an orderly approach for modelers to follow during the calibration process to avoid the kinds of errors already discussed, rather than trying to solve for all inputs at once, which is generally impossible.

A significant problem facing modelers during calibration is figuring out where to start, because the number of changes can be daunting.

THE PROCEDURE

A modeler should try to limit the number of parameters that are in question to each step of the procedure so that the source of any errors can be identified and corrected. An overview of the procedure illustrating the four overall steps is presented in the four photographs on page 57. The terms "macro calibration" and "micro calibration" (Ormsbee & Lingireddy 1997) have been used to describe this type of approach, but those terms are subject to interpretation. By precisely describing the type or data and nature of adjustments at each step, this procedure should reduce uncertainty.

The overall goal is to adjust the model outputs to better match valid field data within prescribed tolerance. However, at any stage in the procedure, inconsistent data should be challenged and discarded if there are doubts about data quality.

Even with valid field data, modelers need to understand data accuracy. If elevation can only be known to ±10 ft, it doesn't make sense to adjust a model for hydraulic grade line (HGL) values to agree within 5 ft. Some data are very helpful for model calibration (e.g., a hydrant flow test far from the source), but others provide minimal insights, such as pressure reading near an elevated tank where the water level is known (Walski 2000).

Steady-state normal flow conditions. During normal- and low-flow periods in most water distribution systems, the HGL is relatively flat because the system's low velocities result in small head losses. This means that the effects of pipe roughness, demands, and closed valves are small. In general, it is not recommended to start model calibration by adjusting pipe roughness. During normal flow conditions, the value of the HGL is primarily determined by water levels in tanks or by pump and/or pressure-reducing valve (PRV) discharge pressures in pressure zones where there are no tanks with water levels that float on the system.

In this case, the HGL should not vary much across the zone, and a

Step 1: Use data when the hydraulic grade line is relatively flat to identify errors and adjust pressure zone boundary valves, elevations, tank water levels, pressure-reducing valve settings, and other boundary conditions (left). Step 2: Conduct hydrant flow tests to provide increased velocity and head loss and make it easier to identify problems with roughness and demands (right). *Source: Thomas Walski*

model should match field data. If it does not, these are the most likely sources of error:

- Incorrect tank water level
- Incorrect PRV settings or reference elevation
- Interconnections between supposedly disconnected pressure zones
- Incorrect pressure zone boundaries
- Reporting the calculated HGL level based on model node level (usually ground level) when pressure sensors at located at a different elevation (e.g., hydrant outlet level)
- Incorrect pump status/speed
- Incorrect node elevations
- Demands when measurements were made are not the same as the demands loaded into the model

Comparisons between a model and field data should be made in terms of HGL values that can potentially be adjusted rather than pressure values. While both are related, HGL values can be compared at a glance unless the ground is completely level; pressures cannot be compared so easily. Parts A and B of Figure 1 show how HGL data can provide more insights than pressure data. Where the tank HGL is 650 ft, HGL values such as 645, 673, and 651 ft can be directly compared, and the 673 ft value stands out immediately as an error. With

Step 3: Match tank water level fluctuations to find errors in demand patterns (left). Step 4: Check pump controls using extended period simulation runs in which pumps are not forced to follow a time pattern (right). *Source: Thomas Walski*

pressure data, such a problem cannot be seen without first correcting for changes in elevation, which could be incorrect. Locations where incorrect pressure zone boundaries are suspected can be easy to detect with HGL measurements near the boundary. Attempting to adjust pipe roughness to compensate for incorrect boundary head leads to a poor model. A comparison of pump-discharge HGL is important but can only show if a single point on the pump curve—not the entire curve—is correct. The curve can be verified in a separate test.

> Comparisons between a model and field data should be made in terms of HGL values rather than pressure values.

Steady-state high flow conditions (system under stress). During normal flows when head loss is low, HGL comparisons cannot reveal problems that occur as a result of head loss between the boundary nodes and pressure measurement locations. During high flow conditions at peak demands, discrepancies that could not be detected when head loss was low become obvious. These are most likely sources of error:

- Closed valves
- Pipe roughness
- Demand locations
- Demand magnitude
- Network connectivity
- Pipe diameter

The key with tests in high flow regimes is to ensure that the head loss between the source and the measurement location is significantly greater than the error in head loss measurement. If the HGL can be reliably measured to within ±5 ft, the head loss should be on the order of 25 ft or more.

In large transmission mains, this can be accomplished by measuring head loss over long distances during peak demand times. For smaller mains, the velocity and head loss are usually too low; in these cases it is best to increase the velocity. This can be done by conducting fire hydrant flow tests. When hydrant flow tests are conducted, it is important to know the boundary heads/pressures (tanks levels, PRV settings, pump status/discharge pressure) at the time of the test. In following the recommended approach, modelers should try to reduce possible sources of error so those that are candidates for modification are manageable.

The usual sources of error under high flow conditions are closed valves, incorrect connectivity, wrong overall demands, or incorrect roughness. If the errors are somewhat uniformly distributed across a pressure zone, the errors are usually due to roughness or demands. Demands can be verified by determining the net flow into the pressure zone. The range of variation of roughness can be constrained by conducting C-factor tests on a range of different types of old pipes (C-factors are generally known for new pipes). If there are many old, unlined cast-iron pipes, the roughness adjustments are usually logical. In systems with mostly plastic or lined pipes, HGL is not very sensitive to roughness adjustments unless there are some unusual sources of roughness.

If discrepancies between measured and modeled HGL values only occur in a few locations and the model predicts HGL higher than measured, the primary source of error is usually closed valves. These can be identified by using multiple residual pressure gauges or data loggers during hydrant flow tests. Locations upstream of the closed valve will show a very low pressure drop during the test, while those downstream will show a significant, abrupt drop.

It is best to collect HGL data far from tanks and other known boundary heads (e.g., PRVs). Conducting a test near a tank provides information only about what is occurring between the tank and the measuring point and provides only minimal insight about what is occurring beyond that point.

Incorrect pipe diameters can also be identified at this stage, although these errors are not common. However, the data are usually not sufficiently precise to identify differences between nominal and actual pipe diameters.

Once the modeler has corrected the model and the field data through these first two steps, the modeler should feel confident that the model can be relied upon for most design problems where steady state analysis is sufficient.

Extended period simulation—known control status. Once a steady-state model is adequately calibrated, the next step is an extended period simulation (EPS). New parameters include temporal variation in demand and changes in the settings for pumps and valves. Comparisons at this step usually center on matching tank water level fluctuations in the model with data from the SCADA system.

There are two kinds of differences that surface during this step: (1) tank levels in the model moving in the wrong direction from the SCADA data and (2) tank levels moving in the correct direction at the wrong slope. The first difference is usually due to problems with pump controls, while the second is due to inaccurate diurnal demand patterns. These two problems should be separated and solved one at a time.

Initially, the uncertainty in pump and controls can be removed from the problem by using time-based controls. With this source of uncertainty removed, the modeler can focus on the demand patterns. At this stage, flow metering data are much more useful than pressure data. If flow meters are available at the district metering-area level, they can guide any adjustments.

Poor model agreement can be caused by differences between the demands loaded in the model (usually average day) and demands from the day on which calibration data were collected, which may have been unusually hot or dry. There may have been a special event that day; e.g., the local university may have gone on break. Using the daily production to scale demands up or down usually accounts for this, although an event such as a large fire may need to be placed at a specific location.

Using time-based controls at this stage enables the identification of cases in which system operators have overridden the rule-based pump control at the time that data were collected. A potential problem in using time-based controls is the length of the polling intervals in some SCADA systems. For example, if a system has a 15-min polling interval, and the pump is off at 8:00 a.m. and on at 8:15 a.m., there may not be a way to determine if it was turned on at 8:01 a.m. or 8:14 a.m. or anywhere in between. An inflection in the tank level data may be helpful in determining the exact time.

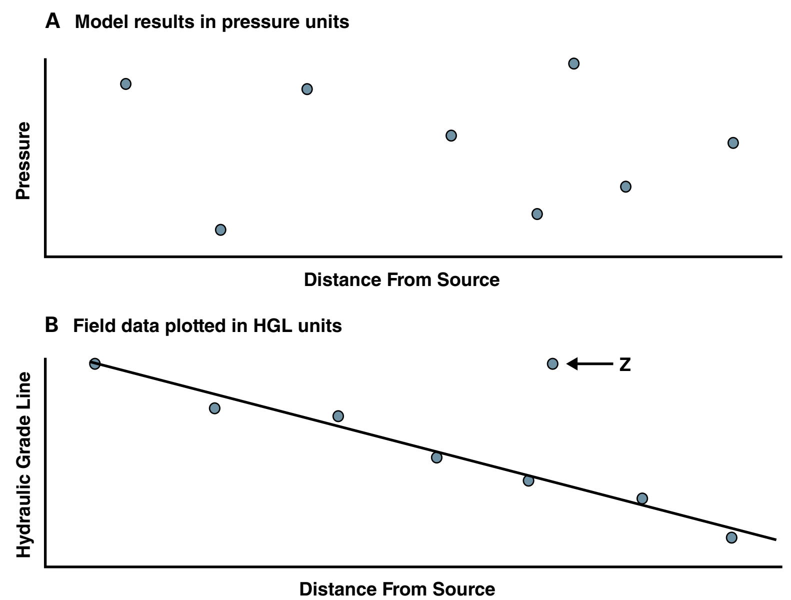
Another consideration in using SCADA data is the need to understand what a value actually represents. For example, a flow or pressure reading may have the SCADA time stamp 10:42, but that value may be the instantaneous value at 10:42 or the average, minimum, or maximum value between 10:42 and the previous polling time. Another source of error that can be identified at this time is incorrect tank dimensions, but this is seldom a problem in most models.

Models with time-based controls can be used only for the specific day (or period) for which it was calibrated. Extrapolating the model beyond that period is not reliable. Even if there isn't a special event, there are always fluctuations in water use from one day to the next, and demands for the "average day" that were loaded into the model almost never occur exactly.

The increased adoption of "live modeling" makes it possible to quickly and frequently compare model results with the current day or any day in the SCADA historian. EPS calibration is also being changed by the ability to use automated meter reading and advanced metering infrastructure to understand individual customer water use at a much more granular level as a basis for developing demand patterns. However, leakage and other nonmetered usage values are usually elusive. To deal with these variations, hydraulic models usually contain rule-based control statements.

Comparing variations in water level, flow, or pressures over time can often lead to poor initial calibration because rule-based controls are frequently overridden by operators. Nevertheless, graphs of these properties showing field and model results should be reasonably close. Otherwise, the rule-based controls should be adjusted, or the operators should provide some explanation for the deviations. Good communication with the operators will greatly support these efforts.

FIGURE 1 Comparison of pressure and HGL data



HGL—hydraulic grade line

A: Displaying model results in pressure units does not provide a way to determine whether values are consistent, as illustrated, because they do not account for the elevation of the pressure measurement.

B: Plotting field data in HGL units makes it easy to identify inconsistent data such as point Z, as illustrated.

> The key with tests in high flow regimes is to ensure that the head loss between the source and the measurement location is significantly greater than the error in head loss measurement.

Extended period simulation—varying control status. While using time-based controls to simulate a specific day may be adequate to check demand patterns, the model must be used for days that differ from the day for which calibration data were collected.

There are two kinds of errors that show up at this stage, namely time shift errors and magnitude errors. Time shift errors involve the model and field data showing similar patterns, but the times vary, creating a shift.

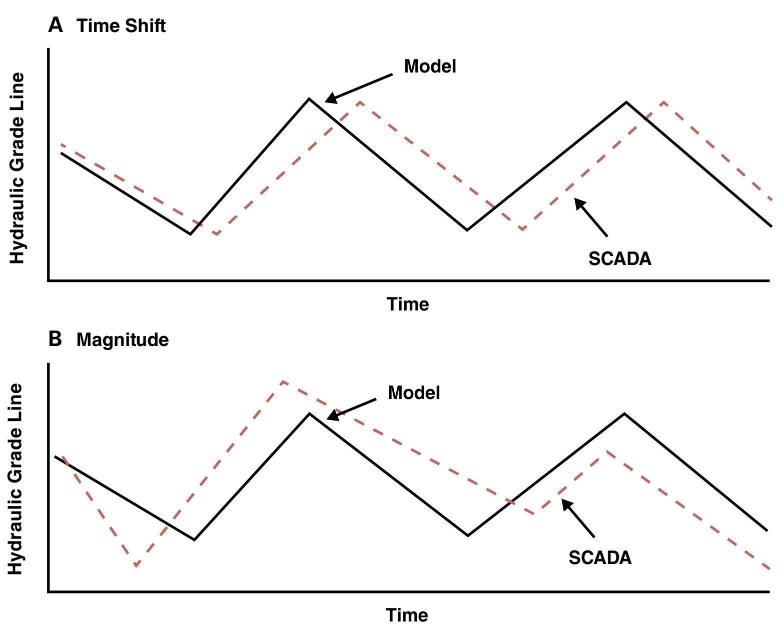
Magnitude errors manifest as different values for properties, even after allowing for time shift. Figure 2, parts A and B, shows these types of discrepancies. Time shift errors are usually due to small errors in demand patterns and control settings. These are difficult to solve but have minimal effect on the usefulness of the model. Magnitude errors are more serious. The modeler needs to determine whether they are simply due to operators not following the control rules or if they are revealing some problem with the data or model that should have been caught earlier.

CALIBRATION FOR OTHER PURPOSES

This article only addresses calibration for system hydraulics. Models are often used for other purposes such as water quality analysis or energy use and cost. Before starting either of those types of analyses, it is necessary to have a well-calibrated EPS model. If water quality or energy results from the model do not match field observations, it can be very difficult to determine the necessary adjustments.

These models can provide information and insights that can help the hydraulic calibration. For example, water quality studies can provide disinfectant decay information or the results of a tracer study that can reveal closed valves or incorrect pipe sizes. Energy use data can demonstrate where pumps are not working on their curves or where rule-based controls are not being followed. In some instances, the results of a water quality or energy calibration exercise may reveal shortcomings in the hydraulic model that will need to be corrected.

FIGURE 2 Comparison of model and SCADA data



SCADA—supervisory control and data acquisition

A: Time shifts in tank water level compared through model and SCADA data are often due to small errors in diurnal demand multipliers.

B: Discrepancies between model and SCADA data that are more than time shift are often due to the rule-based controls in the model not matching operator decisions.

VERIFICATION AND VALIDATION

Once a model has been calibrated, it is recommended that it be verified by making comparisons with field data from a period not used during model calibration. In cases in which the agreement is poor, it is necessary to understand why this occurred and recalibrate that aspect of the model so that it is accurate for both periods.

Some time may pass between the period for which the model was calibrated and when it is applied to solve a problem or prepare a design or master plan. Before using the model, some checks should be made to ensure that the model still reflects the actual system conditions. For example, for a new land development in a specific part of the system, it is advisable to conduct a hydrant flow test at the connection point to check the model's accuracy because calibration data may not have been collected in this specific area.

A related issue is whether a model should be adjusted to match incorrect operational conditions. For example, a model may contain the intended PRV setting or valve status, but in the field, the PRV may have been incorrectly set or a valve incorrectly closed. In these cases, the modeler and operators need to resolve these discrepancies, usually by changing the field conditions.

ACCEPTANCE OF THE MODEL

One of the most common questions that is asked about model calibration after "Where do I start?" is "When are we done?" The answer, unfortunately, is "Never." Water systems are dynamic; new facilities are added, and operating procedures change constantly. Nevertheless, modelers want to know when they can begin using a newly built or recently upgraded model, and this involves setting some system-specific goals for calibration.

There is not a definitive yes/no answer to whether a model is calibrated. Instead, there is a continuum from a perfectly calibrated model to a completely uncalibrated model. All models lie somewhere along that spectrum. The fundamental principle is that model calibration is satisfactory when the cost for additional calibration exceeds the benefits that would accrue (Walski 2015). Of course, it's difficult to quantify this criterion for any individual model. It's even more difficult to develop universal standards.

The acceptability of the model depends on whether it fulfills its purpose in serving as a decision support tool. When there are uncertainties with a model, sensitivity analysis can be conducted to determine whether variations in uncertain model parameters greatly affect the decisions being made. For example, if there is uncertainty in pipe roughness, several different values can be tried, and the engineer can determine the level of confidence in pipe-related decisions.

There are two separate roles in evaluating a model: the modeler who constructed and calibrated the model and the decision-maker (engineer or operator) who will rely on the model to support decisions. Usually, the decision-maker will ask the modeler, "Is the model calibrated?" when it should be the modeler who, after showing the results of calibration to the decision-maker, asks, "Is the model calibrated well enough for your purpose?"

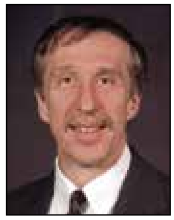
SUMMARY

Most hydraulic models do not adequately agree with field data when they are first developed or upgraded. The model must be calibrated by identifying why the agreement isn't better and making the proper adjustments to achieve agreement. Faced with myriad reasons for discrepancies between a model and field data, modelers can use the procedure described here to systematically make adjustments. Limiting the available adjustments at each step should make it easier to identify the source of any discrepancies and correct the model to use.

ACKNOWLEDGMENT

Sasa Tomic of HDR Inc. and the AWWA Model Calibration Subcommittee provided helpful comments on the initial draft of this article.

ABOUT THE AUTHOR



Thomas Walski *is a senior product manager/Bentley Fellow at Bentley Systems, 3 Brians Pl., Nanticoke, PA 18634 USA; tom.walski@bentley.com. He has 40 years of experience in applied analysis of water distribution systems and has developed a variety of tools and procedures for such work. Walski has prepared several hundred journal and conference papers and has served on numerous AWWA committees including the Model Calibration Subcommittee, which was the motivation for this article. Hydraulic model calibration is his favorite topic. He has learned many lessons over the course of his career, which he is pleased to share with other professionals. Walski is a past winner of the* Journal AWWA *award for the best distribution and plant operation article and has seven patents for hydraulic analysis methods.*

https://doi.org/10.5942/jawwa.2017.109.0075

REFERENCES

AWWA, 2012 (3rd ed.). *Computer Modeling of Water Distribution Systems.* AWWA, Denver.

AWWA Model Calibration Subcommittee, 2013a. Committee Report: Defining Model Calibration. *Journal AWWA*, 105:7:60. https://doi.org/10.5942/jawwa.2013.105.0101.

AWWA Model Calibration Subcommittee, 2013b. Hydraulic Model Calibration: What Don't We Know? 2013 AWWA Water Infrastructure Conference, Itasca, Ill.

Edwards, J.; Cole, S.; & Brandt, M., 2006. Quantitative Results of EPS Model Calibration With a Comparison to Industry Guidelines. *Journal AWWA*, 98:11:72.

Hirrel, T.D., 2008. How Not to Calibrate a Hydraulic Network Model. *Journal AWWA*, 100:8:70.

Ormsbee, L. & Lingireddy, S., 1997. Calibrating Hydraulic Network Models. *Journal AWWA*, 89:2:42.

Speight, V.; Khanal, N.; Savic, D.; Kapelan, Z.; Jonkergouw, P.; & Agbodo, M., 2010. *Guidelines for Developing, Calibrating and Using Hydraulic Models*. Water Research Foundation, Denver. www.waterrf.org/ExecutiveSummaryLibrary/4018_ExecutiveSummary.pdf (accessed Mar. 13, 2017).

Tomic, S., 2015. Steady State Model Calibration. 2015 AWWA Water Infrastructure Conference, Bethesda, Md.

Walski, T.M., 2015. Calibration Basics. 2015 AWWA Water Infrastructure Conference, Bethesda, Md.

Walski, T.M., 2010. Practical Tips on Work Flows for Modeling. 2010 AWWA Distribution System Symposium, Bethesda, Md.

Walski, T.M., 2000. Model Calibration Data: The Good, the Bad and the Useless. *Journal AWWA*, 92:1:94.

Walski, T.M., 1990. Sherlock Homes Meets Hardy Cross, or Model Calibration in Austin, Texas. *Journal AWWA*, 82:3:34.

Walski, T.M., 1986. Case Study: Pipe Network Model Calibration Issues. *Journal of Water Resources Planning and Management*, 112:2:238. https://doi.org/10.1061/(ASCE)0733-9496(1986)112:2(238)#sthash.CKiNlzdX.dpuf.

Walski, T.M., 1983. Technique for Calibrating Network Models. *Journal of Water Resources Planning and Management*, 109:4:360. https://doi.org/10.1061/(ASCE)0733-9496(1983)109:4(360).

Walski, T.M.; Chase, D.; Dragan, S.; Grayman, W.; Beckwith, S.; & Koelle, E., 2003. *Advanced Water Distribution Modeling nd Management*. Bentley Systems, Exton, Pa.

AWWA RESOURCES

- Hydraulic Transient Modeling: The Importance of Calibration, Yang, A., 2016. *Journal* AWWA, 108:7:56. Product No. JAW_0083785.
- Hydraulic Model Improves Contamination Response. Specht, D., 2013. *Opflow,* 39:5:16. Product No. OPF_0078148.

These resources have been supplied by *Journal AWWA* staff. For information on these and other AWWA resources, visit www.awwa.org.