Field Verification of Water Quality Models: Process, Results & Benefits

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Potable water utilities maintain and utilize hydraulic/water quality models to help efficiently plan, operate, and expand their potable water systems. To maximize benefits of the water quality model that include minimizing water age compliance with distribution water quality regulations, utilities can field verify water quality models.

Field verification or calibration is also recommended in the U.S. Environmental Protection Agency's (EPA's) Initial Distribution System Evaluation (IDSE) guidelines for using a water quality model to comply with IDSE mandates.

This article describes the process, results, and benefits of actual field verification experience for major potable water utilities. The detailed process presented maximizes utilization of state-of-the-art supervisory control and data acquisition (SCADA) to minimize field data collection efforts and can benefit other utilities that are considering water quality model field verification. Results of the field verification effort are presented to help other engineers, modelers and managers streamline the process, avoid potential pitfalls and communicate expectations of potential results to utility decision makers.

The benefits of actual water quality model field verification efforts are significant, including understanding the impacts on distribution water quality of different source water quality, disinfectant procedures, storage and pumping operational protocols, pipe diameter- material-roughness effects on disinfectant decay, and most importantly, truthing theoretical models to field conditions.

Verification Procedure

A water quality model verification procedure was developed and applied that included protocol development, team coordination, field data collection, bulk water testing, hydraulic verification and water quality verification. The water quality verification protocol included summarized field data collection requirements and procedures, a recommended schedule for remote pressure recorder data collection, identified and scheduled sampling events to measure free residual chlorine, identified labor requirements, and provided quality assurance/quality control (QA/QC) procedures.

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The level of verification was consistent with recommendations in the EPA's IDSE Guidance Manual and American Water Works Association verification guidelines.

Water quality model verification should simulate water distribution system operation for at least a typical two-day operational sequence. The verification should include adjustment of the hydraulic model to simulate pump operations, tank levels, and system pressure and demands with an accuracy of plus or minus 10 percent. The verification effort included development and incorporation into the hydraulic model of actual high service pump curves, tank operations (fill/draw) and high service pump operations for a typical 48-hour period.

Utilities SCADA systems should be used to the fullest extent possible to increase the accuracy and efficiency of verification. The verification methodology was used on a large potable water system and results are discussed herein.

Data Collection Procedure

The collection of the data required for calibrating the model should be a joint effort among engineering, modeling, operations, water quality, and distribution staffs. Verification data collection includes collected SCADA information such as treatment plant pressure and flow data, as well as additional field water quality and remote, mobile pressure measurements throughout the distribution system.

Coordination between the treatment plant operators and the field personnel is required to ensure the system is operated consistent with normal protocols and that standard customer service levels are maintained. The verification data collection procedure is listed as follows:

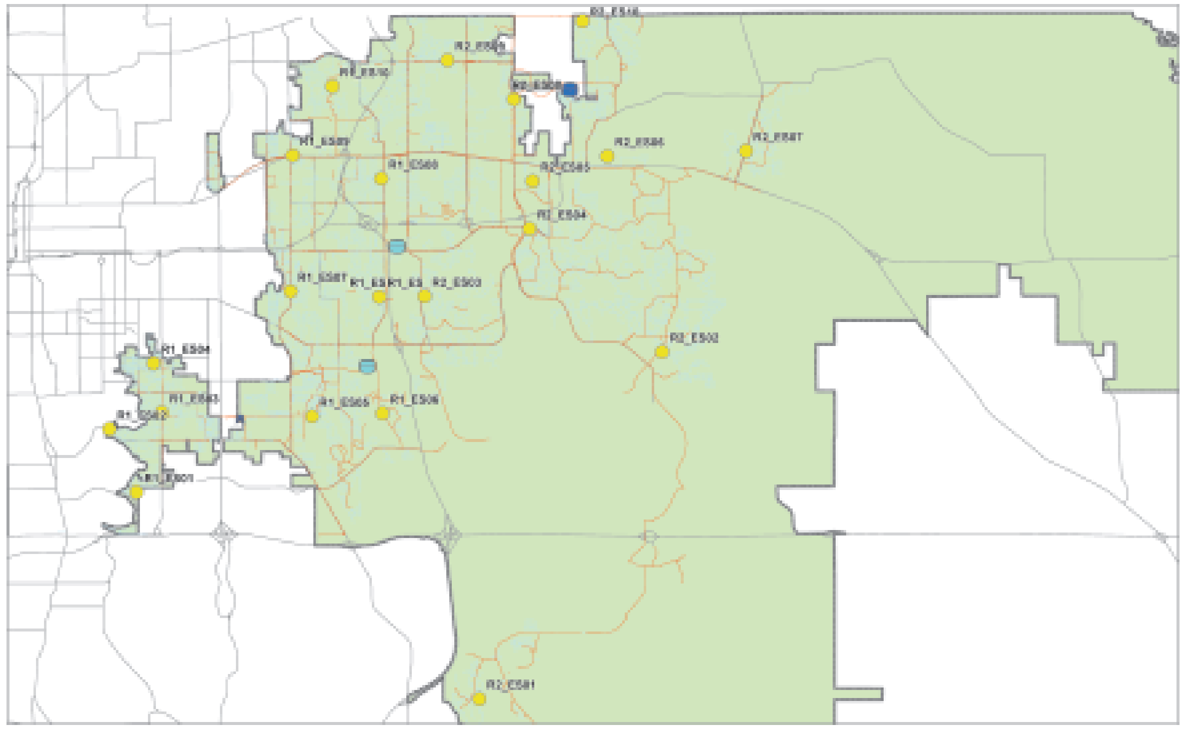

Figure 1: Example Pressure and Water Quality Sampling Locations

<u>All Personnel</u>

1. Review verification memo and provide input.
2. Notify all affected staff of verification.

<u>Pressure Recorders</u>

1. Acquire remote pressure recorders.
2. Test several pressure recorders to determine if calibration is necessary.
3. Execute verification:
   a. Locate pressure recorders at recommended locations, note exact location.
   b. Collect pressure recorder data, move pressure recorders to next location set.
   c. Transmit data to modelers.
   d. Repeat Steps 5a, 5b, and 5c as necessary (three planned moves).
   e. Transmit all collected data to modelers.

<u>Operations/SCADA</u>

1. Confirm calibration of permanent WSF flow meters and pressure recorders.
2. Execute verification:
   a. Collect two to three flow and pressure readings for each high-service pump from SCADA.
   b. Collect SCADA data (one-minute intervals) for each one-week test duration:
      i. Treatment plant flows and pressures
      ii. Treatment plant finished water tank elevations
      iii. Remote/elevated tank elevations
      iv. Booster pump status, flow and in/out pressures
      v. High-service pump status
   c. Collect operator log books for entire test duration documenting manual adjustments.
   d. Transmit all collected data to modelers.

<u>Free Residual Chlorine</u>

1. Meet with water quality staff to coordinate on free chlorine residual analysis protocols.
2. Survey free residual chlorine sample sites for adequacy.
3. Execute verification:
   a. Calibrate instrument and run standards daily, keeping a logbook of verification records per FDEP Quality Manual for Field Activities.
   b. Use the low-range Hach free residual chlorine reagent (0-2 mg/L) for all samples, diluting when necessary.
   c. Run one chlorine standard (pre-prepared by utility staff) before sampling begins to verify instrument calibration.
   d. Run one Hach chlorine gel standard at the beginning of each daily sampling event, verifying that the gel standard is within 10 percent of previously recorded values.
   e. Run a blank using the collected sample for each sampling event.
   f. Run the same Hach chlorine gel standard measured at the beginning of a daily sampling event at the completion of that sampling event, verifying that the standard remains within 10 percent of previously recorded values.
4. Field water quality samplers compile and analyze all collected free residual chlorine data.

Distribution system pressure and water quality sampling should be performed at the same locations. An example system data collection grid is shown in Figure 1. Coordination with field water quality samplers and distribution operations staff to ensure locations are feasible, accessible and valid.

Field Data Collection

The collection of the data required for calibrating the model was a joint effort between utilities and consulting staffs. Distribution staff located and collected data from the portable hydrant pressure recorders. Production staff collected SCADA data and performed the high-service pump calibration while maintaining customer service levels. Water quality staff worked closely with the consulting field chlorine residual samplers and performed the bulk chlorine decay testing. The field data collected included:

1. 20 pressure recorders reading one-minute pressure data in three sets of locations.
2. 60 chlorine residual sampling sites that were sampled twice per day on weekdays.
3. SCADA data including flow meters, high-service pump discharge pressures, high-service pump on/off status, tank levels, WSF point of entry chlorine residuals, and remote chlorine residual monitoring loca-

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tions.

4. High-service pump calibration flow, pressure and tank level info from SCADA.

The field pressure recorders indicated pressures ranging from 40 to 80 psi for the week, as shown in Figure 2. The remote chlorine residual sampling resulted in chlorine concentrations ranging from 0.3 to 2 mg/L free chlorine, as shown in Figure 3. SCADA data, including WSF and remote tank/booster station flow, pressure, tank levels, water quality data, and pump status, were collected by operations staff.

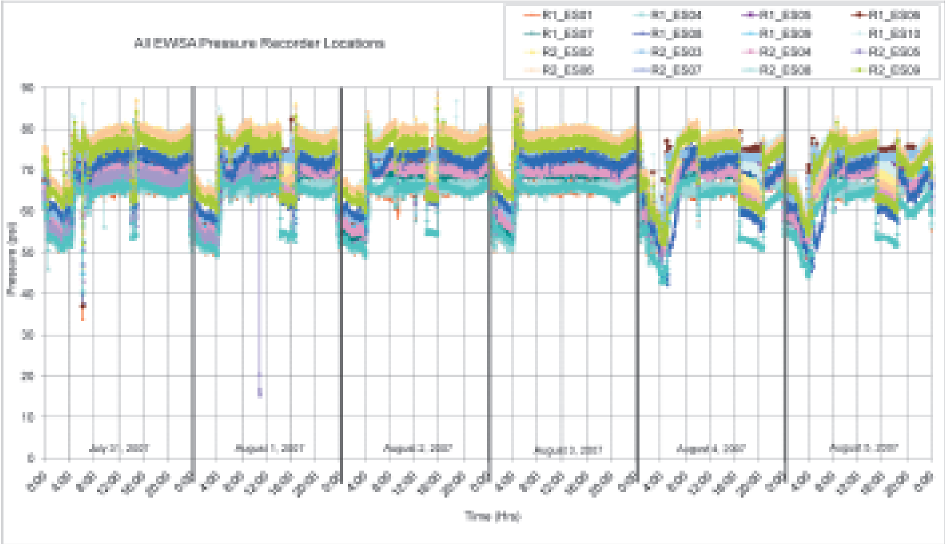

Figure 2: Example Field Pressure Monitoring Results

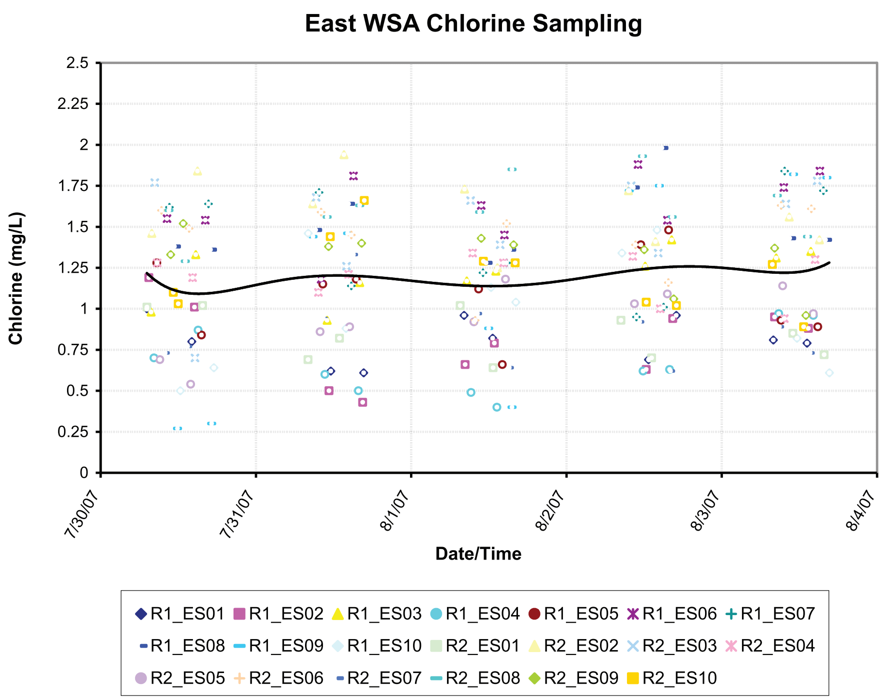

Figure 3: Example Field Chlorine Sampling Results

Hydraulic Model Verification Procedure

`Flow and pressure readings at the treatment plants, pressure (tank level) readings at the elevated tanks, water quality data, and all operator or automated adjusted settings recorded during the verification effort should be collected and summarized. High-service pump flow and pressure information is obtained via the SCADA system or manual measurements to confirm pump curve inputs. Associated piping data should also be checked in the event a discrepancy exists.

Pump operating characteristics, piping sizes, and other system information should be checked for accuracy. Key utility personnel should be interviewed for any knowledge of special conditions such as pressure control valving or other hydraulic appurtenances.

Diurnal demand factors during the verification period are estimated from SCADA flow and tank level data collected. If a distinct difference exists for service areas or diurnal demand patterns on irrigation and non-irrigation days, separate diurnal variation curves for each area/day should be developed based on the collected water production.

The diurnal potable demands for each service area's irrigation and residential non-irrigation days can be determined by summing the water supply facilities production, subtracting or adding remote tank contributions, then dividing the sum by the annual average water demand contained in the "existing" model scenario. Similar data taken from an average water usage period can be used to create more representative average diurnal potable demand patterns.

Following input of diurnal demand patterns, pump status, initial tank levels, and adjusted high service pump curves, the hydraulic model are run on at least a 48-hour extended period simulation (non-irrigation day, then irrigation day). Hydraulic model output is then compared to summarized field data.

Following pump and pipe characteristics confirmation, hydraulic model inputs are adjusted as necessary. Large discrepancies should be discussed with utility staff. Hydraulic model results within 10 percent of the field measurements would be considered acceptable.

Bulk Decay/Formation Coefficient

Bulk decay or formation can be simulated in water quality models. This effort is focused on chlorine decay. Bulk chlorine decay coefficients depend on the nature of the source water, the treatment it has received (amount and type of organic material in the source water), and temperature. Bulk decay coefficients can be determined by running a bottle test on the water entering the distribution system.

Of note is the fact that only one value for chlorine bulk decay is allowed to be entered in the InfoWater Water Quality Calibrator (WQ Calibrator) for each modeled service area; therefore, the WQ Calibrator should be run separately for groups of service areas with similar bulk chlorine decay coefficients.

This limitation is associated only with the WQ Calibrator; normal water quality modeling can be run with a different bulk decay coefficient in each pipe. For manually input pipe wall coefficient scenarios, a source trace can be performed on each pipe and contribution-weighted each bulk decay coefficient assigned based on the percentage of source contribution.

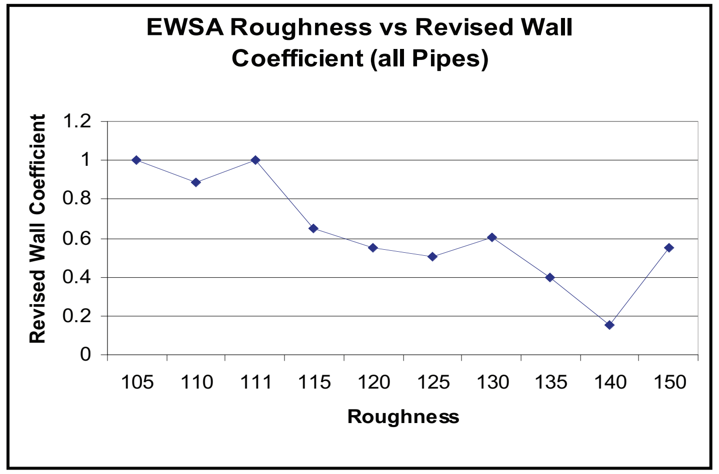

Figure 4: Roughness vs. Wall Coefficient

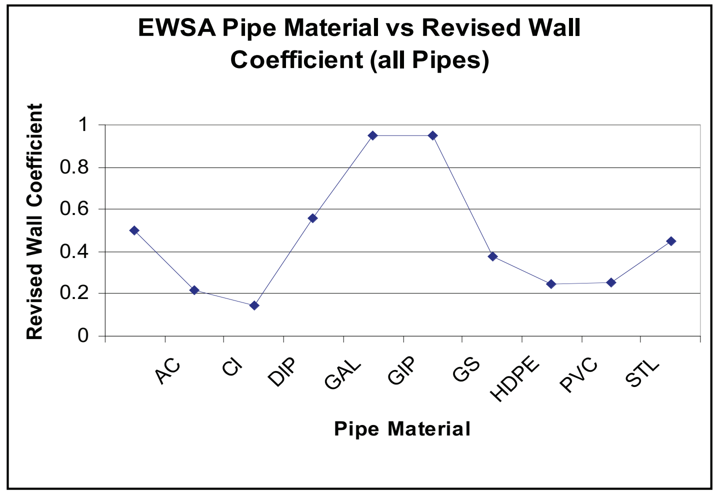

Figure 5: Pipe Material vs. Wall Coefficient

The WQ Calibrator models reactions occurring in the bulk flow with nth order kinetics, where the instantaneous rate of reaction is assumed to be concentration dependent, according to the following equation:

$$R = K_bCn$$

Where:
R = instantaneous rate of reaction (mass/volume/time)
K_b = bulk reaction rate coefficient
C = reactant concentration
n = nth order kinetics

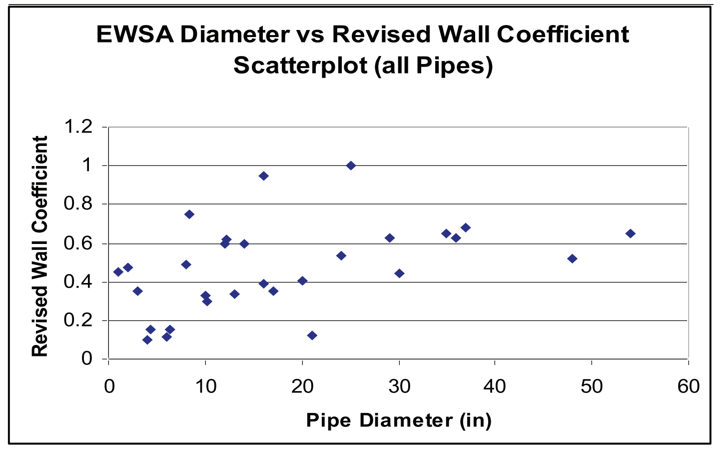

Figure 6: Pipe Diameter vs. Wall Coefficient

The decay of free residual chlorine because of reaction occurring in the bulk water is generally assumed in the literature (Munvalli and Kumar, 2006; AWWA, 2005; Haestad, et al., 2001) to be a first order reaction (i.e. n = 1).

Pipe Wall Chlorine Decay

Pipes in this verification effort were disaggregated into categories based on pipe diameter and roughness, then entered into the hydraulic model WQ Calibrator. Various sources in the literature (Munvalli and Kumar, 2006; AWWA, 2005; Haestad, et al., 2001) indicate that pipe diameter and pipe material are the categories most likely to impact wall coefficient values in a calibration process.

For this case, roughness was utilized as a factor instead of pipe material, since the pipe database had more robust information relating to roughness, as opposed to pipe material. In displaying pipe wall chlorine decay coefficient verification results, three methods were used and plotted for each sampling location, as follows:

1. Global
2. Calibrator
3. Revised Calibrator

The "Global" method assumes one constant value for the pipe wall chlorine decay coefficient for every pipe in the system, regardless of pipe diameter and roughness. The estimated global coefficient results were used as a control, and compared to the WQ Calibrator results. The global pipe wall chlorine decay coefficient value was determined through a trial and error approach, and is unique for each service area.

The "Calibrator" method disaggregates all pipes within a service area based on pipe diameter and roughness, and inputs the field data collected from all 20 sampling locations into the WQ Calibrator. The "Revised Calibrator" method also disaggregates all pipes within a service area based on pipe diameter and roughness, but inputs the field data only from selected high confidence sampling locations into the WQ Calibrator. Sampling locations near areas with non-realistic water demand allocations, or sample locations on pipe diameters less than 12 inches were removed from consideration under the "Revised Calibrator" assumption.

Wall reaction rate coefficients were assumed to vary between 0 and 1.0 foot per day (ft/day), as is typical of most distribution systems. Note that wall reaction rate units for model input are in ft/day; the model internally converts inside the calculation to day^{-1} units. It is possible to see higher wall reaction rate coefficients (as high as 5.0 ft/day), but these values are more typical in older distribution systems.

To verify this assumption, WQ Calibrator runs were allowed to vary the wall coefficient values from 0 to 5.0 ft/day, but didn't result in superior calibration to that achieved by constraining the wall coefficient values to between 0 and 1.0 ft/day for the example distribution system.

In order to determine the primary factors that influence pipe wall chlorine decay coefficients, the WQ Calibrator results were compared with other factors such as roughness, diameter, pipe material, pipe velocity and water age to identify possible correlations. Figures 4, 5, and 6 represent wall coefficient values determined under the "Revised Calibrator" assumption plotted against pipe roughness, pipe material, and pipe diameter, respectively.

Figure 4 shows a clear relationship between pipe roughness and wall coefficient values. As the pipe wall roughness increases (as indicated by a decreasing roughness value), the wall coefficient value determined by the WQ Calibrator increases. This result is consistent with the literature.

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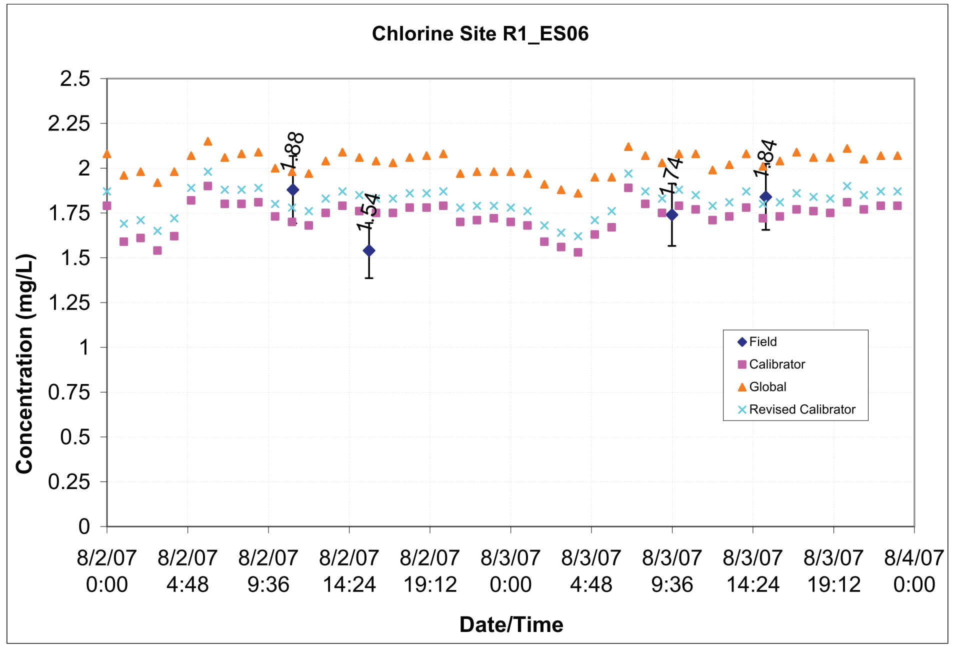

Figure 7: Example of WQ Calibrator Model Results

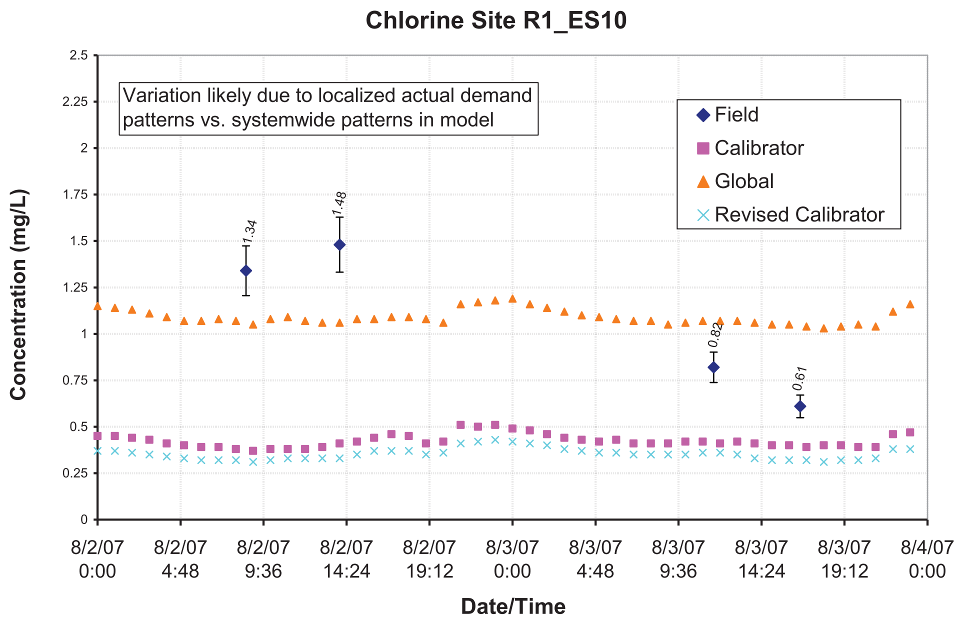

Figure 8: Example Water Quality Model Results

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Figure 7 is an example of WQ Calibrator Model results for a specific location in the east service area. The dark blue dots in the figure represent field measurements of chlorine concentrations at a specific location. The yellow, pink, and light-blue series of markings in the figure represent modeled results for the "Global", "Calibrator", and "Revised Calibrator" assumptions for the same location using the WQ Calibrator.

In the case of the specific location specified in Figure 7, modeled results are consistent with field measurements, but Figure 8 presents a sample location with lesser agreement between modeled results and measured field data. In this case, it was deduced that greater than modeled diurnal and day-to-day demand variations produced an average result in the model, with the field data indicating greater chlorine residual variations.

Water Quality Verification

Following hydraulic verification, bulk chlorine decay factors and point-of-entry WSF chlorine residuals are entered and the model is run as a water quality simulation for an extended period of 200 to 400 hours to stabilize remote tank water ages. This process can be a repetition of the 48-hour irrigation, non-irrigation day sequence developed in the hydraulic verification. Water quality model output (chlorine residual) is then compared to summarized field data for several different pipe wall decay coefficients, including using the WQ Calibrator extension.

The WQ Calibrator, developed by MWH Soft Inc. for use with H2ONET/InfoWater modeling software package, minimizes the difference between site-specific field measurements of residual disinfectant concentrations and model concentration predictions for any continuous dynamic simulation (EPS).

The WQ Calibrator divides disinfectant residual decay into bulk decay and wall coefficient disinfectant decay components. Also, water quality of the point of entry in each water service area must also be entered into the model in order to specify the model's initial conditions.

The essence of the water quality calibration process is to adjust wall disinfectant decay coefficient values assigned to each pipe in the model based on field-measured disinfectant residual concentrations in the system.

Before the development of software capable of calibrating water quality models using genetic algorithms and global search control strategies, water quality modelers used a time-consuming, trial-and-error approach to attempt to reconcile measured field data in the distribution system with model results. This trial-and-error approach involved adjusting wall decay coefficients based on engineering judgment until satisfactory results were obtained.

Since there are a vast number of possible wall decay coefficient combinations that could be considered, especially for large distribution systems, a trial-and-error evaluation of all possible wall coefficient values is not practically feasible, resulting in less-accurate calibration. The WQ Calibrator therefore should be used to help determine the primary factors that influence pipe wall chlorine decay and select the best fit set of coefficients for the verified model.

The network model can be disaggregated into various logical groupings (such as diameter, roughness, pipe material) and interfaced with H2ONET/Infowater to evaluate the fitness under various demand and operating conditions. Pipes can be disaggregated into categories based on pipe diameter and roughness, and entered into the WQ Calibrator. Various sources in the literature indicate that pipe diameter and pipe material are the categories most likely to impact wall coefficient values in a calibration process.

Verification Results

The water quality verification methodology presented in this article was performed for a large potable water transmission system. Key results of the water quality verification, including adjustments to the model are discussed in this section:

Water Quality Model Adjustments

Based on the field data collected and the bulk/pipe wall chlorine decay coefficient determinations, the water quality model was run and results compared. Based on a comparison of the results, the following hydraulic and water quality adjustments were made to the model:

1. *Demand Patterns and Adjustments* – Data queries for service area demand data sets were created to apply a separate diurnal pattern to each service area. Patterns were calculated as a ratio of the "existing" average daily flow to preclude further adjustments.
2. *Source Traces* – Source traces were performed for each WSF to calculate a unique source-weighted bulk chorine decay coefficients for each pipe in the system based on the percent source contribution and the source bulk decay coefficient. Initial chlorine levels were input for each WSF based on SCADA data. Pipe wall decay coefficient groups were created to determine significant variables that influence coefficient values.
3. *Elevation Baseline* – The junctions in the hydraulic model represent approximate pipe centerline elevations, which in the case of buried mains is four to six feet or more below grade. The pressure data for this effort was collected at hydrant level or approximately two to three feet above grade, so field-to-model comparisons required a post processing of field pressure to adjust for the elevation baseline in the hydraulic model.
4. *Specific Elevations* – Based on a review of specific pressure recording site elevations, sampling location model elevations were adjusted to one-foot contour elevation map.
5. *High Service Pump Curves* – The pump curves were adjusted as needed to the high head, design head, shutoff head, high flow, and design flow. Each fixed-speed pump was given a 48-hour pattern controlling, whether it was in operation or shutdown for a given hour. Each pump at every plant and re-pump facility was given its own pattern.
6. *High Service Pump Controls* – Each fixed-speed pump was given a 48 hour pattern controlling, whether it was in operation or shutdown for a given hour based on the actual operating status SCADA output. Variable-speed pumps were given a pattern based on a system analysis using the variable speed drive tool in the hydraulic modeling software.
7. *Tank Max and Min Levels* – Tank maximum and minimum levels were adjusted based on actual observed levels in the SCADA data.
8. *Tank Initial Levels* – Initial tank levels were adjusted to match levels observed at the start of the selected two-day verification period.
9. *Fill Valve Settings* – Each remote storage tank fill valve was given a 48-hour pattern based on system pressures and time periods of filling tanks.
10. *Point of Entry Chlorine Residual* – An hourly average chlorine concentration pattern was developed based on SCADA information and input into each WSF supply reservoir to simulate chlorine injection into the water system.
11. *Pipe Wall Chlorine Decay Coefficients* – Pipe wall chlorine decay coefficients were adjusted using a global best fit analysis first, then using the water quality calibration tool in the Model to better predict an optimal set of pipe wall coefficients.
12. *C Factor Adjustments* – C factor adjustments were attempted on a global level but did not significantly improve calibration results; therefore, no global C factor adjustments were performed. There were some isolated C factor adjustments made in the Conway area to improve Conway elevated tank filling and drawing performance.
13. *Bulk Decay Coefficients* – Chlorine bulk decay rates were determined by taking a source-weighted average of bulk decay coefficients from each contribution source for each pipe. For example, a pipe with a

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50 percent contribution from WSF1 and 50 percent from WSF2 received a bulk decay coefficient equally averaged between the two source bulk decay coefficients.

14. *Bulk Decay Coefficients Adjustment* – Adjusted bulk chlorine decay rates slightly versus the bottle test based on Model results and field chlorine SCADA data.
15. *Pipe Wall Decay Coefficients* – Adjusted pipe wall decay coefficients according to pipe roughness correlation and best fit with field data.
16. *Remote and Elevated Tank (bulk+wall) Reaction Rates* – These were calculated based on SCADA chlorine residual data for those sites.
17. *WSF Discharge Pressure Elevations* – WSF discharge pressure elevation was adjusted to match actual elevations and field data.
18. *Demand Allocations* – These were adjusted in obvious dead-end areas with no allocation.

Field checked disagreement locations and located two closed valves.

Benefits

The addition of verified water quality capabilities in the hydraulic model can provide significant benefits to utility engineering, modeling, water quality, distribution, and production staff. With water quality modeling capability, utility staffs will have detailed distribution pipe data in the hydraulic-water quality model, allowing accurate evaluation and troubleshooting of distribution systems and GIS data verification. The verification process and end result can provide the following specific benefits to potable water utility staffs:

- Help meet mission statement to provide highest quality water to customer tap.
- Improve accuracy and usefulness of hydraulic model.
- Improve accuracy and application of water quality model.
- Help understand differences in source water bulk decay/formation characteristics.
- Optimize water age and chlorine residual in a distribution system.
- Optimize capital projects size and routing.
- Optimize pressure at the customer's tap.
- Enable distribution water quality troubleshooting.
- Evaluate impact of future alternative water supplies.
- Utilize for emergency pipe closure scenarios.
- Improve coordination between engineering and operations staff.
- Optimize development pipes sizes based on water quality, not just fire flow.
- Potentially save developer capital encouraging cost-effective development.
- Potentially save future water flushing requirements.
- Improve water quality at the tap in addition to transmission pipes.
- Optimize flushing locations and quantities.
- Minimize flushing water volume and lost revenue.
- Empower water quality staff with theoretical baseline distribution water quality values.
- Empower operations staff with tool to analyze alternative operations strategies.
- Assist with locating closed valves in the system.
- Help comply with water quality regulations, including Stage 2 Disinfection By-Product (DBP).

References

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