From Start to Finish: Calibrating Pinellas County's 2,000-Mile Hydraulic Water Distribution System Model

Christopher C. Baggett, Guohua Li, Roberto A. Rosario, Ameena Y. Khan,
William A. Lovins III, Robert M. Powell, and Tony Reed

Pinellas County Utilities provides drinking water to approximately 800,000 customers along Florida's central west coast. The raw water sources include 11 wellfields (e.g., Eldridge Wilde Wellfield), two rivers (Alafia River, Hillsborough River), the Tampa Bypass Canal, and Hillsborough Bay. The transmission and distribution system contains approximately 2,000 miles of piping (diameters ranging from ¾ of an inch to 66 inches), six pumping stations, pressure-reducing valves (PRVs), and an elevated storage tank (Figure 1). The six pumping stations and their functions include:

- **S.K. Keller Pumping Station (KPS)**—The KPS purveys (1) aerated and chloraminated groundwater from the S.K. Keller Water Treatment Plant and (2) regionally blended water provided by Tampa Bay Water into the central/southern portion of the Pinellas County Water System. It includes eight horizontal split-case-type pumps and has a firm nominal rated capacity of 34,375 gallons per minute (gpm).
- **North Booster Pumping Station (NBPS)**—Flow to the NBPS is supplied by a 66 inch/60-inch transmission main from Tampa Bay Water. The pump station boosts water pressure through horizontal split case booster pumps that have a nominal rated capacity of 17,350 gpm and a firm nominal rated capacity of 34,700 gpm. Also, water can be stored in one of the four 5-million-gallon ground storage reservoirs (GSRs) and then re-pumped into the distribution system using one of two horizontal split-case injection pumps that have a nominal rated capacity of 14,000 gpm and a firm nominal rated capacity of 14,000 gpm.
- **Logan Pumping Station (LPS)**—The LPS includes two 5-million-gallon GSRs and four identical horizontal split-case pumps, each with a nominal capacity of 4,700 gpm. The station functions as an injection station so that when local demands are low, the tanks are filled; when demands are high, the injection pumps are used to supplement the system's demand requirements.
- **Oakhurst Pumping Station (OPS)**—The OPS is typically used as an injection station, but it can also be used to boost pressure. The valve configuration of the pump station can be changed to allow the 3-million-gallon standpipe to "float" on the system pressure. This station, with a firm nominal rated capacity of 4,000 gpm, includes two horizontal split-case pumps, both of which have a nominal rated capacity of 4,000 gpm.

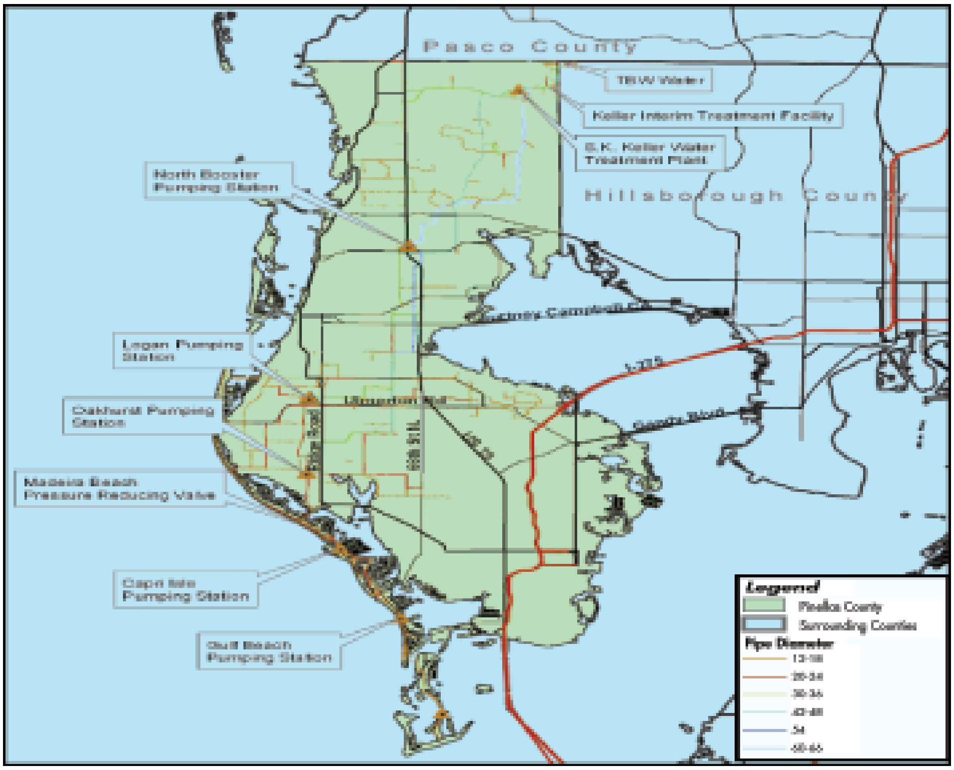

Figure 1. Pinellas County Water System

Christopher C. Baggett, P.E., is a utilities department manager with the Gainesville office of the Florida-based consulting firm Jones Edmunds & Associates. Guohua Li, Ph.D., Roberto A. Rosario, and Ameena Y. Khan, Ph.D., are engineer interns with the firm. William A. Lovins III, Ph.D., P.E., is a senior engineer with AECOM Water, formerly Boyle Engineering Corporation, in Orlando. Robert M. Powell is director of the utilities laboratory for Pinellas County Utilities in Clearwater. Tony Reed is a senior water quality management specialist with Pinellas County Utilities. This article was selected as a Top Paper at the Florida Section AWWA Fall Conference in November 2007.

- **Capri Isle Pumping Station (CIPS)**—The CIPS, which is strictly used for injection, includes one 5-million-gallon GSR as well as three constant-speed horizontal split-case pumps. Two of these pumps have a nominal rated capacity of 2,500 gpm, and the other pump has a nominal rated capacity of 1,500 gpm. When demand is low, the ground storage tank is filled; when demand increases, the injection pumps are used to meet system demands. The firm nominal rated capacity of this station is 4,000 gpm.
- **Gulf Beach Pumping Station (GBPS)**—The GBPS includes one 2-million-gallon GSR as well as three horizontal split-case pumps (nominal rated capacity of 1,400 gpm each), one of which is a diesel engine-driven pump on standby for emergency use. The firm nominal rated capacity of this station is 1,400 gpm.

Hydraulically, the Pinellas County Water System functions as two large distribution networks: the northern system and the central/southern system. These are integrated by a variable-pressure interface zone whose size and location depend on system demands and operations.

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The northern system (i.e., the North County service area east of Lake Tarpon and Clearwater) is served by groundwater from the Eldridge Wilde Wellfield and a mixture of desalted water, surface water, and groundwater (provided by Tampa Bay Water). A 36-inch transmission main feeds the northwest with the regional blend, while a 48-inch pipe serves the northeast with groundwater. The central/southern portion of the Pinellas County Water System is served entirely by the regionally blended water.

The use of numerous water sources and the implementation of chloramination in 2002 have created water quality and operational challenges. To improve water quality and distribution system management, Pinellas County Utilities implemented a series of projects to develop a calibrated model for predicting flow, pressure, and total chlorine throughout its water system.

Hydraulic Model Formation

Developing the hydraulic model involved the following steps:

1. Creating a pipe network from the water system GIS files using WaterGEMS© (Bentley Systems, Inc.) and ArcGIS (Environmental Systems Research Institute).
2. Spatially allocating customer demands and pipe leakage to pipe network nodes.
3. Assigning elevations to pipe network nodes.
4. Incorporating boundary condition elements (e.g., pumps, ground storage reservoirs, elevated storage tank, pressure-reducing valves).
5. Performing calibration and a quality control review of the resulting model.

Pipe Network

The pipe network model was developed from GIS-based shapefiles using WaterGEMS© and ArcGIS. The model retained the pipe properties—diameter, length, spatial location in the system, etc.—defined in the shapefiles and used the nodes to represent the pipe connections and the end of pipes. Anomalies in the model were checked and corrected using record drawings. The model consisted of approximately 80,900 pipes and 76,450 nodes. Pumps, storage reservoirs, tanks, and control valves were then added to the model based on record drawings.

An appropriate Hazen-Williams coefficient (C) was assigned to each pipe by combining the Hazen-Williams and the Darcy-Weisbach equations to create Equation (1). For older pipes, the authors applied suggested safety factors (15 to 20 percent; Cameron Hydraulic Data 19th ed.) and reported variability in pipe absolute roughness values.

Tables of Hazen-Williams coefficients for various pipe sizes and materials for the range of expected velocities in the pipes were compiled as the initial ranges for calibration. The initial Hazen-Williams coefficients for the Pinellas County Water System model ranged from values of 115 to 155. The coefficients were then adjusted to better match non-ideal conditions arising from tuberculated pipes, damaged pipes, air-bound pipes, or pipes containing other flow obstructions.

$$C = 17.34 f^{-0.54} D^{-0.092} V^{-0.081} \qquad (1)$$

Where:
= Hazen-Williams coefficient
= pipe diameter
= Darcy-Weisbach friction factor
= flow velocity

Allocating Demands

Retail meter demand and spatial data were linked to model nodes using GIS techniques. More than 96 percent of the total retail flow (40.6 MGD) was allocated to the model nodes, after which the total wholesale meter flow (22.65 MGD) was assigned.

The unaccounted water (i.e., leakage) was estimated by calculating the difference between the total allocated demand from the billing records and the water system's total average daily supply for the same period. The unaccounted water was then distributed to the nodes based on an "allowable leakage formula," Equation (2). No demands or leakage were attributed to the pump station suction piping, dedicated fill lines, or model nodes related to boundary condition elements.

$$Q_{Li} = \frac{0.5 * \Sigma(LD)_i}{\Sigma(LD)} \bullet \sqrt{\frac{P_i}{P_{avg}}} \bullet Q_{TL} \qquad (2)$$

Where:
Q_{Li} = Leakage rate at node i (gpm)
L = Length of pipe (ft)
D = Diameter of pipe (in)
P_i = Pressure at node i (psi)
P_{ave} = Average Pressure for entire system (psi)
Q_{TL} = Total Leakage rate (gpm)
$\Sigma(LD)_i$ = Sum of the product of L and D of all the pipes connected to node i
$\Sigma(LD)$ = Sum of the product of L and D of all the pipes in the system

Note: Formula is based on commonly used allowable leakage formula and the approach used by Haestad Method, Inc. for leakage distribution.

Assigning Elevations

Pinellas County provided one-foot contours derived from a county-wide airborne laser swath mapping/light detection and ranging (ALSM/LIDAR) effort. Through ArcInfo, the one-foot contours were used to create a triangulated irregular network (TIN) by interpolating between elevation contours to produce a continuous surface representing the varying elevations.

In the present study, one-foot contours with a surface grid resolution of approximately two feet were used to create the TIN. The ground surface elevations were assigned to the corresponding model nodes using GIS.

Incorporating Boundary Conditions

Boundary conditions, as defined in this study, are the known parameters from which hydraulic properties such as pressures and flow rates are calculated. The Pinellas County Utilities SCADA system provided a vast amount of data to define the boundary conditions, including pump station pressures, flows, and tank levels; wholesale meter flows; various water main flows; valve positions; and various chemical levels. Other parameters used to define the Pinellas County Water System include:

- ***Storage Tanks***: tank geometry of diameter and depth, initial water surface elevation (real-time data), and ground elevation.
- ***Pumps***: field-verified or field-adjusted pump curves.
- ***Pressure-Reducing Valves***: field-verified or design pressure set-points.
- ***Variable-speed pumps***: relative speed ratio specific to each time period simulated.

System Monitoring

Seven modeling scenarios were developed to assess the accuracy of the model with respect to field data. These scenarios—maximum hourly demand scenario, minimum hourly demand scenario, and five hydrant flow scenarios—were established using the following information gathered through system monitoring over a two-week period:

- Pumping station inlet and outlet pressures and flows.
- Variable-speed pump operation status and speed.
- Tank levels.
- Wholesale meter flows.
- Retail meter flows.
- Storage tank fill valve positions.
- Pressures at 26 hydraulically remote sites in the transmission and distribution mains located near critical boundary conditions.
- Static and residual pressures, flow rates, and flow durations during five fire hydrant flow events.

A fluoride tracer study was also conducted over six weeks to help quantify the model's ability to predict flow direction and water age. Systematic control over the fluoride input, coupled with water quality sampling at 50 strategic points within the Pinellas County Water System, helped to further characterize the system. Influent fluoride concentrations at the points of entry were entered into the

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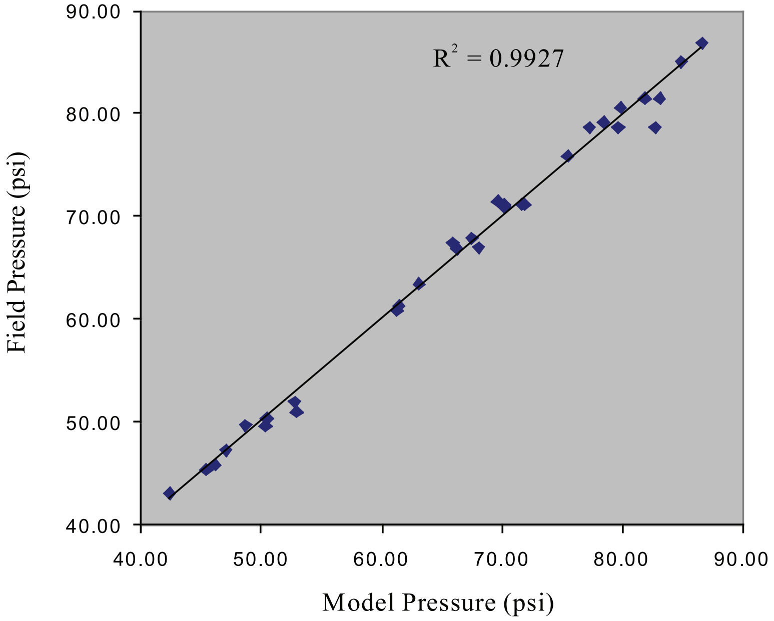

Figure 2. Comparison between Field and Model Pressure Data at Maximum Hour Demand

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model as the inlet concentration profiles. Pump station GSRs were modeled using the last-in first-out (LIFO) tank model based on the results from the hydraulic assessment of the Logan Pump Station GSR, presented later.

Calibration

The hydraulic model was calibrated by adjusting Hazen-Williams coefficients according to the maximum-hour-demand period. This was accomplished by forming calibration sets of pipes around each field-pressure location.

Each calibration set was divided into two subsets: 10-inch-and-less diameter pipes and greater-than-10-inch diameter pipes. The C value of each subset was manipulated to reflect a logical pattern of friction change while maintaining consistency among neighboring pipes of similar size. C values were also kept in a reasonable range according to pipe size, age, and material for the expected range of velocities.

Model run iterations ceased once the majority of model-reported system pressures were within 4 to 5 pounds per square inch (psi) of the field-measured pressures during the maximum-hourly-demand scenario.

Hydraulic Modeling Results

Pressure Correlation

Field data and simulation results agreed well, according to Pearson product moment correlation coefficients (Mendenhall and Sincich, 1994), which exceeded 0.97 in all cases. For the seven steady-state hydraulic simulations, the average difference between model-calculated and field-measured pressures was 1.3 psi. A total of 79.6 percent of the model pressures were within 2 psi of the field pressures, and 98.6 percent of the model pressures were within 5 psi of the field pressures. See Figure 2 for a comparison between the model and field pressure at the maximum hour demand.

Fluoride Tracer

Parts A and B of Figure 3 illustrate the typical correlation between field and model fluoride data observed at northern and southern sectors of the distribution network following a 744-hour simulation. The results correlate well, suggesting that the model successfully simulates flow direction and water age in the Pinellas County Water System. The model may therefore be used as a tool to tailor a flushing program to

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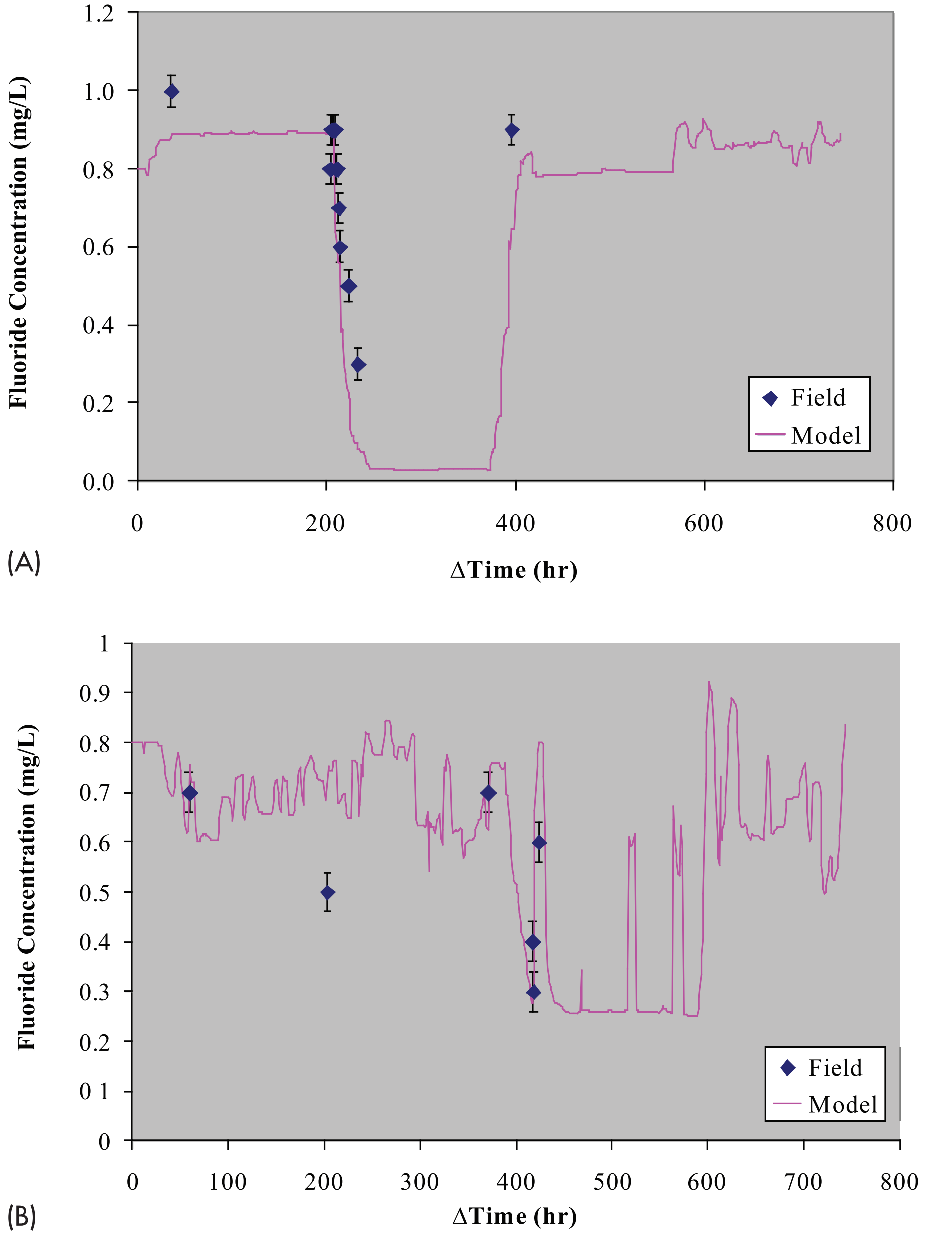
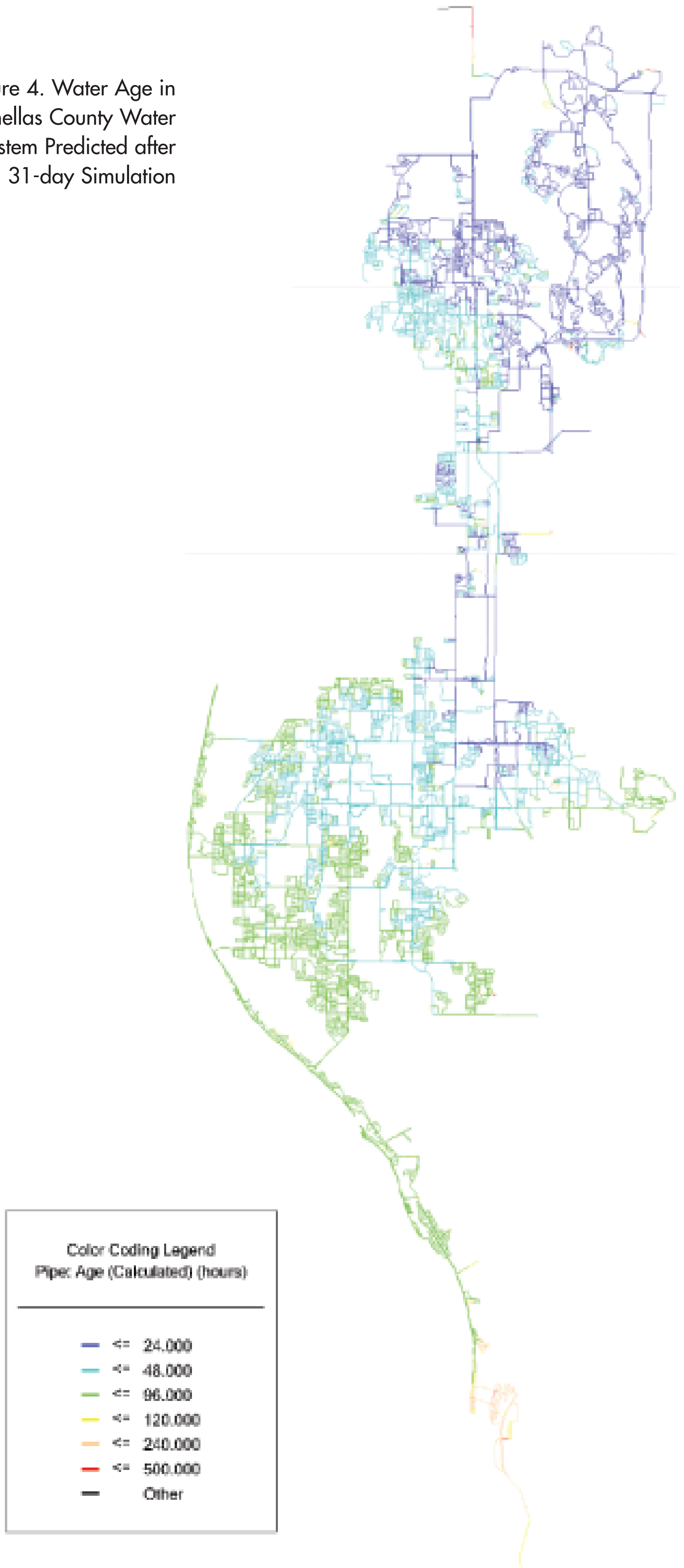


Figure 3. Comparison between Field and Model Fluoride Concentration Data: (A) North Pinellas County Water System, (B) South Pinellas County Water System

Figure 4. Water Age in Pinellas County Water System Predicted after 31-day Simulation



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minimize stagnation and mitigate common associated problems such as disinfectant decay, taste and odors, and corrosion. The ability to simulate water age is illustrated in Figure 4.

The model can also be used as a tool to understand the effect of leaks, valve closures, and flow dynamics. For example, Figure 5 identifies the predicted location of the pressure interface zone—whose size and location vary with system conditions—and the percentage of groundwater for four timeframes.

Total Chlorine Residual Modeling

Because of the growing complexity of regulations, consumer expectations, and the desire to optimize water treatment and distribution operations, water quality modeling is an increasingly important tool for purveyors of potable water. Computer-aided simulations can dramatically improve understanding of the fate and transport of, for example, disinfection chemicals, thereby offering a tool to improve treatment practices and ultimately lower overall costs. Nevertheless, to ensure the accuracy of the model, it is critical that the constituent reactions and decay/growth mechanisms on which the model is based are sound and appropriate.

To calibrate the model for predicting disinfectant residual concentration, chlorine degradation rates were determined by collecting field samples as well as conducting laboratory "bottle tests." The data were then analyzed to understand those reactions occurring in the main portion of the stream flow (bulk reactions), as well as those occurring on or near the pipe wall (wall reactions).

Defining Bulk Reaction Coefficients

Bulk reactions are reactions that are unaffected by processes involving the pipe walls and can be described by n-th order kinetics (Clark and Grayman, 1998):

$$R(C) = K_b C^n \qquad (3)$$

Where:
R = reaction rate
C = reactant concentration
K_b = bulk reaction rate coefficient
n = reaction order

Chlorine decay is usually represented as first order (i.e., n = 1), with the decay coefficients typically being between 0.05 and 15 d$_{-}$; note that coefficients for decay reactions can be reported as negative values. The site-specific decay coefficient is typically determined using bottle tests where chlorine decay in a particular volume of water is monitored over the natural maximum water age of the system. A plot of the decay versus time is then constructed, from which K_b is extracted using the following relationship (Clark and Grayman, 1998):

$$K_b = \frac{Ln(\frac{C_1}{C_2})}{(t_1 - t_2)} \qquad (4)$$

Where:
K_b = bulk reaction rate coefficient
t_1 = start time
t_2 = end time
C_1 = concentration at t_1
C_2 = concentration at t_2

The global average bulk decay coefficient (at T = 20°C: 0.07 d^{-1}) for samples taken from the Pinellas County Water System was incorporated into the model using a first-order reaction rate. Initial chlorine concentrations were specified regionally according to field concentration data—instead of assigning one global initial concentration—to increase model accuracy.

Defining Wall Reaction Coefficients

Wall reactions depend on the bulk conditions, pipe dimensions (i.e., pipes with smaller diameters encourage greater solution/wall interaction and therefore greater reaction rates), and pipe wall condition (Wu, 2006):

$$R(C) = (\frac{A}{V})K_w C^n \qquad (5)$$

Where:
K_w = wall reaction rate coefficient
A/V= surface area per unit volume within a pipe

The dependency of K_w and the reaction order on pipe material and condition (i.e., age, encrustation, corrosion) make determining the coefficients difficult. Although conceptually K_w may be measured under ideal conditions (i.e., long isolated pipes, no connections, controlled flow, inline chlorine measurements), in real-world conditions such measurements are infeasible (Haestad Methods, Inc., 1999); therefore, models generally incorporate a calibrated K_w (Wu, 2006) with initial estimates based upon pipe roughness coefficients, flow velocity, and pipe diameter, as demonstrated by Equations (6) through (8). This approach is practiced widely in the industry because wall decay coefficients vary greatly due to pipe condition (material, roughness, corrosion, and biofilms) and can not be measured reasonably for large distribution systems.

Wall decay coefficients were assigned using Equation (6), an α of -6.5, and the hydraulically calibrated Hazen-Williams C coefficients (Table 1). The α of -6.5 was selected with the knowledge that on average it would result in a K_w value of -0.050 ft/d. This K_w is in the mid-range of typical values that have been estimated for the types of pipes found in the Pinellas County Water System.

Decay rates for isolated sites exhibiting irregular chlorine degradation were adjusted

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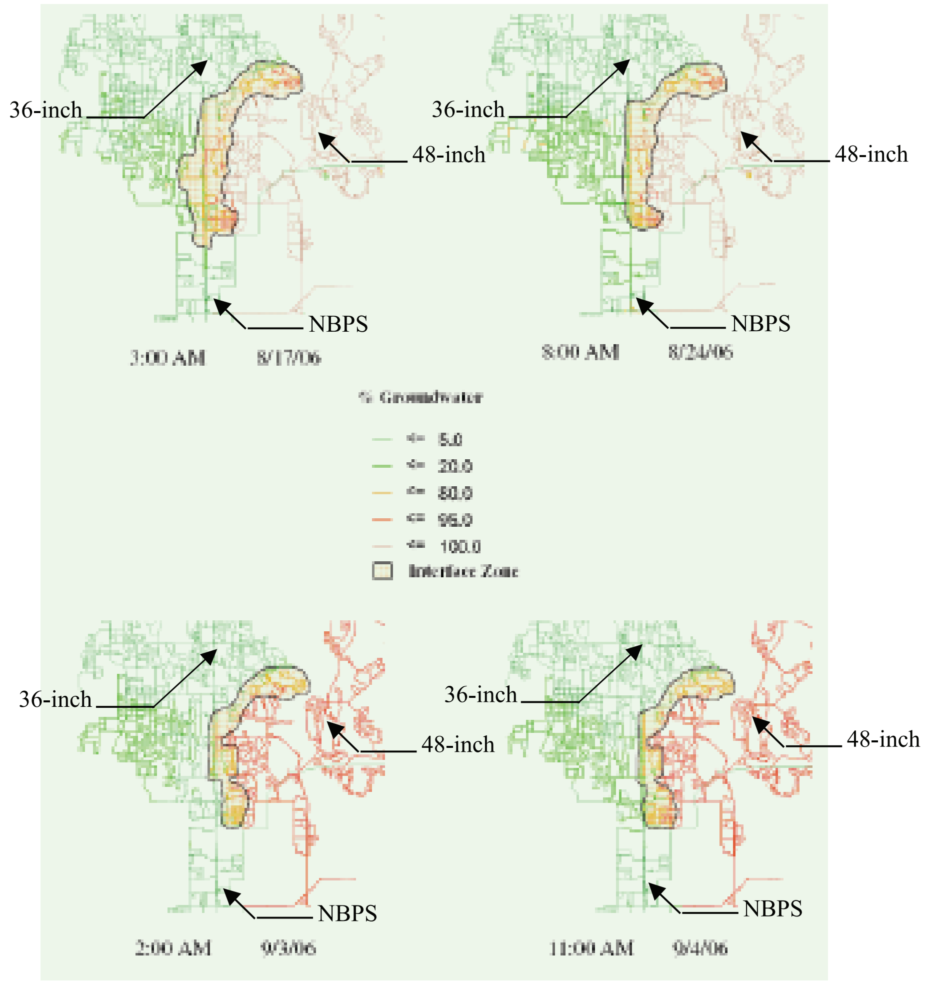

Figure 5. Predicted Interface Locations and Groundwater Percentages at Various Times

Coefficients Used in Calculating K_w	
Hazen-Williams C Coefficient	K_w (ft/day), $\alpha = -6.5$
120	-0.054
126	-0.052
130	-0.050
135	-0.048
158	-0.041

Table 1

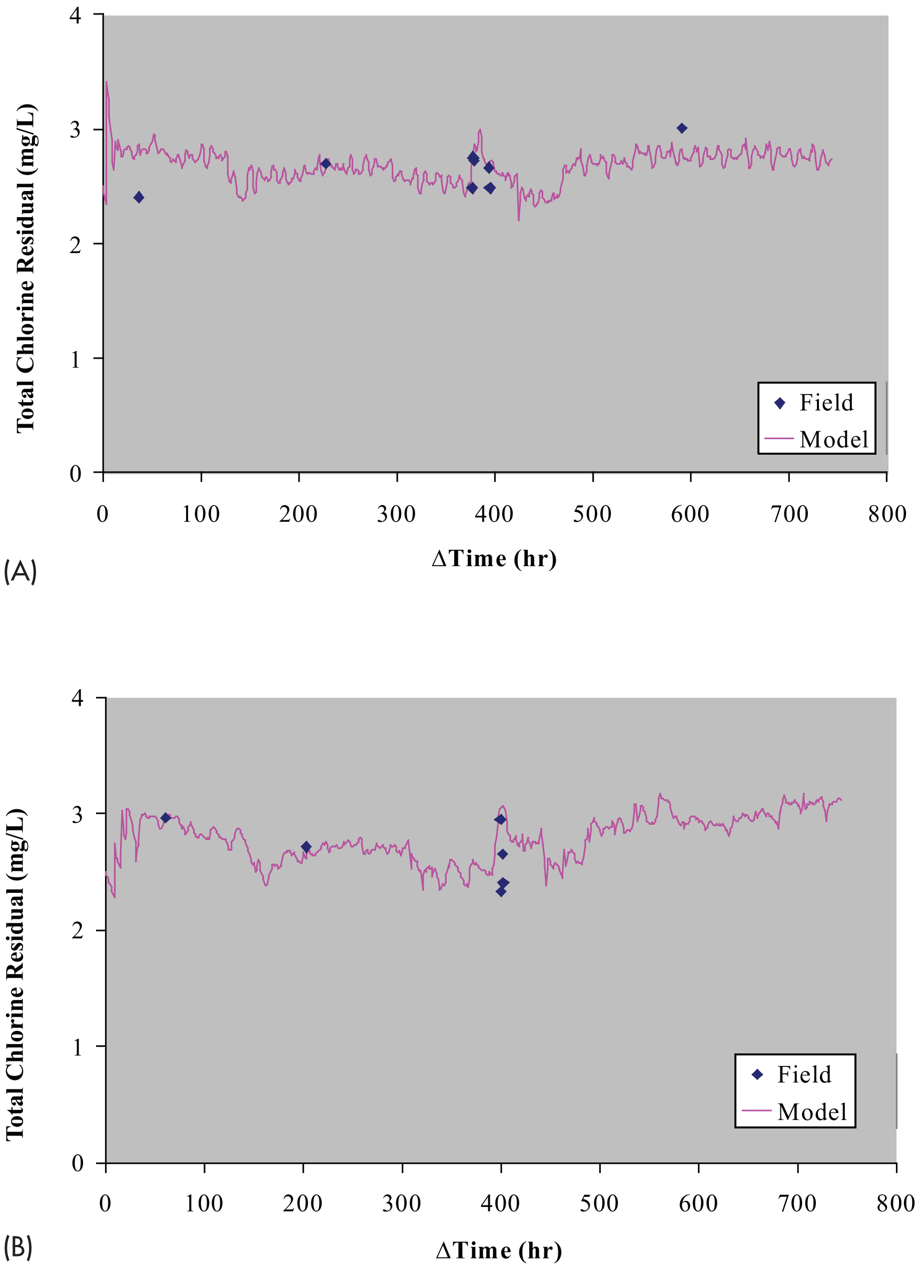

Figure 6. Comparison between Field and Model Total Chlorine Concentration Data: (A) Northern Pinellas County Water System, (B) Southern Pinellas County Water System.

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by increasing or decreasing α to achieve higher or lower decay, respectively. The adjusted α values ranged from 2.025 to -100.00, resulting in adjusted K_w values that ranged from -.015 ft/d to -0.833 ft/d.

$$Hazen-Williams: K_w = \alpha / C \quad (6)$$

$$Darcy-Weisbach: K_w = \frac{-F}{\log(\varepsilon / d)} \quad (7)$$

$$Chezy-Manning: K_w = F * N \quad (8)$$

Where α and F are correlation coefficients of wall reaction and pipe roughness and the remaining variables are as detailed previously.

After the bulk and wall decay coefficients were established, the model was run for 744 hours and the resulting total chlorine concentrations were compared to field data from 50 sites throughout the Pinellas County Water System.

Total Chlorine Residual Modeling Results

Parts A and B of Figure 6 illustrate the typical correlation between field and model data observed at northern and southern sectors of the distribution network. The simulated total chlorine concentrations at these select sites are in good agreement with the field data. The model provides practical value by reasonably predicting locations of low chlorine residual and help to establish flushing programs.

Hydraulic Assessment of GSR

The system-wide fluoride tracer study afforded a unique opportunity to assess mixing within the Logan Pump Station GSR. Inlet fluoride concentrations—measured during the increasing wave-front after fluoridation resumed—and SCADA tank level data were used as boundary conditions in the following tank mixing models:

- Completely Stirred Tank Reactor (CSTR)
- Two-Compartment
- Last-In First-Out (LIFO)
- First-In First-Out (FIFO)

The modeling results were then compared to the actual GSR outlet fluoride concentrations to determine which mixing pattern best represented that of the Logan tank. Interestingly, the commonly used CSTR model did not correlate with the outflow profile satisfactorily (Figure 7). In the same way, modeling the tank as two CSTR compartments was also insufficient (data not shown).

Similar to the compartment model, the ele-

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mental models FIFO and LIFO divide the total volume of water into independent parcels. What is unique about the elemental models, however, is that the segments move through the storage vessel as opposed to being stationary zones.

FIFO, also known as "plug flow," assumes an ordered movement of water where the first segment to enter the tank is also the first to exit. Its converse, LIFO, also known as the "short-circuiting model," predicts that the last volume of water to enter the tank during the fill stage is the first volume to leave during the draw period.

The outlet fluoride profile generated by the FIFO model was not consistent with the actual results (not shown), but the data did appear to follow the projection generated by the LIFO system (Figure 8). While the finding was unexpected, the following points support it:

- Outlet samples generally exhibited the highest fluoride concentrations during times when the tank was filling and the inlet concentrations were high.
- During the filling period at high flows, the water can enter the tank through three check valves (one located at an elevation of 22 feet and two at 11 feet) on the inlet diffuser assembly; however, under certain conditions, the upper inlet may be inoperative and therefore may not provide the inflow momentum necessary to approximate completely mixed conditions.
- Temperature stratification is anticipated to occur within the GSR, such that colder, denser water may settle to the bottom of the reservoir. During the fill period, the incoming colder, denser water may also sink to the bottom of the GSR where the outlet is located. In this situation, the last volume of water entering during the fill period may be quickly withdrawn.

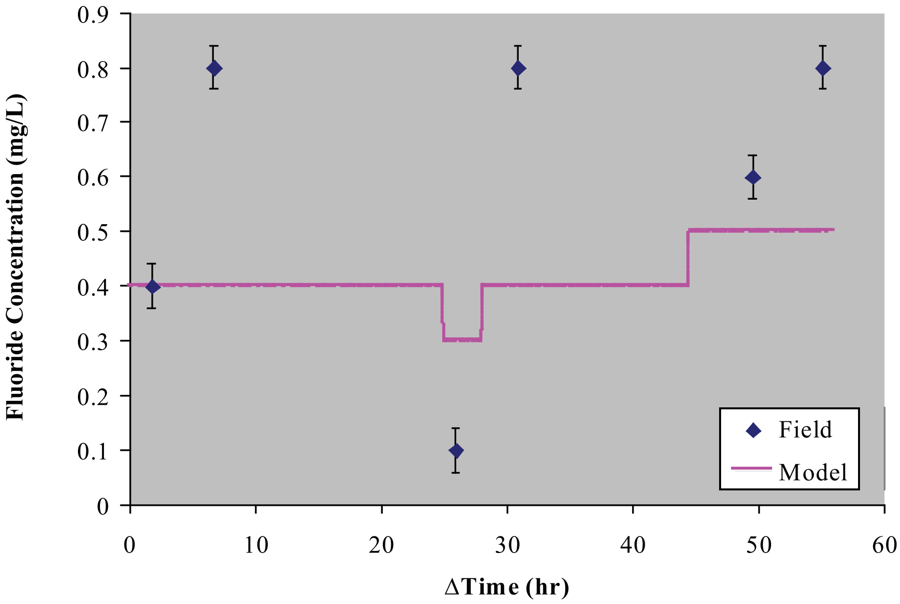

Figure 7. Outlet Fluoride Concentrations at Logan GSR: Actual Versus CSTR Model Output

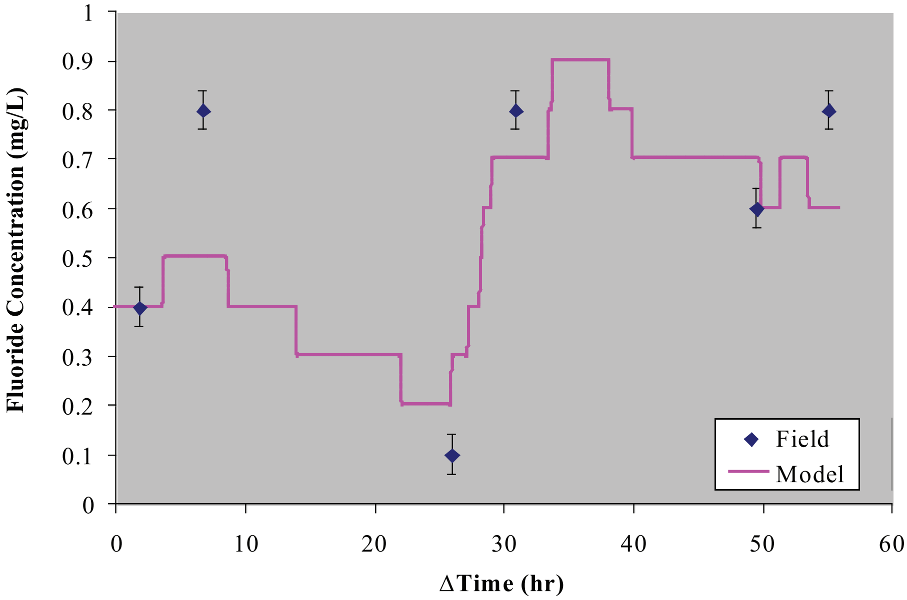

Figure 8. Outlet Fluoride Concentrations at Logan GSR: Actual Versus LIFO Model Output

Conclusions

The model described in this paper was created as a tool to characterize the Pinellas County Water System. By extensively defining the parameters of the water system and performing detailed calibration, the resulting model predicts flow, pressure, and total chlorine residual throughout the system. It therefore can be used effectively for many important purposes, such as:

- Designing improvements and tailoring flushing programs to minimize stagnation and mitigate common problems such as disinfectant decay, taste and odors, and corrosion.
- Modeling the effect of leaks, valve closures, and flow dynamics.
- Characterizing and better understanding the influence of variable-pressure interface zone.
- Refining standard procedures for performing chlorine maintenance (periodic conversion from combined to free chlorine).
- Simulating emergency operations.

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