Using Water Quality Modeling as a Decision Making Tool to Plan Distribution System Improvements for Pinellas County Utilities

Guanghui Hua, Roberto Rosario, Christopher Baggett, Robert Powell, and James Hall

Guanghui Hua, Ph.D., P.E., is assistant professor in the department of civil and environmental engineering at South Dakota State University in Brookings, S.D. Roberto Rosario, P.E., is project engineer and Christopher Baggett, P.E., is senior engineer at Jones Edmunds & Associates Inc. in Gainesville. Robert Powell is director—water and sewer division and James Hall, P.E., is director—division of engineering at Pinellas County Department of Environment and Infrastructure in Clearwater.

Pinellas County Utilities currently provides drinking water to approximately 700,000 people along Florida's central-west coast. The County's water system is large, with multiple points of entry into the distribution system. The water sources for Pinellas County include groundwater and a variable blend of groundwater, surface water, and desalinated water. Figure 1 shows the County's water system. Its source water treatment system consists of the S.K. Keller Water Treatment Plant and the Regional Treatment Facility. The treatment plant treats groundwater from the Eldridge Wilde Wellfield and the treatment facility treats the regional blended water supplied by Tampa Bay Water.

The utility uses chloramines to maintain residual chlorine in the distribution system. Nitrification episodes have been observed in the distribution system since it was converted to chloramines for secondary disinfection in 2002. Nitrification has caused adverse effects on water quality, including low disinfectant residuals that are being remediated through increased water flushing and periodic free chlorine maintenance. The utility authorized Jones Edmunds & Associates Inc. to develop a water quality model and use the model to recommend corrective actions to mitigate persistent nitrification issues.

First, the utility's historical water quality data and operation and maintenance data were evaluated to enhance the understanding of the system. Then, the distribution system hydraulic model was updated to incorporate the latest pipe network revisions, spatial distribution of recent water demands, and current operating condition information to accurately predict water age throughout the system.

Following the model updates, an extended-period simulation water quality model was developed to calculate total residual chlorine (TRC) concentrations in the system. Future-constituent-concentration 10-day extended-period simulation analyses were performed for various simulation scenarios to plan for short- and long-term system improvements to better control system nitrification and reduce flushing.

The results of the water quality modeling and the recommended distribution system improvements for the county are summarized. The nitrification control experiences of the utility have significant implications for other Florida utilities that are considering augmentation through alternative water supplies and chloramination for disinfection byproducts rule compliance.

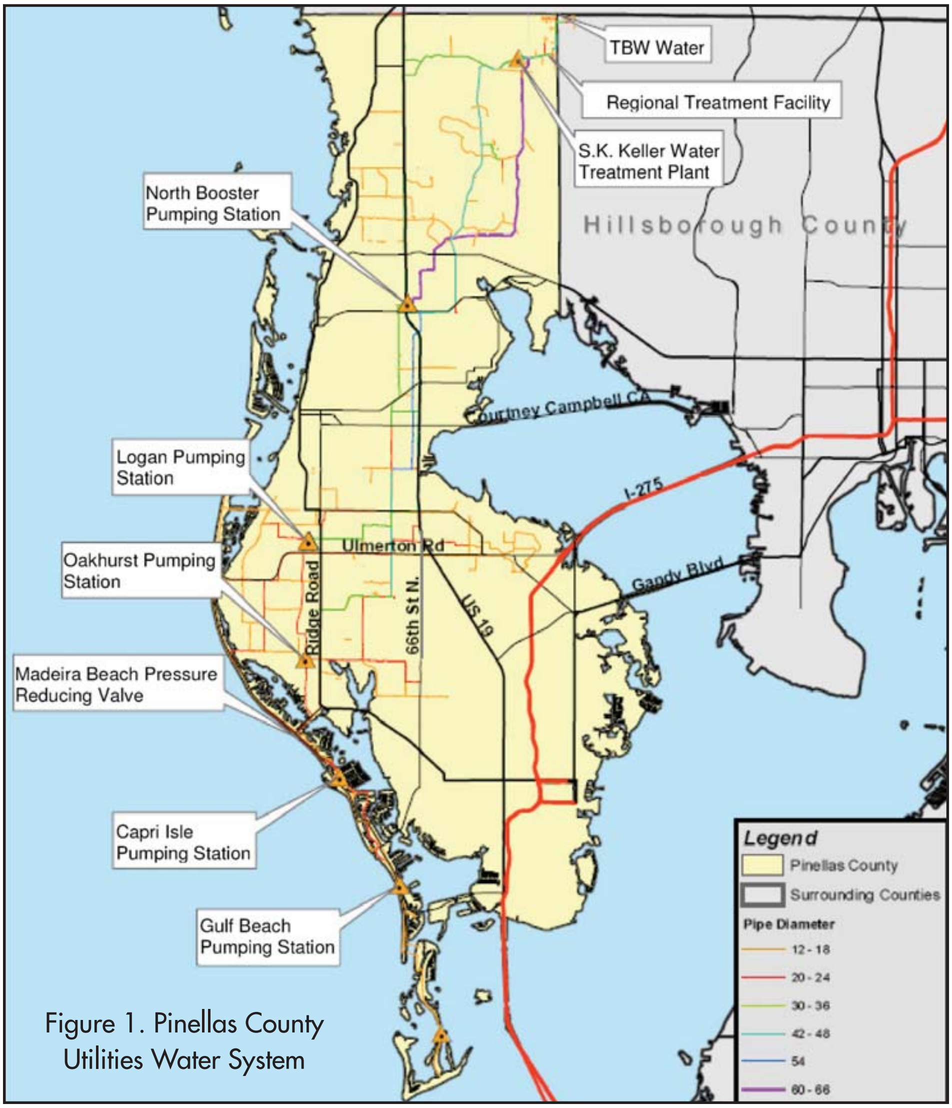

Figure 1. Pinellas County Utilities Water System

Water Supply

The water sources for the system include groundwater from 11 wellfields, surface water from two rivers (Alafia River and Hillsborough

Continued on page 54

Continued from page 52
River) and the Tampa Bypass Canal, and desalinated water from lower Old Tampa Bay. Figure 2 shows the annual average water supplies from the groundwater for the treatment plant and the regional blended water. The total water demand of the system has decreased from an average of 69 mgd in 2002 to an average of 55 mgd in 2010, representing a 20 percent reduction in less than 10 years. Reasons for the reduced water demand of the system include water conservation efforts, reduced population growth rates, water system development of the wholesale customers, economic recession, and other factors.

Because of the reduced water demand and the occurrences of nitrification episodes in the distribution system, the utility had to use a relatively high flushing volume to reduce the system water age and maintain the water quality. Distribution system nitrification is a common problem associated with water utilities that use chloramines for secondary disinfection. Nitrification is a microbial process by which free ammonia released through chloramines decay is sequentially oxidized to nitrite and nitrate. Nitrification in the distribution system can have serious adverse effects on water quality, such as loss of chlorine residuals, release of free ammonia, production of nitrite/nitrate, decreased pH and dissolved oxygen, and increased microbiological activity (Wilczak et al, 1996).

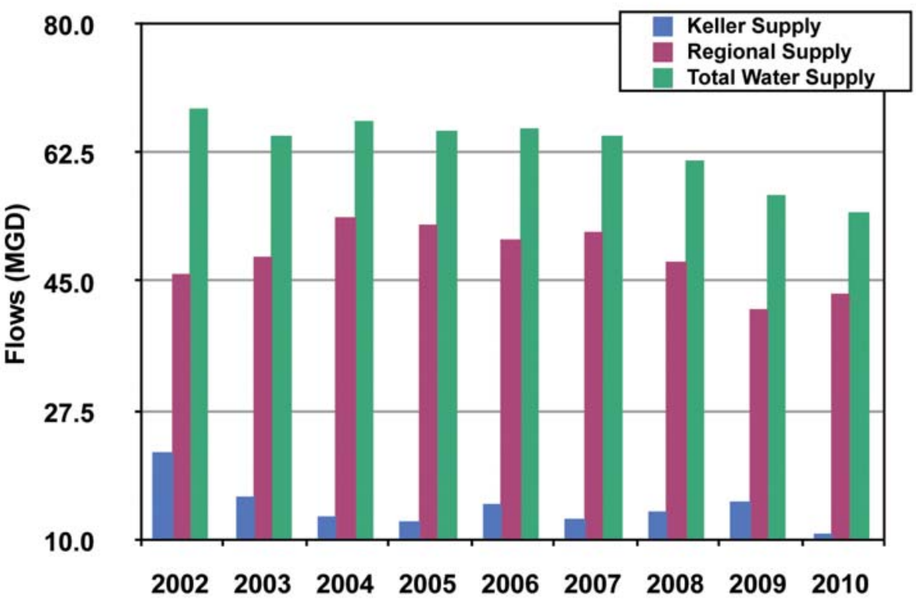

Figure 2. Pinellas County Utilities Water Supply (2002-2010)

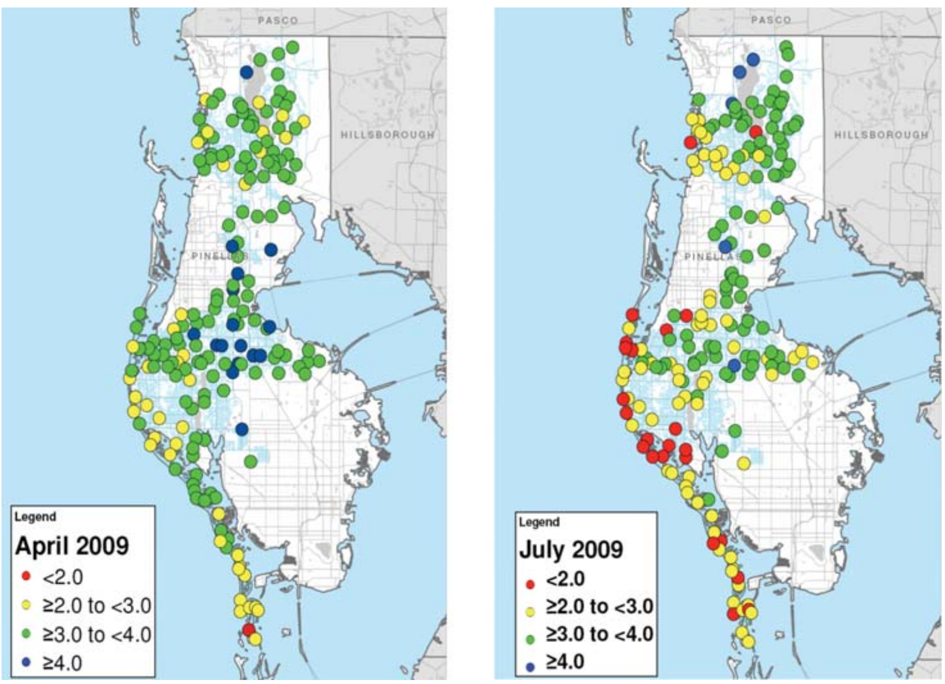

Figure 3. Pinellas County Utilities Total Residual Chlorine Maps

Nitrification in the water system typically occurs in the summer when the water temperatures are high. Figure 3 shows the monthly average total chlorine of each routine monitoring site for April and July 2009. The TRC map of April 2009 represents the normal distribution system conditions where there is minor or no nitrification. The July 2009 map represents the severe nitrification conditions. The utility was able to maintain the total chlorine above 3 mg/L for the majority of the distribution system in April 2009. However, substantial reductions in total chlorine levels were observed with the onset of severe nitrification episodes in July 2009. Many areas of the system had total chlorine levels below 2 mg/L during that month. The total chlorine maps also suggest that the beach communities in the southern system present the most challenge for the county to maintain water quality.

Historical water quality data for the utility were evaluated to enhance the understanding of the system. This evaluation focused on TRC, ammonia, and nitrite, which are direct indicators for system nitrification. The results of this evaluation indicate that the TRC levels and NH_3/TRC ratios have strong correlations with nitrite levels in the system. Maintaining appropriate TRC levels in the system helps prevent severe nitrification episodes (Hua et al, 2011). In view of this, TRC modeling was used as a tool to plan the distribution system improvements.

Hydraulic Model Updates

As the first part of this modeling effort, the utility's hydraulic model was updated to accurately predict water age throughout the system. The updates to the model included monthly demands (retail, wholesale, and other unbilled use), flushing use (locations, rates, and flushing device actuation times), near-term future system piping modifications, and operating strategies and settings for system components.

Model Demand Development

The county's water demand is comprised of retail, wholesale, routine maintenance, and other water-loss-type demands. To allocate the retail and wholesale demands, actual customer-metered demands from billing records were assigned to model nodes.

The county's routine-maintenance-type demand consists of 55 automatic flushing devices with routine flushing demands. These flushing devices are composed of Hydro-Guards and custom-made devices. The flow rate of each automatic flushing unit depends on the system pressure. The model predicts the instantaneous demand based on the instantaneous system pressure for each automatic flushing unit.

Model Piping Modifications

The model was updated using the latest geographic information system (GIS) data for the water system and information about portions of the system that had been modified. Areas had been modified because of pipe replacement, the installation of new water mains, and the bypassing of a pressure reducing valve.

The utility plans more modifications in the near future. Nearly 48,000 lin ft of water main are to be installed and about 20,000 lin ft of water main are to be removed or replaced. These modifications were incorporated in the model simulations representing future conditions.

Total Residual Chlorine Modeling

After completing the county's hydraulic model updates, a TRC model was developed. To calibrate the model to predict TRC concentrations, chlorine degradation rates—total chlorine bulk decay and wall decay coefficients—were needed.

Bulk reactions are those that occurred in the bulk phase of the water. The total chlorine bulk decay can be described by the following equation (Clark and Grayman, 1998):

$$R(C) = K_b C^n \qquad \text{(Equation 1)}$$

Where: R is the reaction rate; C is the reactant concentration; K_b is the bulk reaction rate coefficient; and n is the reaction order.

Chlorine decay is usually represented as first order (n = 1), with the decay coefficients typically ranging between 0.05 and 15^{d-1}. The global average bulk decay coefficients were determined from bottle tests using samples taken from the system.

Wall reactions depend on the bulk conditions, pipe material and dimensions, and pipe wall conditions, and can be described by the following equation:

$$R(C) = (A \div V) K_w C^n \qquad \text{(Equation 2)}$$

Where: K_w is the wall reaction rate coefficient; and A/V is the surface area per unit volume.

Therefore, the model incorporates a calibrated K_w, with initial estimates based on pipe roughness coefficients, fluid velocity, and pipe diameter.

The TRC model was calibrated to reasonably match field-measured TRC concentrations at 156 sample sites in July 2009. To achieve a reasonable residual chlorine match, the wall decay coefficient, K_w, for select pipes was adjusted. Figure 4 shows a map with the field-measured and model-calculated TRC concentrations for the July 2009 simulation, referred to as *Simulation 1*. Good correlation (R^2=0.9682) was achieved for the simulation. The minimum total chlorine concentration maintained in the entire system is approximately 1.0 mg/L, based on model predictions.

After the TRC model was calibrated, future-constituent-concentration 10-day extended-period simulation analyses were performed for the simulation scenarios described. These simulation scenarios were selected to evaluate the impact of the potential system improvements on TRC levels.

Simulation 2 (Future) – This analysis includes the future reduction in wholesale water customer demands, planned major water system modifications identified by the utility, and the current flushing use.

Simulation 3 (Future without Flushing) –

Continued on page 56

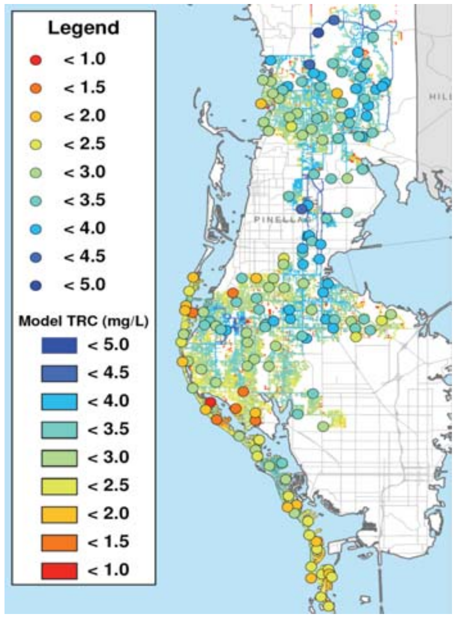

Figure 4. Total Residual Chlorine Map with Field-Measured (circles) and Model-Calculated Concentrations

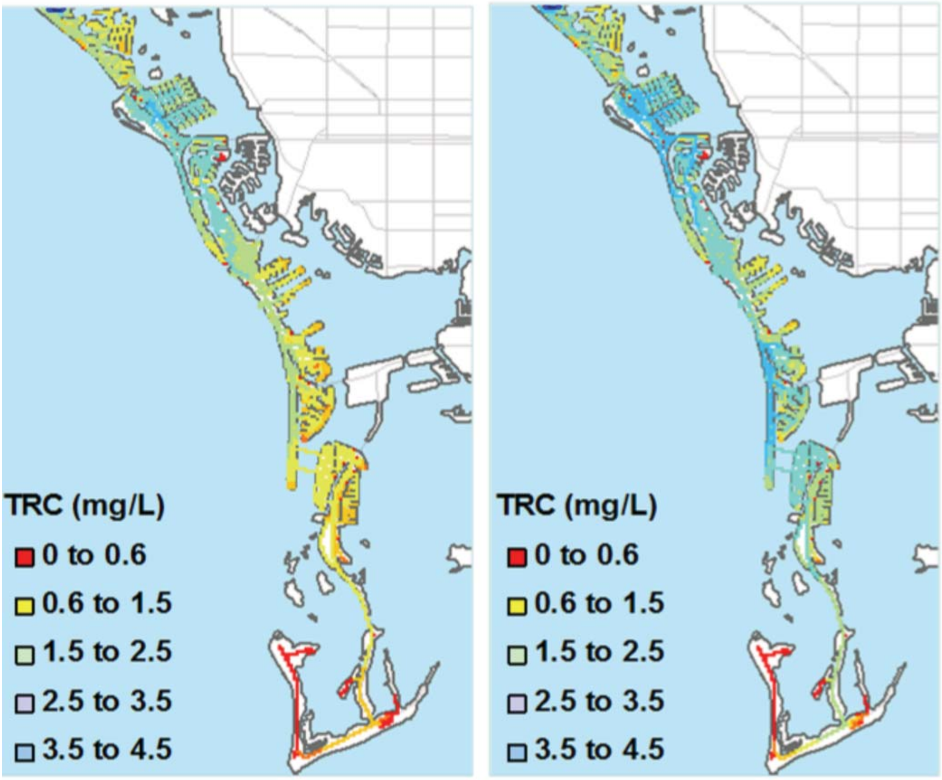

Figure 5. South Beach Total Chlorine Improvements by Pump Station Total Residual Chlorine Boosting

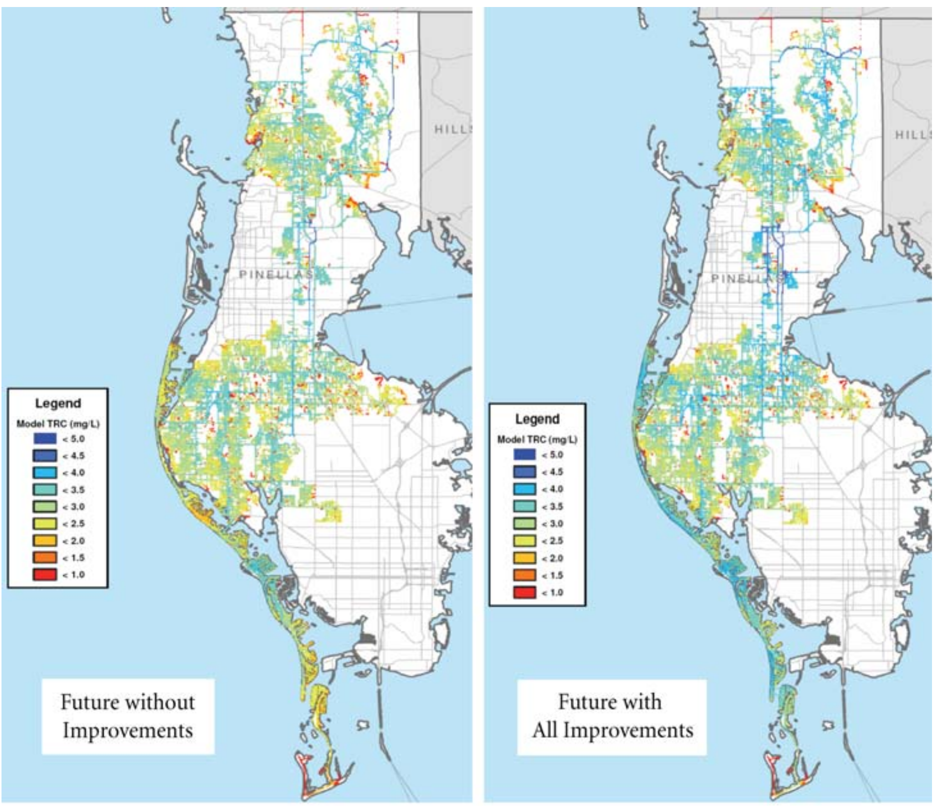

Figure 6. Total Residual Chlorine Maps of Future Conditions

Continued from page 55

This analysis is the same as Simulation 2, except the current flushing is removed. This simulation serves as the baseline condition for other simulations with future system improvements.

Simulation 4 (Future Pump Station TRC Boosting) – The TRC is boosted to at least 4.0 mg/L at all existing distribution pump stations. Other conditions remain the same as Simulation 3.

Simulation 5 (Future North Beach Recirculation and TRC Boosting) – New pressure boosting stations are added to the North Beach Area. The water is recirculated from the North Beach (low-demand) area to the central (high-demand) area. Chemical feed systems are added to each pressure boosting station to increase the TRC to 4 mg/L. Other conditions remain the same as Simulation 4.

Simulation 6 (Future Crystal Beach Recirculation) – New pressure boosting stations are added to the Crystal Beach Area. The water is recirculated from the low-demand areas to the high-demand areas. Other conditions remain the same as Simulation 4.

Simulation 7 (Future North Booster Pump Station [NBPS] Rerouting) – All flow north of NBPS is routed through the station and is only pumped south to eliminate the hydraulic interface in the northern system.

Simulation 8 (Future, All Improvements) – This analysis includes all the proposed modifications.

Figure 5 presents the TRC levels in the South Beach areas as a result of the proposed system improvements. Significant increases in TRC levels were observed for these areas after the proposed system improvements. For example, the water volume with total chlorine higher than 3.5 mg/L increased from 102,000 to 1,080,000 gal in the South Beach area based on model predictions.

Figure 6 shows the TRC maps of the entire water system for future conditions, with and without the system improvements. The TRC levels of the system (especially in the southern system) increase substantially after the proposed system improvements are implemented.

Distribution System Improvements

Based on the TRC modeling results, the following short- and long-term improvements were proposed to increase the TRC levels in the county's water system and reduce the required flushing volumes.

Recommended Short-Term (ST) Improvements

Keller Transfer Station (ST-1) – Treat the finished water with the regional water at the treatment facility. This improvement will eliminate the long-standing water quality problems associated with the interface zone between Keller groundwater and the regional water in the northern system.

Primary Station Total Chlorine Boosting (ST-2) – Boost TRC concentration at the Capri Isle Pump Station, located in South Beach area, to 4.0 mg/L. Increasing the total chlorine levels at this pump station will help maintain the TRC concentrations in the South Beach area.

Secondary Station TRC Boosting (ST-3) – Boost TRC concentration at Gulf Beach Pump Station and Oakhurst Pump Station to 4.0 mg/L. This improvement will increase TRC concentrations in the central system, the North Beach area, and the South Beach area.

Recommended Long-Term (LT) Improvements

Crystal Beach Recirculation (LT-1) – Add a pressure-boosting station in the Crystal Beach area located in the northern system. The new station will force water to continuously flow from the Crystal Beach area to the high-demand area.

Primary North Beach Recirculation (LT-2) – Add a pressure-boosting station at the central part of the North Beach area. The station will force water to continuously flow from the North Beach area toward the mainland.

Secondary North Beach Recirculation (LT-3) – Add a pressure-boosting station at the northern part of the North Beach area. The station will promote additional water flow through the North Beach area in the southward direction.

System TRC Boosting (LT-4) – Install up to three total chlorine boosting stations in the North Beach area. Model predictions show that implementing this improvement will increase the TRC levels in the North Beach area.

LT-1, -2, and -3 improve the TRC levels by decreasing the travel time of water through the areas in which they are implemented.

A new mathematical model was developed to evaluate the order of magnitude of the reduction in flushing water associated with the proposed improvement alternatives. First, total chlorine concentration versus cumulative volume curves were developed from the results of each model simulation. Then, the cumulative volume curve was divided into several segments, with relatively linear relationships between the cumulative volumes and TRC concentrations. The total water volume of each segment was determined based on the chlorine decay kinetics. The required flushing volume was then determined to achieve the target TRC level.

This mathematical model involved piecewise calculation of intermediate concentration values and needed flushing volumes. The Excel "Goal Seek" tool was used to iterate through Equations 3 and 4 to find a solution.

The condition of Future without Flushing (Simulation 3) is used as an example to illustrate this method. The corresponding cumulative volume versus concentrations graph is shown in Figure 7. The beginning and ending concentrations for each of the segments on the graph were tabulated as shown in Table 1. The formulas were used to determine the required flow rate that would result in each segment's predicted TRC concentrations.

Continued on page 58

$$Q_o = k \cdot V_o / \ln(C_i/C_o),\ Q_{i+1} = k \cdot V_{i+1} / \ln(C_{i+1}/C_i) \ldots Qn = k \cdot V_n / \ln(C_n/C_{n-1}) \quad \text{(Equation 3)}$$

$$C_i = C_o \cdot k{\cdot}V_o/(Q_o + Q),\ C_{i+1} = C_i \cdot k{\cdot}V_i/(Q_i + Q) \ldots C_n = C_{n-1} \cdot k{\cdot}V_{n-1}/(Q_{n-1} + Q) \quad \text{(Equation 4)}$$

Where: Q is the flow through the model segment to achieve a given end concentration based on a given start concentration; k is the global decay rate constant; V is the volume of model piping with concentrations between the given start and end concentrations for a segment; C is a given TRC concentration; and Q is the calculated flushing rate.

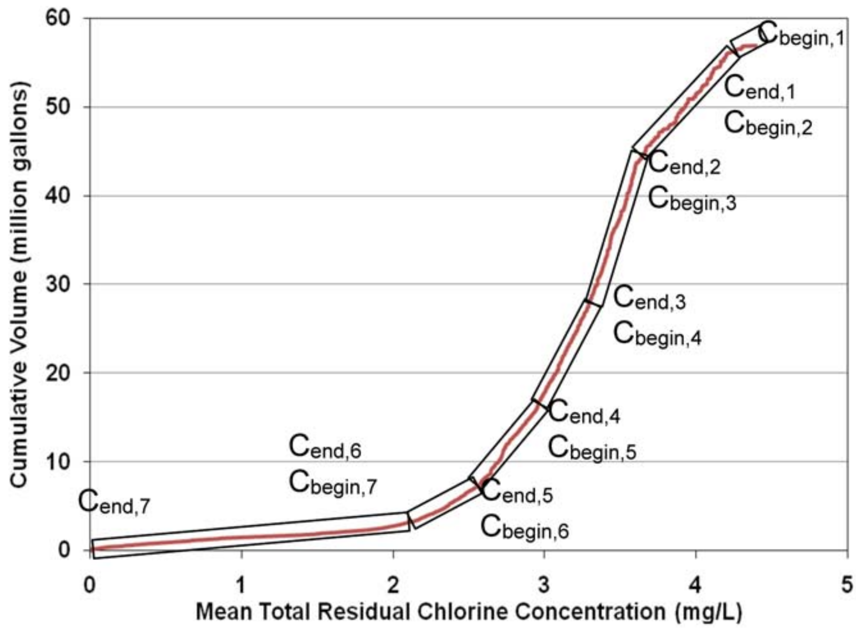

Figure 7. Total Residual Chlorine Concentrations versus Cumulative Volume Curve for Future Without Flushing

Table 1. Model Calculated Flushing Rate to Increase the Total Residual Chlorine

Segment	Volume (gal)	C_{begin} (mg/L)	C_{end} (mg/L)	$k_{overall}$ (d^{-1})	Q (gpd)	ΔQ (gpm)	C'_{begin} (mg/L)	C'_{end} (mg/L)
1	1048200	4.29	4.19	-0.40	16817100	1094	4.29	4.19
2	12355700	4.19	3.60	-0.40	32570700	1094	4.19	3.63
3	16553500	3.60	3.26	-0.40	66337400	1094	3.63	3.30
4	11250800	3.26	2.92	-0.40	40610100	1094	3.30	2.97
5	8590600	2.92	2.51	-0.40	22279700	1094	2.97	2.57
6	3518500	2.51	2.11	-0.40	8151700	1094	2.57	2.23
7	3222100	2.11	0.00	-0.40	88000	1094	2.23	1.03

Continued from page 57

Theoretically, increasing the flow rate through each segment would increase the ending TRC concentration. In the real system, this corresponds to the routine flushing of pipes to increase system TRC concentrations. Using the established segments, the theoretical required increase in flow rate to achieve a goal TRC concentration everywhere in a water system can be calculated.

The results in Table 1 show that the flushing water rate of 1,094 gpm is required to increase the model-predicted minimum TRC levels from 0 to 1.0 mg/L for the entire system at future reduced demand conditions.

This newly developed model was applied to each proposed system improvement and the required flushing rates to achieve different target TRC levels. Table 2 presents a summary of the estimated flushing volume reduction for various combinations of the proposed short- and long-term improvements for the utility. In this table, the current condition (2009, TRC > 1.0 mg/L) was used as a baseline to determine the potential flushing reductions through system improvements. Negative values indicate increases in the required flushing volumes.

The results in Table 2 suggest that the required flushing rate can be potentially reduced by 35 percent in the future (reduced demand) to maintain target TRC of 1.0 mg/L, if all of the proposed improvements are implemented. The target TRC can be potentially increased to 1.5 mg/L in the future if the current flushing rate is maintained.

Table 2. Estimated Flushing Volume Reduction by System Improvements

Conditions/Alternative Improvements	Order of Magnitude Potential Annual Flushing Reduction			
	Target TRC >= 1.0 mg/L	Target TRC >= 1.5 mg/L	Target TRC >= 2.0 mg/L	Target TRC >= 2.5 mg/L
Current	0%	-30%	-166%	-492%
Future	-7%	-56%	-224%	-630%
ST-1	-1%	-52%	-221%	-623%
ST-1, -2, -3	18%	-18%	-144%	-456%
ST-1 , -2, - 3 & LT-1	18%	-18%	-145%	-458%
ST-1 , -2, - 3 & LT-2, -3	23%	-23%	-162%	-493%
ST-1 ,- 2, - 3 & LT-1, -2, -3, -4	35%	-1%	-120%	-421%

Summary

Distribution system nitrification has negatively affected water quality in the utility's water system. To improve water quality and reduce the flushing volume, the county's hydraulic model was updated. A calibrated TRC model was developed to simulate the total chlorine levels for different system improvement alternatives. The model results were used to help develop recommended corrective actions to mitigate persistent nitrification issues and reduce the flushing. The following major improvements were proposed to improve the distribution system water quality based on the modeling results:

- Combine the two water sources (groundwater and regional blend) into one water source to eliminate the water quality interface in the northern system.
- Provide total chlorine boosting at major distribution pump stations.
- Provide recirculation pump stations in low-flow areas to improve the hydraulic conditions.

The TRC model results showed that these improvements significantly increase the total chlorine levels and reduce the required flushing volume. The results of this project suggest that water quality modeling is a useful tool to investigate system water quality and plan system improvements. Pinellas County Utilities is implementing these recommended improvements to help maintain the system's water quality and improve its operation.

Acknowledgements

The authors thank the Pinellas County Utilities engineering and environmental services, laboratory, operations, and maintenance staff who participated in, and provided the data for, this project. The authors also gratefully acknowledge the technical support from William Lovins, Ph.D., of AECOM, and Steven Duranceau, Ph.D., of the University of Central Florida.

References

- Clark, R.M. and Grayman, W.M. (1998) "Modeling Water Quality in Drinking Water Distribution Systems," American Water Works Association, Denver, CO.
- Hua, G.H.; Baggett, C.; Hall, J.; Powell, R.; Reed, T.; Friedrich, T.; Stasis, P. (2011) "Controlling Nitrification in a Distribution System Receiving Blended Multiple Source Waters: The Experience of Pinellas County Utilities," *Florida Water Resources Journal*, December, 42-48.
- Wilczak, A.; Jacangelo, J.G.; Marcinko, J.P.; Odell, L.H.; Kirmeyer, G.J.; and Wolfe, R.L. (1996) "Occurrence of Nitrification in Chloraminated Distribution Systems," *Journal AWWA*, 88(7), 74-85.