CHLORAMINES & COLIFORM: SHOULD YOU BE CONCERNED?

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Can a switch in the type of secondary disinfectant used in a drinking water distribution system result in an increase in coliform detects in drinking water as measured at consumer taps? The maintenance of a disinfectant residual in distribution systems has been historically used to protect against microbial water quality health impacts, but experiences reported by utilities have shown that microbes survive in actual distribution systems despite the presence of disinfectant residuals.

While utilities convert from chlorine to chloramines for secondary disinfection primarily to comply with disinfectant byproduct (DBP) regulations, their ability to maintain water quality during distribution and storage can be difficult. This has been shown by trends in the percentage of samples testing positive for total coliforms used to monitor bacteriological activity, as well as increases in heterotrophic plate counts within the distribution system. In addition, the amount of water used to routinely evacuate water lines and storage facilities containing undesired water quality (i.e. hydraulic flushing) increases.

Although discussed at length among water professionals across the country, less is published about subtropical conditions, such as those encountered in Florida, on the conversion of water systems from chlorine to chloramines as a secondary residual. This article discusses the issues and debate concerning the use of chloramines as a secondary residual and offers insight into solutions that lead to obtaining low coliform occurrence in warm-water distribution systems.

Total coliform bacteria are regulated under the Total Coliform Rule (TCR). They are used as indicator organisms for the presence of pathogens and alert for possible fecal contamination. It is well documented that drinking water quality can deteriorate during passage through distribution systems [Larson 1966]. Coliforms are found frequently in tap water; however, a tolerance of 5 percent for water samples testing positive is allowed under the TCR.

Bacteria are able to grow in distribution systems, even in the presence of a disinfectant residual. Also, bacterial regrowth can result in positive coliform samples [LeChevallier et al 1987]. Because many coliforms are able to survive and regrow in distribution systems, their presence does not necessarily indicate recent contamination. The factors that affect bacterial regrowth include temperature, amount of biodegradable organic matter (BDOM) disinfectant residual, corrosion products, and accumulation of sediments.

Coliforms are a group of bacteria that are widely present in both the environment and digestive tracts of humans and animals. These organisms comprise a group of closely related single-cell microorganisms that are rod-shaped and in the family *Enterobacteriaceae.* The coliform group includes most species of *Citrobacter*, *Enterobacer*, *Klebsiella* and *Escherichia (E.) coli*, and some species of *Serratia*, among others. While most of these bacteria are harmless, their presence in water at levels that are above the Environmental Protection Agency (EPA) standard indicates that pathogens may also be in the water.

Among the health problems that pathogens can cause are diarrhea, cramps, nausea, and vomiting. Together these symptoms comprise a general illness category known as gastroenteritis. While gastroenteritis is not usually dangerous for healthy adults, it can lead to more serious problems or even death for people with undeveloped or weak-

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ABOVE: Photograph of coliform on MacConkey's agar.
PHOTO BY MARSHA PRYOR, courtesy Pinellas County Utilities

LEFT: Syed Ali and John Hoffman perform coliform analysis for Pinellas County Utilities.
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ened immune systems.

Testing water for each of a variety of microbes would be difficult and expensive, but coliform can be detected easily in water; therefore, coliform levels are used to indicate whether a water system may be vulnerable to pathogens in the water.

Under the Total Coliform Rule, the EPA set a health goal of zero for total coliforms. Systems may not find coliforms in more than 5 percent of the samples they take each month [USEPA 1999]. If more than 5 percent of the samples contain coliforms, water system operators must report this violation to the state and the public. Most water systems test coliforms throughout the distribution system on a monthly basis. Some test many times per day, depending on the system size, with larger systems generally testing the most often.

Chloramines & Coliform

Chloramine is generally considered to be a less-effective disinfectant than free chlorine because higher concentrations of chloramine are needed for an equivalent level of bacterial inactivation. Regardless, many utilities have switched to chloramines as a secondary disinfectant in order to comply with DBP regulations, rather than to control total coliforms [Kreft et al 1985].

Although chlorine is less efficient for the inactivation of biofilm bacteria than for bacteria present in bulk water in northern (cold climate) water systems, relatively low chlorine residuals (between 0.05 mg/L and 0.5) have been successful in controlling the presence of coliform bacteria in a distribution system in those same systems [Besner et al 2001; Kiene et al 1999]. Free chlorine threshold values of about 0.1 mg/L have been successful in keeping the rate of coliform detects low; that is, as soon as chlorine could be detected in the system, it was found to inactivate the coliforms in the bulk water phase [Parent et al 1996].

The use of chloramine for DBP control does not necessarily make it the ideal choice for coliform control in warm-water systems because it is less efficient than free chlorine in controlling a sudden pulse of contamination and can lead to nitrification [Snead et al 1980; Wilczak 1996]. Recent work has demonstrated that choramines have a negligible benefit in terms of protection against intrusion for even relatively susceptible organisms such as *E. coli.* [Baribeau et al 2005]. The work recommended that the current trend of replacing free chlorine with chloramines for secondary disinfection should be re-evaluated in terms of the loss of protection against possible microbial intrusion. Other findings included:

- Heterotrophic plate counts (HPCs) were more predominant among water utilities using chloramine for residual disinfection than those reliant upon chlorine. Chloramine users that experienced bacteriological episodes that occurred in the presence or absence of significant chlorine residual found that they were likely due to nitrification in chloraminated systems.
- The practice of maintaining free chlorine residual in the distribution system protects against intrusion.
- Free chlorine was more efficient at inactivation of suspended and attached HPC than monochloramine at similar CT values. The results differed from the common understanding that chloramines were more efficient at inactivation of biofilm bacteria than free chlorine.
- The proportion of the total chlorine residual comprised of organochloramines was significant, and increased with water age. The results suggested that total chlorine residual measured at distribution system sample sites with high water age may overestimate the efficacy of the disinfectant residual. The presence of organochloramines is important because it suggests that disinfection potential may be compromised.

Case Study: Pinellas County Utilities

The following case study highlights the challenges observed in a variable water-quality environment—the Pinellas County Water System (PCWS)—resulting from conversion of free to combined chlorine residual disinfection and augmentation with a regional blend comprising variable amounts of treated ground, surface, and desalted sea water.

Background

Pinellas County Utilities (PCU) serves approximately 657,000 customers along Florida's Gulf Coast. In addition to supplying water to customers in unincorporated portions of the county, PCU is the wholesale supplier of potable water on a continuous basis to the cities of Oldsmar, Clearwater, Pinellas Park, Tarpon Springs, and Safety Harbor. PCU also supplies water intermittently to the city of Belleair and to Pasco County, as well as the city of St. Petersburg on an emergency basis.

Groundwater from the Floridan Aquifer was the exclusive source of potable water for Pinellas County for more than 50 years. Water quality from this extensive aquifer system is very stable, with relatively little variation in important parameters such as mineral content, pH, organic carbon, and alkalinity.

The county operates the S.K. Keller Treatment Plant, comprising two separate facilities. Treatment includes an advanced aeration process that uses forced draft aeration to strip hydrogen sulfide contaminants from the water, a corrosion inhibitor injection, and a chlorination process for purification.

From a hydraulic and operational standpoint, the PCWS functions as two large distribution systems. The northern system is generally served and controlled from the S.K. Keller Plant, and the central/southern system receives water from the regional supplier, Tampa Bay Water (TBW) that is controlled by the North Booster Pumping Station. Water entering the system from these two locations intermingles in the distribution system with a variable interface location, depending on demand.

In 2002, source waters delivered to the county by TBW changed from 100-percent groundwater to include a variable blend of groundwater and surface-water sources. Desalinated seawater was added to the mix in April 2003. Prior to blending multiple source waters, the groundwater sources, although supplied from separate wellfields, were very similar and received similar treatment prior to introduction into the distribution system.

The TBW regional system is extensive, spanning approximately 45 miles from the desalination plant on the eastern shore of Tampa Bay to the delivery point in Pinellas County west of Tampa Bay. It comprises 12 wellfields, surface water from a river and canal system, and desalinated water from Tampa Bay. A combination of water from any of these sources may be delivered to Pinellas County by TBW at any given time. Another change includes the introduction of treated water from a large surface-water reservoir. Travel time under average flow conditions is approximately two days through large-diameter concrete pipelines.

TBW elected to change secondary disinfectant to chloramine from free chlorine to comply with the DBP Rule. Removal of organic precursors to levels sufficient to permit secondary disinfection with free chlorine was considered but was not implemented because of significantly higher capital costs. The Pinellas County Board of County Commissioners opted to change secondary disinfectant to chloramine for the same reason. As a result of the implementation of alternative water supplies by TBW, Pinellas County and its consecutive and wholesale customers now receive water substantially different from the groundwater sources that have historically supplied their systems.

Water Quality Master Planning – Analysis of Probable Impacts

In anticipation of changes in supply, water-quality master planning activities were performed to conceptually analyze impacts by examining existing information and water quality of predicted blends to be supplied to PCU by TBW (JEA-Boyle, December 2000).

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TABLE 1

Historical Water Quality for Ground and Alternative Blended Supplies

Parameters	SK Keller WTP Groundwater			Keller Connector TBW Regional Blend		
	Min	Average	Max	Min	Average	Max
Alkalinity (mg/L as $CaCO_3$)	183	195	205	101	151	254
Calcium Hardness (mg/L as $CaCO_3$)	180	187	197	146	208	278
Chloride (mg/L)	14.0	17.7	24.0	6.0	24.2	67.0
Color (CPU)	0	0	0	0	3	10
DO (mg/L)	6.7	8.3	9.2	0.5	6.5	12.3
Fluoride (mg/L)	0.00	0.03	0.16	0.00	0.20	0.60
HAA5 (mg/L)	28	36	77	0	9	24
Iron, total (mg/L)	0.00	0.02	0.27	0.00	0.06	0.26
Monochloramine (mg/L)	2.5	3.6	4.6	2.1	3.5	4.8
Nitrate (mg/L as N)	0.00	0.08	0.16	0.04	0.28	0.59
Ortho-Phosphate (mg/L as PO_4)	0.37	0.51	0.58	0.06	0.33	0.49
pH (Std. Units)	7.26	7.78	7.92	7.25	7.78	8.23
Conductivity (mmhos/cm)	381	413	501	206	552	850
Sulfate (mg/L)	0.0	0.9	4.0	2	103	217
TDS (mg/L)	232	256	320	231	334	484
Temperature (!C)	21.8	24.9	27.1	18.9	24.4	30.0
Total Chlorine (mg/L Cl_2)	3.2	4.2	4.9	2.1	3.8	5.0
Total Hardness (mg/L as $CaCO_3$)	200	208	219	157	234	308
TOC (mg/L C)	3.5	4.0	4.3	1.4	2.4	3.5
Total Phosphorus (mg/L as PO_4)	0.71	1.11	1.29	0.00	0.57	1.10
TTHM (mg/L)	40	58	93	3	17	79
Turbidity (NTU)	1.24	2.00	3.24	0.11	0.33	1.25
UV-254 (cm^{-1})	0.10	0.12	0.13	0.03	0.05	0.07

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Many potential adverse impacts were predicted, including corrosivity, iron release, elevated HPC levels, increased brominated DBPs, chloramine residual loss, nitrification, taste and odor events, and colored water problems.

Most importantly, biofilm destabilization was predicted with uncertain impacts on TCR compliance, since the presence of significant amounts of coliforms within existing biofilms was unknown at the time. High probabilities were projected for regulatory compliance problems with the TCR, the Lead and Copper Rule (LCR), the Safe Drinking Water Act (SDWA) secondary standards, and annual consumer confidence reporting.

General Observations Following Introduction of Multiple Source Waters

Although the county currently complies with existing regulations, its ability to maintain water quality during distribution and storage has become increasingly challenging. This is supported by trends in the percentage of samples testing positive for total coliforms used to monitor microbial activity, increases in HPCs within the distribution system, consumer complaints (particularly rusty water and odor), and the amount of water routinely used to evacuate water lines and storage facilities containing undesired water quality (hydraulic flushing).

The significant differences in water quality between groundwater and the new regional blend is shown in **Table 1**. This data provides historical treated water quality at the county's two points of entry (POE) into the distribution system, one supplied by groundwater (S.K. Keller Water Treatment Plant) and the other supplied by the regional blend (Keller Connector). These values reflect the consistency of groundwater and variability of the regional blend.

Nitrification & Control

Nitrification was anticipated because of the switch to secondary disinfection with chloramines. The sheer volume of the PCWS, coupled with the particularly warm climate, made nitrification a serious concern for the county's system.

Storage facilities have been found to be most susceptible to nitrification. The PCWS contains eight concrete ground storage tanks providing approximately 40 million gallons of storage. Originally these tanks were constructed as "last-in, first-out," and several have no drain to permit wasting the water to storm drains or sewer systems if the need should arise.

Nitrification occurrences in the PCWS followed the classical response pattern of residual loss accompanied by decreases in free ammonia and dissolved oxygen, and increases in HPC, nitrite, and nitrate. By the fall of 2002, four finished-water storage tanks in the southern part of the distribution system began to experience low residuals, despite efforts to provide daily turnover of water through operational protocols. Total chlorine residuals declined from over 2.0 mg/L to nearly zero over approximately 30 days.

During the sample period, free ammonia declined to less than detectable and nitrite was measured in samples from the tank at 0.6 mg/L. Elevated HPC levels of greater than 2,000 cfu/mL were noted in some tanks undergoing nitrification. Areas of the distribution system served by the tanks also showed measurable nitrite levels and elevated HPC counts. Background levels of nitrite were less than the minimum detectable of 0.02 mg/L during free chlorine operations.

Nitrification control measures involve treating tanks with free chlorine at approximately 3.5 mg/L for 24 hours to stop nitrification. In two tanks, no drains were present, so the free chlorinated water was used as normal in the distribution system. Tanks were then typically re-filled with chloraminated water after being drawn down to a low level, and residuals were monitored in the tank and the distribution system to verify adequate residuals.

One of the four tanks was taken out of service indefinitely. The remaining tanks were monitored closely to detect early signs of nitrification, including chloramine residual loss, lower free ammonia, and elevated HPC and nitrite levels. Two tanks that remained in service required treatment with free chlorine approximately every four months to maintain acceptable water quality.

Estimated cost of additional monitoring at storage tanks was approximately $41,000 for 2004. Total estimated cost of additional monitoring related to nitrification and biostability for the operations department was $124,000 for 2004.

Engineering evaluations with regard to distribution system operation and maintenance practices recommended that each tank be drawn down to at least 50 percent of the maximum level on a daily basis (JEA and Boyle, 2001). At sites with multiple tanks, individual tanks are drained and emptied once every two weeks. After nitrification occurred in tanks on the southern end of the system, operating plans specified that tanks be filled no more than half full to facilitate turnover. Booster chlorination is provided at most stations to re-combine or scavenge free ammonia leaving the tank and to increase total chlorine levels. Given the constraints of system demand and fire protection, this was the best that could be done from an operational standpoint.

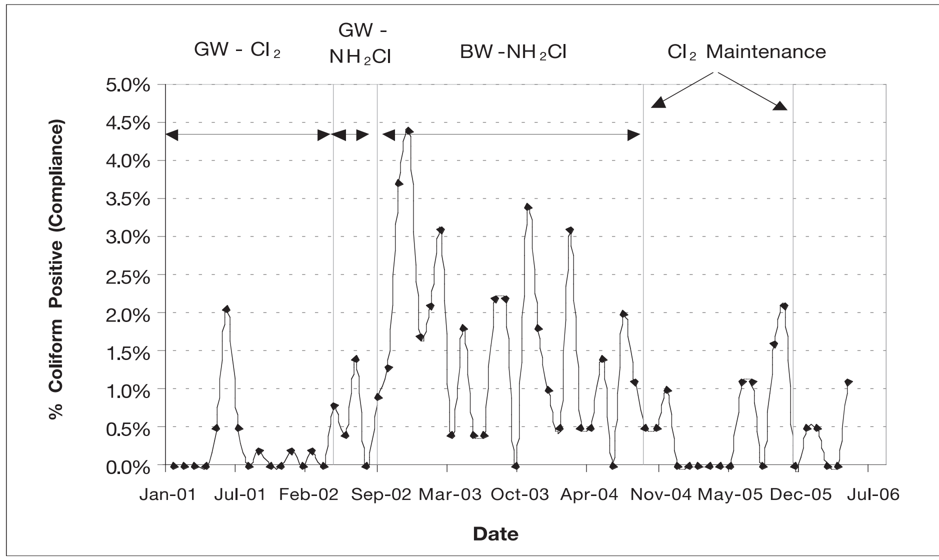
The system evaluation also identified the need to modify storage tank inlet and outlet pipe configurations. Following nitrification events and difficulty maintaining chlorine residuals, modifications were undertaken to convert storage tanks to "first-in, first-out" flow with complete mixing to minimize water age. In addition, chlorination systems at the stations were modified to permit circulation of water from the tank through the station chlorinators to boost residuals in the tanks.

The initial tank modification project began in July of 2004. Seven additional tanks have been modified for a total project cost of exceeding $1 million.

Biostability

A reduction in biological stability has consistently been the county's leading challenge since conversion to chloramines and alternative supplies. This problem is well documented and of primary concern because the margin of safety against regulatory non-compliance is significantly lower than prior levels with free chlorinated groundwater.

FIGURE 1
Routine Total Coliform Compliance Percent Positive Results



GW = Groundwater
BW = Blended Water

Cl2 = Free chlorine
NH2Cl = Chloramines

Changes in microbial water quality began in May of 2002 almost immediately after chloramination was implemented, with a significant increase in total coliform positive samples in the distribution system. Historical monitoring data for total coliform positives are presented for three different site classifications in **Figure 1**. It can be seen that coliform, under conditions of chlorine as the secondary disinfectant, was detected on average at a much lower rate than when chloramine was used as the secondary disinfectant. In fact, the total coliform occurrence rate prior to chloramine implementation was 0.25 percent (40 out of 15,441 compliance samples collected from October 1996 to May 2002).

Not shown, but equally important, are results of monitoring for coliform at non-compliance sites, used by the county laboratory to ascertain the overall quality of the county's system. Over 26 percent of the county's non-compliance sites were coliform positive in May of 2002, peaking in October of 2002 with over 54 percent of the non-compliance sites positive for coliforms. These high percentages should be qualified by the relatively low number (13) of non-compliance sites collected per month.

Main clearance samples averaged 2.4-percent total coliform positive in the 16 months prior to May of 2002, with a peak of 8.3. The percent total coliform positive for main clearance samples for May 2002, when chloramination was implemented, was almost 26 percent with an average of 12.5-percent over the 24 months following the switch to chloramination. The number of main clearance samples, while considerably larger than the number of non-compliance sites, was still much lower than the roughly 200 compliance sites collected monthly.

Leading up to the change in disinfectant and source of supply, the average percent coliform positive rate from 1996 to April 2002 was 0.25 percent. The average percent positive coliform rates increased to more than 1.5 percent for the period May through December 2002. Further increases were noted with the 2003 annual average percentage over 2.5 percent.

Biofilms

After the switch to chloramines, water and biofilm samples were collected throughout the distribution system and analyzed for field and laboratory parameters in addition to *Legionella*, *Mycobacteria*, and *Helicobacter pylori.* (Pryor, M. et. al., 2004). Coliforms were added as a parameter of interest because of significant increases in positive coliform samples in the distribution system with chloramination.

Several separate studies were conducted during a four-year period using various methods to evaluate biofilms. In general, the different methods produced similar results. Each analytical method indicated more biomass on iron surfaces than on PVC surfaces, a decline in overall viable biomass with chloramination on iron surfaces, but biomass increasing over time on PVC surfaces with both chloramines and chlorine.

A report by the University of Central Florida supported the observations noted by the county; in addition, the study showed that cement-lined ductile iron pipe supported greater biomass than unlined iron for the subtropical conditions studied (Taylor et al, 2004). In biofilms collected from pipe coupons cut from actual distribution system pipes, coliforms were detected at approximately 50 percent of the sites. Pipe material was not related to the presence or absence of coliforms, which were detected in biofilms more frequently than in bulk water samples.

A study done in conjunction with the Centers for Diseases Control regarding shifts in *Legionella* and *Mycobacteria* populations in the distribution system pre- and post-chloramines indicated that *Legionella* occurrence diminished with chloramination. The number of sites positive for *Legionella* declined after chloramination, although the number of organisms in positive samples did not decline. *Mycobacteria* did not diminish with chloramination, but increased, both in frequency of occurrence and number of organisms. Denaturing gradient gel electrophoresis (DGGE) analysis of biofilms from distribution system sites indicates *Mycobacteria* became a dominant group in system biofilms after chloramine implementation. The shift in dominant organism may indicate a shift toward higher assumed acute health risk, and more work should be performed to investigate this apparent change in biofilm.

Flushing

Flushing is a primary method of addressing water-quality deterioration in the PCWS. Deteriorated water quality generally includes reduced disinfectant residual, positive coliform samples, high HPCs, and customer complaints. The county employs staff trained specifically to evacuate water from the system by manually opening fire hydrants, blow-off valves, or maintaining

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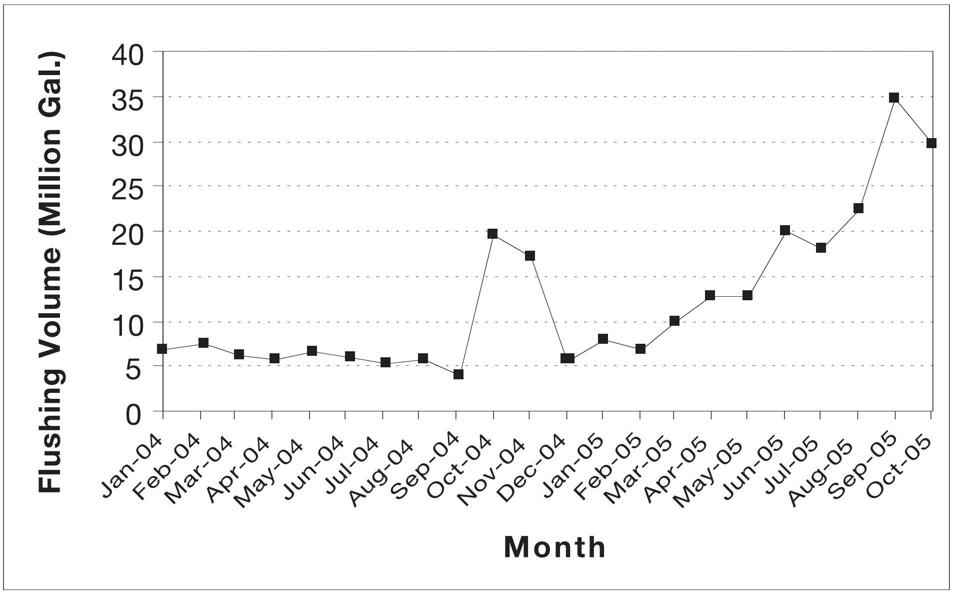
FIGURE 2
Monthly Flushing Volumes from January 2004 to September 2005



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automated flushing devices. Flushing is also used to facilitate a rapid conversion between disinfectants at the start and end of chlorine maintenance events. The amount of water used for flushing is presented in **Figure 2**. This data showed:

- Average flushing totals ranged from 4 to 6.8 million gallons (MG) per month prior to initiating chlorine maintenance in October 2004.
- More aggressive flushing was implemented from December 2004 to September 2005, with volumes gradually increasing from 5.7 to 35 MG per month.
- Chlorine maintenance requires high flushing volumes, as shown in the months of October and November 2004, when 37 MG were used. The volume required for disinfectant changeover is estimated at 20 MG.

The dramatic increase in flushing volumes during the post-chlorine maintenance period reflects the county's attempt to maintain water quality and maximize the time between chlorine maintenance events.

Flushing represents a significant cost to the county's distribution system water quality management program. These costs include, but are not limited to, labor, equipment, data management, and administration. Unbilled revenue is another cost that has increased considerably due to flushing. At a current billing rate of $4.04/kgal, the county loses $40,400 for every 10 MG used for flushing.

Beginning in May 2005, flushing volumes routinely exceeded 10 MG. This experience suggests a 28-percent cost savings could be realized by conducting chlorine maintenance two times per year instead of once per year.

Using the 12-month period from October 2004 to September 2005, flushing averaged 15.6 MG per month. This equals 187 MG total volume, or $881,000 in unbilled or lost revenue. Projected flushing volumes for a six-month frequency are based on the average flush volume of 11.2 MG observed during October 2004 through March 2005.

While still a significant volume, the 28-percent reduction translates into a $340,000 annual cost savings. Additional savings may also result from reductions in distribution system operations, but they will be partially offset by additional labor requirements by treatment plant staff required to implement chlorine maintenance twice per year instead of once per year.

Comparison of Free and Combined Chlorine

An important aspect of the county's experience is increased difficulty in maintaining disinfectant residual within the system—particularly during warm weather and periods of low demand. The county has historically used distribution main flushing to maintain residual disinfectant levels and address rusty water or other water-quality issues. Prior to chloramine implementation, it was reported by some that the need for flushing would decrease because of the increased stability associated with chloramines, but the county's actual experience has demonstrated otherwise, as chloramines have been found to dissipate quicker than free chlorine in some portions of the distribution system.

Chloramine instability is underscored by the county's routine maintenance flushing totals having increased from around 1 MG per month during free chlorine operations to up to 10 MG per month with chloramination. A $40 million galvanized pipe replacement program initiated in May 2003 and completed within 18 months helped address residual decay and rusty water complaint issues by replacing 116 miles of two-inch diameter galvanized pipe throughout the county's system.

Experience has also identified a 2.0 mg/L trigger level for flushing system to avoid complete loss of chloramine residual in dead ends and storage facilities. If not properly maintained, septic odors commonly result when residuals dissipate and HPC bacteria flourish.

Summary

Water purveyors should be concerned about how secondary disinfectant residuals impact coliform detects; however, little to no research has been conducted in Florida to investigate the interactions and relationships between a change to chloramines and the detection of coliform as impacted by changes in water chemistry under *subtropical conditions*.

Until the TCR is revised, water utilities will continue to use total coliform bacteria to assess the microbiological quality of their drinking water to comply with regulations (Pontius 2000). The potential impacts and total costs of changing secondary disinfectants should be carefully considered by utilities seeking to comply with a variety of drinking water regulations while optimizing water quality in distribution systems.

It can be expected that utilities in Florida considering augmentation through alternative supplies may encounter unwelcome surprises, particularly those that opt to meet Stage II DBP Rule compliance via chloramines rather than DBP precursor removal. This is because of the greater challenge in maintaining residual, rigorous flushing requirements, and increases in microbiological activity in the system.

As a result, the key elements of sound distribution system operation, monitoring, and maintenance will play an important role in Florida's ability to successfully manage water quality from multiple sources of supply. Consequently, utilities need to be aware of the real long-term costs associated with changing supplies and disinfectants when producing potable water and to plan fiscal budgets and staffing requirements accordingly.

References

- Baribeau, H. et al. 2005. *Impact of Distribution System Water Quality on Disinfection Efficacy*. Denver, CO: American Water Works Association.
- Besner, M.C. et al. 2001. "Understanding Distribution System Water Quality." *Jour. AWWA*. 93:7:101.
- Kiene, L et al. 1999. "Limit and Benefit of

Chloramine Residual for Water Quality Management in Drinking Water Distribution Systems: What is the Right Chlorine Residual?" *Jour. Applied Bacteriol.* 80:4:458.
- Kreft, P. et al. 1985. "Converting from Chlorine to Chloramine: A Case Study." *Jour. AWWA*. 77:1:38.
- Larson, T.E. "Deterioration of Water Quality in Distribution Systems." *Jour. AWWA*. 58:10:1307.
- LeChevallier, M.W et al. 1987. "Examination and Characterization of Distribution System Biofilms." *Applied & Envir. Microbiol.* 52:12:2714.
- Parent, A. 1996. "Control of Coliform Growth in Drinking Water Distribution Systems." *Jour. CIWEM*. 10:6:442.
- Pontius, F. 2000. "Reconsidering the Total Coliform Rule." *Jour. AWWA*. 92:2:14.
- Snead, M.C. et al. 1980. "The Effectiveness of Chlorine Residuals in Inactivation of Bacteria and Viruses Introduced by Posttreatment Contamination." *Water Res.* 14:403.
- USEPA. 1999. *25 Years of the Safe Drinking Water Act: History and Trends*. EPA 816-R-99-007, Office of Water (4606).
- Wilczak, A. et al. 1996 "Occurrence of Nitrification in Chloraminated Distribution Systems." *Jour. AWWA*. 88:7:74.
- Jones Edmunds & Associates and Boyle Engineering Corp. (December 2000) Water Quality Master Plan – Phase 1 Analysis of Impacts, Pinellas County Utilities, FL, December 2000.
- Jones Edmunds & Associates and Boyle Engineering Corp. (October 2001) Distribution System Operation and Maintenance Practices Evaluation, Pinellas County Utilities, FL, December 2000.
- Sutherland, D. January 2002. "Central Florida Drinking Water Could Run Out in Five Years." **www.monitor.net/monitor/0201a/floridawater.html**.
- Taylor et al. May 2004. "Required Treatment and Water Quality Criteria for Distribution System Blending of Treated Surface, Ground and Saline Sources - Draft Report." Denver, CO: American Water Works Association.
- Pryor, Marsha et. al. Proc. WQTC, 2004 – "Fate of Opportunistic Pathogens in a Drinking Water Distribution System During Changing WQ Conditions."

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