Experiences with Blending Multiple Source Waters In a Common Water Distribution System

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Many communities throughout the United States and its territories face a variety of environmental infrastructure challenges. Often they find it difficult to comply with the multitude of environmental regulations, not the least of which is the U.S. Environmental Protection Agency's Safe Drinking Water Act. Also, diminishing water resources have required communities to seek alternative water supplies that may or may not be compatible with existing supplies.

Continuing advances in regulatory constraints and aesthetic criteria for consumer water quality have driven the water community to seek new water supplies and treatment technologies that meet these criteria. Foremost among regulatory constraints are disinfection requirements, disinfection byproduct formation, and corrosion control regulations.

Consumers have become aware of regulatory violation through mandated public notification and Consumer Confidence Reports, and they have always been aware of the appearance, taste, and odor of drinking water.

Reasons for Blending Multiple Source Waters

Water-management issues across the state of Florida indicate that groundwater consumption is rapidly approaching sustainable yields. Of all the water consumed by Florida's 16 million residents, an estimated 93 percent of them rely on groundwater for their drinking water (Sutherland, 2002).

Because of projected population growth and its associated demand, it is becoming increasingly difficult to adequately meet demands exclusively with groundwater without adversely affecting lakes, rivers, streams, springs, and marshes. These bodies of surface water respond by receding or drying out completely due to the hydrogeological effects of potentiometric surface drawdown in the groundwater aquifer.

Responses to dwindling groundwater supply have taken various forms across the state. Among them are increasing conservation measures, developing alternative supplies, using alternative technologies, shifting coastal wellfield production inland, and culminating regional water authorities through interlocal agreements.

One long-term solution to meeting increased demands with limited water resources is to develop alternative sources from surface water, brackish water, and seawater. These supplies would then augment existing groundwater systems using water from each source, individually, or in combination.

This is an appealing approach because it better balances community and environmental needs; however, while it addresses the problem of limited water supply quantity, its implementation requires careful consideration with respect to managing water quality in potable-water distribution systems. This is particularly important when withdrawals are made in variable amounts from diverse sources because of the changing water-quality environment it creates. If it is ignored in the planning and implementation stages, unintended chemical and microbiological impacts on the distribution system can result.

Balancing Water Quality And Quality Objectives

The principle goal of any potable-water distribution system is to convey water on demand at sufficient quantity and quality. Unfortunately, treated water is subject to a myriad of chemical and biological reactions that diminish its quality en route to the consumer. Aside from breaches in the mechanical integrity of the piping network, leading factors responsible for water-quality degradation include:

- Loss of disinfectant residual.
- Bacterial regrowth.
- Reduced clarity caused by sediment re-suspension.
- Release of metal corrosion products within iron and/or dissolution of lead and copper pipe materials.
- Disinfection byproduct formation.
- Taste and odors from chemical and biological reactions.

Influential factors affecting the magnitude of these impacts are the quality of water entering the system, the condition of system piping and storage facilities, and water age. Consequently, the following four fundamental water-quality goals are inherent to any well conceived and operated potable water system:

- Comply with existing and known proposed regulatory standards.
- Produce water that is aesthetically pleasing by taste, smell, and appearance.
- Maintain high water quality throughout the distribution system.
- Produce water that is compatible and consistent within the water system.

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Achieving these goals requires continual evaluation to define optimal conditions. Defining these conditions involves finding a middle ground for cost, system dependability, and acceptable risk for water-quality degradation. Once a desired combination of these factors is determined, maintaining consistent operational set points maximizes their overall benefit.

Yet, consistency in operation is a far greater operational challenge in systems that utilize multiple source waters. Significant variation in the percent blend and the introduction of finished waters with dissimilar chemistry at different entry points into the system make managing water quality a considerably more difficult task.

Case Study: Pinellas County Utilities

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 Pinellas 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 on an intermittent basis to the city of Belleair and to Pasco County, as well as the city of St. Petersburg, but only on an emergency basis.

Groundwater from the Floridan Aquifer was the exclusive source of potable water for Pinellas County for more than 70 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.

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FIGURE 1: Interim Chemical Feed Facility used for regional blended water treatment.

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In 2002, source waters delivered to the county by the regional supplier, Tampa Bay Water (TBW), changed from 100-percent groundwater to include a variable blend of groundwater and surface water. Desalinated seawater was added to the mix in April 2003. Before these blended multiple source waters, the groundwater sources, although supplied from separate wellfields, were very similar and received similar treatment before being introduced into the distribution system.

From a hydraulic and operational standpoint, the Pinellas County Water System (PCWS) functions as two large distribution systems. The northern system is generally served and controlled from the S.K. Keller Water Treatment Plant, whereas the central/southern system controls water received from the regional supplier through the North Booster Pumping Station.

At the S.K. Keller Plant, the county treats forced draft aerated groundwater supplied by TBW for disinfection, corrosion control, and fluoridation. As for the finished water from the blended regional supply, it is received at the county's Interim Chemical Treatment Facility, shown in **Figure 1**, where it undergoes fluoridation on a continuous basis, and pH adjustment and disinfectant residual boosting as needed. Waters from these facilities enter the system from two separate points of entry and then intermingle in the distribution system with a variable interface location, depending upon demand.

The map presented in **Figure 2** shows that the 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. Travel time under average flow conditions is approximately two days through large-diameter concrete pipelines. The regional system comprises 12 wellfields, surface water from a river and canal system, and desalinated water from Tampa Bay. Another change will occur when a large surface-water reservoir is completed for raw surface-water storage.

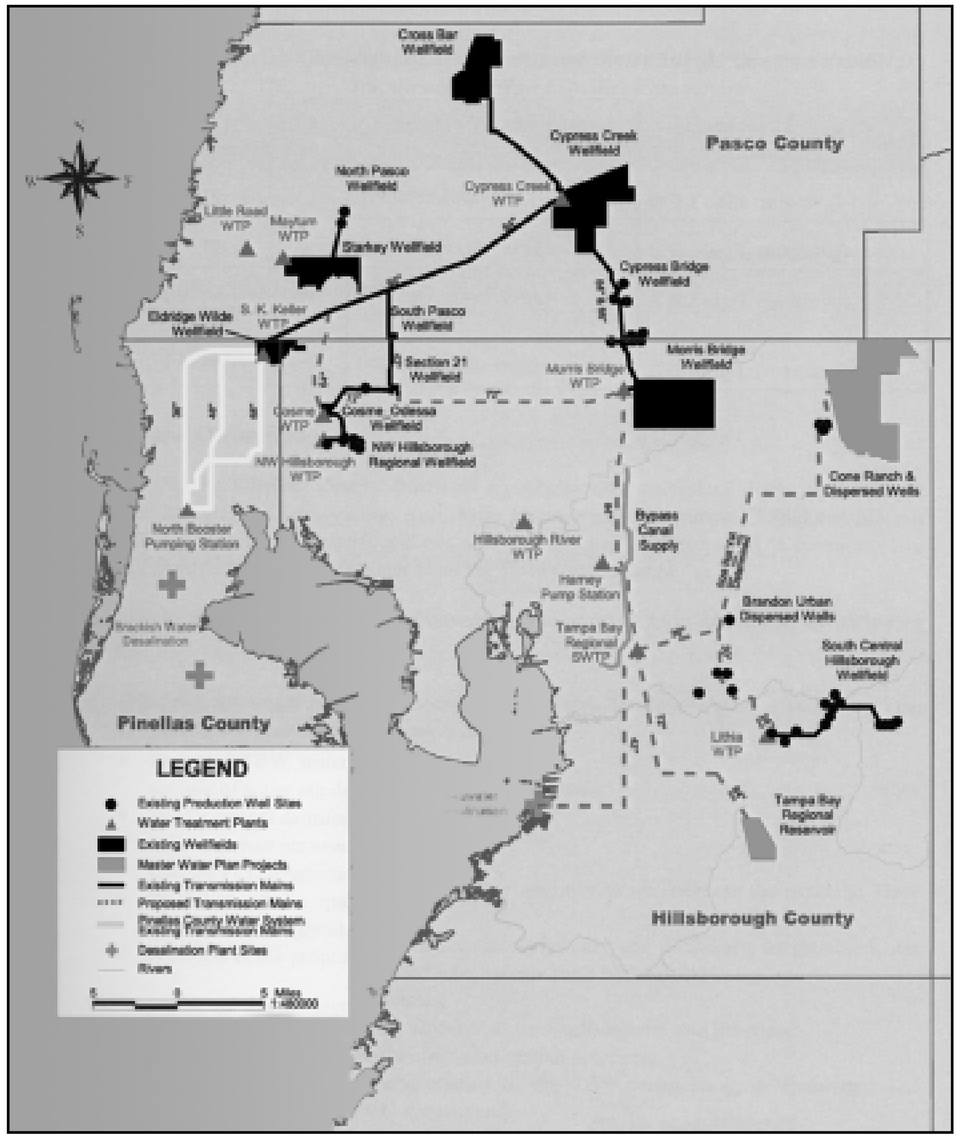

FIGURE 2: The Tampa Bay Water Regional Water System.

The regional supplier elected to change secondary disinfectant to chloramine from free chlorine to comply with the Disinfectants/Disinfection By-products Rule. Removal of organic precursors to levels sufficient to permit secondary disinfection with free chlorine was considered but precluded due to significantly higher capital costs. The board of county commissioners opted to change secondary disinfectant to chloramine for the same reason. As a result of the implementation of the alternative water supplies, PCU 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). Many potential concerns were predicted, including corrosivity, iron release, elevated heterotrophic plate count (HPC) levels, increased brominated disinfection byproducts (DBPs), chloramine residual loss, nitrification, taste and odor events, and colored water problems.

Also, biofilm destabilization was predicted with uncertain impacts on Total Coliform Rule (TCR) compliance, since the presence of significant amounts of coliforms within existing biofilms was unknown at that time.

General Observations Following Introduction of Multiple Source Waters

Many of the anticipated challenges identified in PCU's planning process have come to pass. While the county currently complies with existing regulations, its ability to maintain water quality during distribution and storage has become increasingly difficult. This situation is supported by the following increasing distribution system monitoring trends:

- Percentage of samples testing positive for total coliforms.
- Heterotrophic plate counts (HPCs).
- Consumer complaints (particularly rusty water and odor).
- Amount of water used to flush water lines and storage facilities containing undesired water quality.

Parameters	S.K. Keller WTP Groundwater			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 (µg/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 (µmhos/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 (µg/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

TABLE 1: Historical groundwater and regional blended water quality.

The significant differences in water quality between groundwater and the new regional blend are shown in **Table 1**. This data provides historical treated water quality at the county's two points of entry into the distribution system, the S.K. Keller groundwater and the regional blend received at the Interim Chemical Feed Facility. These values reflect the consistency of groundwater and variability of the regional blend.

Nitrification and Control

Nitrification was anticipated because of the switch to secondary disinfection with chloramines. Typical water age of three to five days, coupled with a warm climate, made nitrification a serious concern. Reviews of distribution system operation and maintenance practices recommended tank modifications and also a drawdown of each tank to at least 50 percent of the maximum level on a daily basis (JEA and Boyle, 2001). Despite these operational improvements, experiences to date show that storage facilities are particularly susceptible to nitrification.

The PCWS contains eight concrete ground storage tanks providing approximately 40 million gallons of storage. These tanks were designed as "last-in, first-out" and several have no drain to permit wasting the water to storm drains or sewerage systems if the need should arise.

Nitrification occurrences have 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 in an approximately 30-day period. During the sample period, free ammonia declined to less than detectable and nitrite was measured at 0.6 mg/L. In some tanks, elevated HPC levels higher than 2,000 cfu/mL were noted.

Areas of the distribution system served by the tanks also showed measurable nitrite levels and elevated HPC counts. These levels were significantly higher than the <0.02 mg/L background nitrite levels observed with free chlorine prior to chloramine operations.

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 are then typically refilled with chloraminated water after being drawn down to a low level and residuals are monitored in the tank and the distribution system to verify adequate disinfectant residual.

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. The two tanks that remained in service required treatment with free chlorine approximately every four months to maintain acceptable water quality.

The 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.

At sites where multiple tanks exist, individual tanks are drained and emptied once every two weeks. After nitrification occurred in tanks on the southern end of the system,

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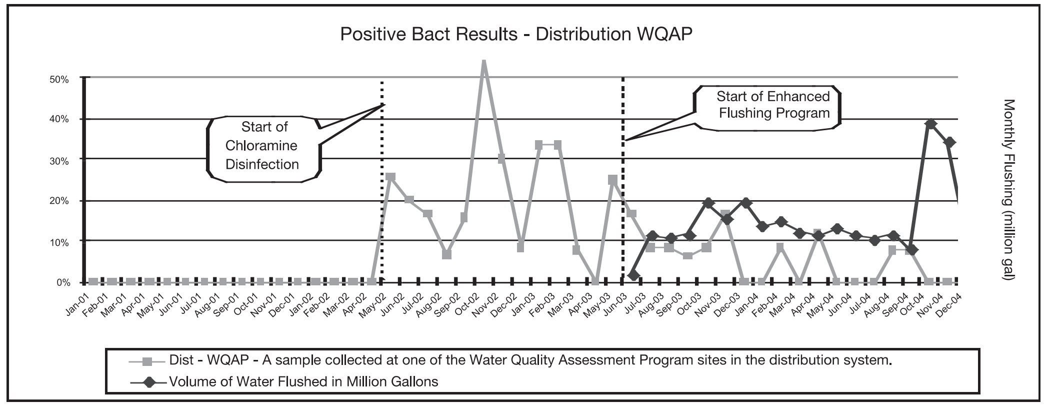

FIGURE 3: Positive coliform results at water quality assessment program sites.
Note: These sites not counted toward Total Coliform Rule compliance.

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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 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 engineering evaluations identified the need to modify storage tank inlet and outlet pipe configurations. Following nitrification events and difficulty maintaining chlorine residuals in storage tanks, modifications were undertaken to convert the 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 tank residuals.

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

Biostability

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

Changes in microbial water quality began in May of 2002, soon after chloramination was implemented, with a significant increase in total coliform positive samples in the distribution system. Historical monitoring data for total coliform positives is presented for three different site classifications in Figures 3 through 5.

The increased number of positive results was first noted at Water Quality Assessment Program (WQAP) sites and main clearance samples. **Figure 3** shows that 26 percent of the WQAP sites were coliform positive in May of 2002, peaking in October of 2002 with over 54 percent. In contrast, only one WQAP site tested positive when free chlorine was used.

As for main clearance samples, coliform positives averaged 2.4 percent, peaking at 8.3 percent with free chlorine in the 16 months leading up to conversion (**Figure 4**). Following the conversion to chloramines, percent positives reached 26 percent during the first month, then decreased over the next 24 months to an average of 12.5 percent.

Figure 5 shows coliform samples collected at Total Coliform Rule (TCR) compliance sites. Similar to the WQAP and main clearance sites, total coliform positives increased once chloramines were implemented. In May 2002, positive hits were approximately 1 percent, which was above average but within what was considered a possible worst-case range compared to historical results.

Leading up to the change in disinfectant and source of supply, the average percent coliform positive rate for all samples collected at compliance sites (whether or not they were TCR compliance samples) 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 of over 2.5 percent representing an order of magnitude increase from pre-chloramine conditions.

Biofilms

After the switch to chloramines, water and biofilm samples were collected at distribution system sites and analyzed for field and laboratory parameters, in addition to Legionella, Mycobacteria and Helicobacter pylori. Coliforms were added as a parameter of interest due to significant increases in positive coliforms.

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

One study showed unlined ductile iron pipe supported greater biomass than cement-lined iron (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. Coliforms were detected in biofilms more frequently than in bulk water samples.

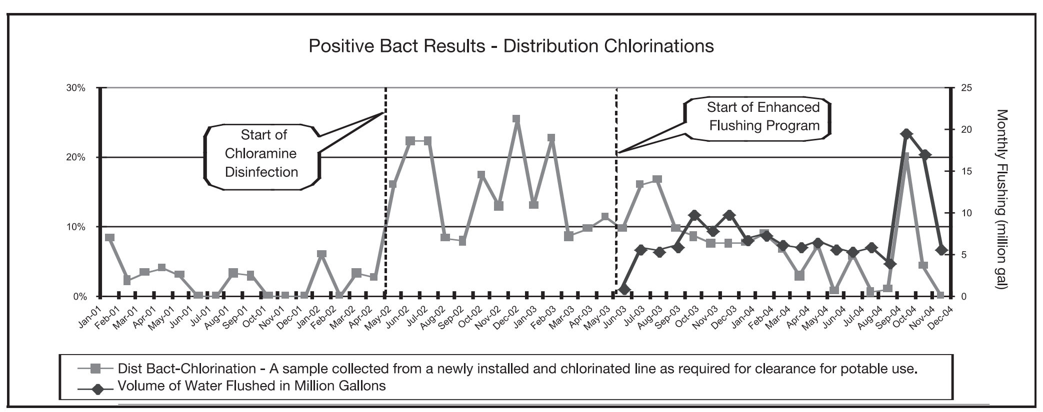

FIGURE 4: Positive coliform results at distribution main clearance sites.
Note: These sites not counted toward Total Coliform Rule compliance.

A study was done in conjunction with the Centers for Disease Control regarding shifts in Legionella and Mycobacteria populations in the distribution system. Comparison of pre- and post-chloramine levels indicated that chloramination diminished Legionella occurrences.

The number of sites positive for Legionella declined after chloramination, although the number of organisms in positive samples did not. Mycobacteria increased with chloramination, both in frequency of occurrence and number of organisms.

Denaturing gradient gel electrophoresis analysis of biofilms from distribution-system sites indicates Mycobacteria became a dominant group in system biofilms after chloramine implementation. This shift in dominant organism to Mycobacteria may affect any presumed acute health reduction due to lower Legionella occurrence.

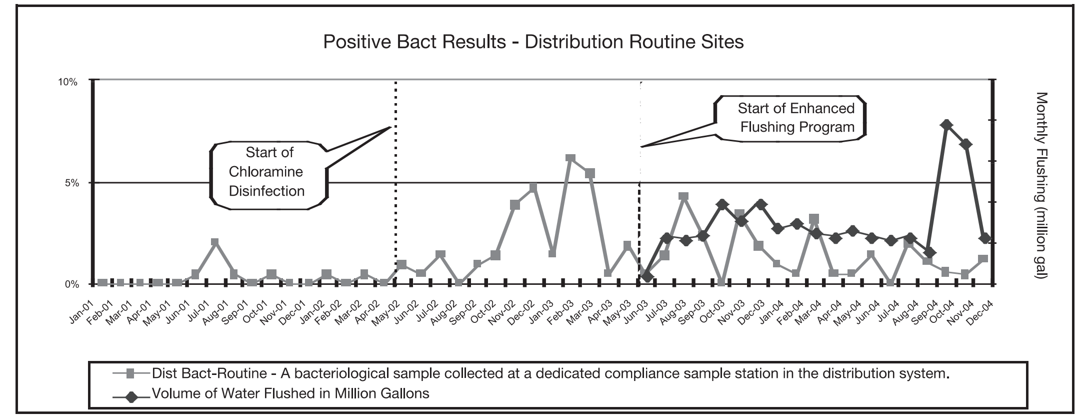

FIGURE 5: Positive coliform results at routine TCR compliance sites.

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/or periods of low demand. Historically the county has used distribution main flushing to maintain residual disinfectant levels, in addition to addressing 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; however, 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, which have increased from around 1 million gallons per month during free-chlorine operations to up to 10 million gallons 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 2-inch diameter galvanized pipe throughout the county's system.

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

Summary

In most groundwater distribution systems, some state of quasi-equilibrium has typically been achieved, and as a result, these systems often have minimal problems. As the Pinellas County experience indicates, however, continual changes in water quality and conditions can significantly affect water distribution systems when alternative water supplies supplement existing systems—such as when groundwater systems are converted to a mixture of surface water, groundwater, and desalted water. The shifting chemical equilibrium between the bulk water column and internal pipe surfaces creates more perishable finished water of generally lower quality.

In response to these challenges, the regional supplier has implemented processes such as alkalinity adjustment that have benefited the regional member governments. Moreover, the county and TBW are working together to solve water-quality issues as they arise to enhance alternative source-water utilization in the region. Continued attention to water quality is also significant in maintaining long-term consumer confidence.

Other utilities in Florida that are considering augmentation through alternative supplies can expect to encounter unwelcome surprises if water-quality considerations are not taken into account at every phase of planning and during implementation—particularly for systems that opt to meet Stage II DBP Rule compliance via chloramines rather than DBP precursor removal.

This situation results from the greater challenge in maintaining residual and the associated flushing requirements required to control microbiological activity in chloraminated systems. As a result, the key elements of sound distribution system operation, monitoring, and maintenance are even more important in successfully managing water quality from multiple and diverse sources of supply disinfected with chloramines. Hence, utilities need to be aware of the real long-term costs associated with changing supplies and disinfectants when producing potable water and to plan their fiscal budgets and staffing requirements accordingly.

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