Controlling Nitrification in a Distribution System Receiving Blended Multiple Source Waters: The Experience of Pinellas County Utilities

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Introduction

Pinellas County Utilities provides drinking water to approximately 800,000 customers through over 110,000 retail service customer connections and 24 wholesale customer connections. The Utility's public water system distribution network includes five pump stations and approximately 2,000 miles of piping.

All water supplied by the Utility is derived from sources owned and operated by Tampa Bay Water, the region's wholesale provider. The Utility's source water treatment system consists of the S.K. Keller Water Treatment Plant and the Regional Treatment Facility. The Keller plant treats groundwater from the Eldridge Wilde Wellfield. The treatment facility treats Tampa Bay's regional water. The northern Utility water system distribution network is served by the Keller plant's finished water and the regional supply water. The central/southern portion of the Utility's water system distribution network is served almost entirely by the regional supply water. The regional supply water is typically composed of a mixture of groundwater, surface water, and desalinated water. The mixture composition is variable.

The Utility has observed nitrification episodes in the distribution network since the system was converted to chloramines for secondary disinfection in 2002 (Powell et al, 2004). In the summer and fall of 2009, the Utility experienced the earliest reoccurrence of nitrification to date following a chlorine maintenance event in the beach community areas of the water system distribution network. This early onset of nitrification within the system was likely linked to low customer water consumption resulting from water use restrictions brought on by early drought conditions and possibly from a localized decrease in population.

This decreased water use in the chloraminated water system distribution network has contributed to persistent nitrification issues and low disinfectant residuals that are being remediated through increased water flushing and periodic free chlorine maintenance. The Utility authorized Jones Edmunds & Associates to upgrade its water system distribution network model and to help develop recommended corrective actions to mitigate persistent nitrification issues.

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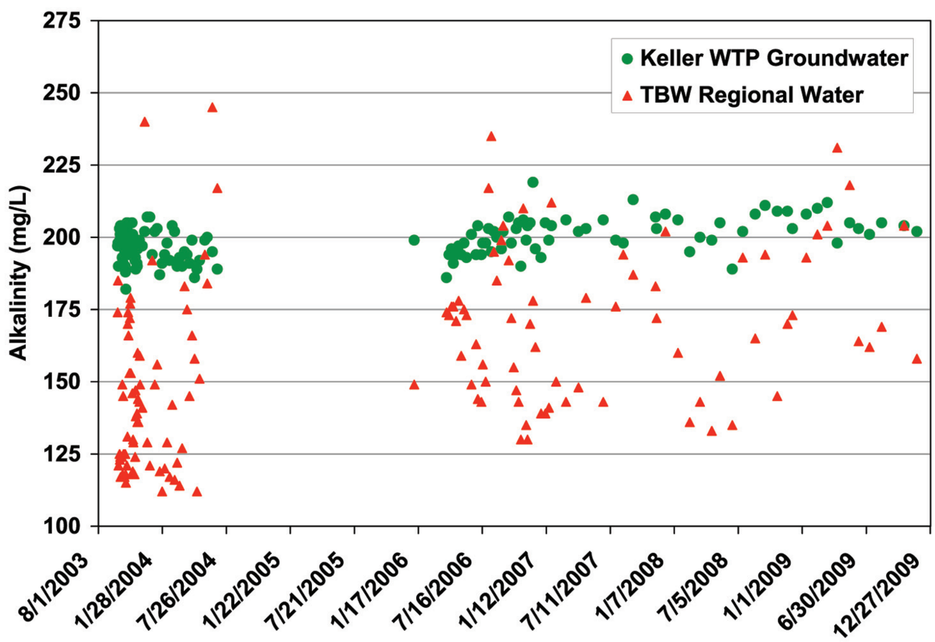
The Utility's historical water quality data was evaluated and system improvements were recommended based on the water quality modeling results. The nitrification control experiences of the Utility have significant implications for other Florida utilities that are considering augmentation through alternative water supplies and chloramination for disinfection byproducts (DBP) rule compliance.

Figure 1: Utility Distribution Network Points of Entry Water Quality – Alkalinity



Source Water Treatment and Quality

The Utility's water treatment goals under normal operating conditions at the distribution network points of entry (POE) are:

- Maintain 4- to 4.5-mg/L monochloramine residual
- Limit the concentration of free ammonia to less than 0.1 mg/L-N
- Maintain a pH of 7.7 to 7.9
- Maintain an ortho-phosphate concentration of 0.55 to 0.7 mg/L

Based on the Utility's 2009 monthly operation reports, the free-chlorine-to-ammonia ratio during chloramination varied from 3.7 to 4.9, with an average of 4.3 for the Keller plant. Total residual chlorine (TRC) in the Keller plant finished water ranged from 3.4 to 4.8 mg/L, with an average of 4.1 mg/L. Free ammonia entering the distribution network was between 0.06 and 0.32 mg/L. The average free ammonia concentration in the Keller plant finished water was 0.10 mg/L in 2009, and the finished water pH varied from 7.7 to 7.9 in 2009.

The treatment facility used free-chlorine-to-ammonia ratios from 3.4 to 5.5 for chloramination in 2009. The average ratio was 4.6. The TRC in the treatment facility finished water ranged from 3.5 to 4.9 mg/L, with an average of 4.4 mg/L. The finished water free ammonia varied from 0 to 0.47 mg/L, with an average 0.03 mg/L. The average pH of the treatment facility treated water was 7.9 in 2009.

These results suggest that the treatment processes at the Keller plant and treatment facility are well controlled to meet the treatment goals. The chlorine-to-ammonia ratios at the two facilities are controlled at approximately 4.5 to limit the POE free ammonia levels.

The water quality of two source waters for the Utility is significantly different. Figure 1 uses alkalinity as an example to illustrate the different water quality of the groundwater and the regional supply water. These two water sources create a water quality interface zone in the Utility's northern system. It has been challenging for the Utility to maintain water quality in the interface zone due to the variable water quality.

Table 1 compares the water quality of the two Utility water sources. These historical water quality data were measured at two POE to the distribution network—the Keller plant finished water and the regional supply water at the treatment facility. From 2003 to 2009, the Keller plant finished water showed lower levels of iron, bromide, chloride, and sulfate than the Tampa Bay regional water. The regional blend had lower alkalinity, total organic carbon (TOC), trihalomethanes (THMs), and haloacetic acids (HAAs) than the groundwater. The hardness, free ammonia, total chlorine, and pH of these two waters were comparable. Tampa Bay's regional water also showed a substantial variation in alkalinity, sulfate, bromide, chloride, and nitrate, while the groundwater was more consistent in water quality.

Continued on page 44

Table 1: Historical Keller Water Treatment Plant Groundwater and Tampa Bay Water Regional Blend Water Quality (2003–2009)

Parameter	Keller WTP Groundwater			TBW Regional Water			MCL
	Min	Ave	Max	Min	Ave	Max	
Alkalinity (mg/L as $CaCO_3$)	182	199	219	112	157	245	-
Bromide (mg/L)	0.000	0.002	0.100	0.000	0.062	0.220	-
Chloride (mg/L)	11	19	23	13	29	86	250
Free Ammonia (mg/L as N)	0.0	0.3	1.8	0.0	0.3	0.7	-
HAA5 (μg/L)	4.0	43.6	77.0	1.8	10.2	48.0	60
HPC (CFU/ mL)	0	37	2000	1	92	2000	-
Nitrate (mg/L)	0.000	0.030	0.190	0.000	0.216	0.600	10
pH (Std. Units)	7.3	7.7	8.1	7.4	7.8	8.1	6.5-8.5
Sulfate (mg/L)	2	3	5	5	94	185	250
TOC (mg/L)	3.1	3.9	4.8	1.3	2.3	3.9	-
Total Ammonia (mg/L as N)	0.0	1.0	2.6	0.3	1.0	1.8	-
Total Chlorine (mg/L Cl_2)	1.5	4.1	5.5	2.7	4.4	6.0	4.0
Total Hardness (mg/L as $CaCO_3$)	195	213	245	157	231	301	-
THM (μg/L)	43.5	68.4	104.0	9.1	18.8	79.2	80

MCL = Maximum Contaminant Level. HPC = Heterotrophic Plate Count.

Continued from page 43

Nitrification Control Practice

Many water utilities have switched from free chlorine to chloramines for secondary disinfection, primarily to comply with DBP regulations. 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 chloramine decay is sequentially oxidized to nitrite and nitrate. The nitrification is primarily accomplished by two groups of autotrophic nitrifying bacteria: the ammonia oxidizing bacteria (AOB) and the nitrite oxidizing bacteria (NOB). The AOB use free ammonia as an energy source and oxidize ammonia to nitrite (Equation 1). Subsequent oxidation of nitrite by NOB produces nitrate and completes nitrification (Equation 2).

$$NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2_e^- \quad (1)$$
$$NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2_e^- \quad (2)$$

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). Therefore, controlling nitrification is critical for chloraminated systems to provide high-quality water that protects the health and safety of the customers. Typical nitrification control measures include:

- Increasing entry-point and distribution TRC levels
- Reducing free-ammonia levels by using high Cl_2: NH_3 ratios
- Reducing water age through hydraulics improvements and storage facility management
- Flushing distribution pipes and replacing aged pipes
- Periodic free chlorine maintenance

The Utility has implemented an extensive nitrification control program to limit water system distribution network nitrification. Major nitrification control practices are summarized below.

Monitoring Distribution Network Water Quality

The Utility uses a number of water quality monitoring programs to assess its distribution network water quality. The Water Quality Assessment Program implemented in 1999 includes six storage tanks and over 30 distribution network sites in consecutive systems and the Utility's distribution network. Monthly samples are analyzed for an extensive list of microbial, chemical, and physical parameters. The Routine System Maintenance Program includes over 230 Utility distribution network sites monitoring multiple water quality parameters.

The Flushing and Monitoring Program records the system flushing practice and water quality parameters including pH, temperature, nitrite, and TRC, both before and after flushing. The Remote Stations Monitoring Program records the total chlorine, pH, temperature, nitrite, free ammonia, and total ammonia of each storage tank. In addition, the Utility has a long history and ongoing collaboration with various organizations to study the distribution network's water quality.

Distribution Network Remedial Actions and Triggers

The Utility has established distribution network nitrification control warning levels and action limits for the chlorine-to-ammonia ratio, total chlorine, free ammonia, pH, and nitrite. Table 2 summarizes the nitrification control action levels.

Reducing Available Free Ammonia

Free ammonia is the energy source for AOB. Maintaining the appropriate chlorine-to-ammonia ratio during chloramination can

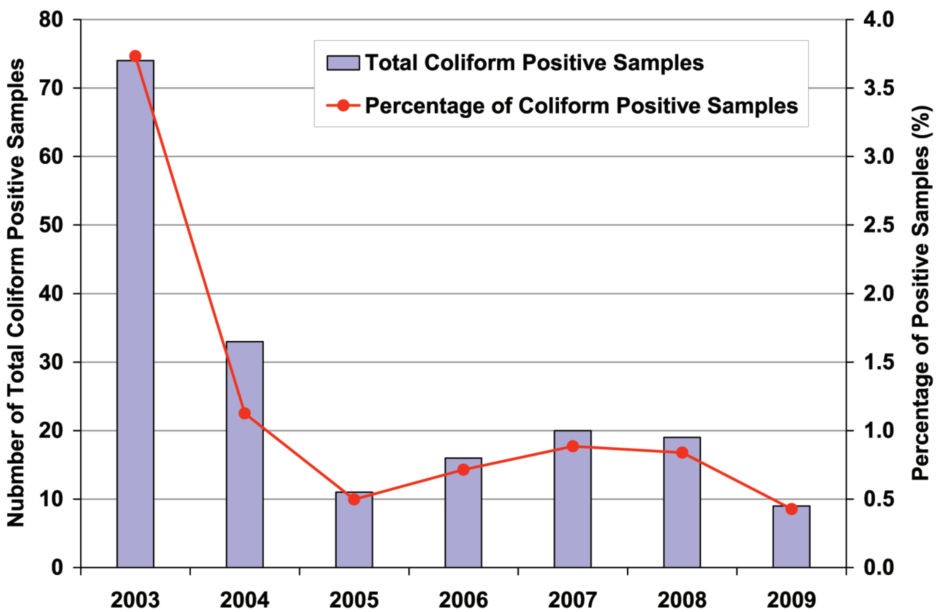
Table 2: Utility Distribution Network Nitrification Control Action Levels

Parameter	Normal Conditions	Warning Levels	Action Limits
Chlorine to Ammonia-N Ratio	4.5:1		
Total Chlorine	3.5 to 4.0 mg/L	< 2.5 mg/L	< 2.0 mg/L
Free Ammonia	< 0.2 mg/L	0.2 to 0.3 mg/L	> 0.3 mg/L
pH	7.6 to 7.9	< 7.6 and > 7.9	< 7.6 and > 8.0
Nitrite	< 0.005 mg/L	0.005-0.025 mg/L	> 0.025 mg/L

Table 3: Summary of Historical Free Chlorine Maintenance Events (2004–2009)

Year	Start	End	Duration (Days)
2004	October 25	November 14	21
2005	December 5	January 9, 2006	35
2006	September 18	October 23	35
2007	September 10	October 8	28
2008	August 25	September 29	35
2009	July 30	September 7	39

Figure 2: Utility Distribution Network Routine Monitoring Water Quality – Total Coliform



minimize the concentration of free ammonia and decrease the potential for nitrification. The current target for free ammonia at the Utility's POE is 0.02 mg/L. Free chlorine is added at the booster station storage tanks to remove free ammonia leaving the tanks.

Improving System Retention Time

The Utility has refurbished and modified its storage tank and standpipe facilities to improve storage tank mixing and reduce water retention times. The distribution network flushing volume has been substantially increased to maintain the system water quality (Lovins et al, 2007).

Breakpoint Chlorination

Utilities have periodically switched from chloramines to free chlorine for short-term nitrification control. The Utility has implemented a free chlorine maintenance program to improve distribution network water quality. Table 3 summarizes the historical free chlorine maintenance of the Utility from 2004 to 2009. Free chlorine residuals at POE were typically maintained at 3 to 5 mg/L during these free chlorine maintenance events.

Galvanized Pipe Replace Program

The Utlity replaced approximately 100 miles of small diameter (2-inch) galvanized steel distribution network piping. The primary purpose of this replacement was to reduce customer complaints associated with rusty water caused by changes in the chemical constituents of source water and chloramines. Replacing the pipes with polyvinyl chloride (PVC) pipe was recognized as an important enhancement to maintain chloramine residual by lowering the reactivity of chloramine with the pipe wall.

Distribution System Water Quality

Total coliform rule (TCR) compliance has been a concern for chloraminated distribution systems (Duranceau et al, 2006). Figure 2 shows the number of total coliform positive samples and the percentage of total coliform positives from 2003 to 2009. The total coliform positive samples have decreased substantially from 2003 to 2009. The routine monitoring sites showed 74 and 33 total coliform positives for 2003 and 2004, respectively. The annual total coliform positive samples were below 20 from 2004 to 2009. The annual positive rate decreased from 3.7 percent in 2003 to 1.1 percent in 2004 and have remained below 1 percent since 2005. The annual total coliform positive rates of 2005 to 2009 were well below the 5 percent TCR compliance threshold for monthly samples. These data suggest that the Utility currently maintains a relatively low rate of total coliform positive samples using chloramines as a secondary disinfectant. This suggests that a system may need time to stabilize the distribution microbial activity after the system is converted to chloramines from free chlorine. The operation and maintenance practice for water quality control may need to be adjusted for TCR compliance after the conversion. The high total coliform positive sample numbers that occurred in 2003 and 2004 resulted from multiple causes, including variable distribution water quality, operational changes, and infrastructure modifications. No apparent relationship between total coliform positives and total chlorine was observed. The total chlorine for the total coliform positive samples from 2003 to 2009 ranged from 0.6 to 4.4 mg/L, with an average of 3.2 mg/L.

Figure 3 shows the TRC results of the entire distribution network from 2003 to 2009. The annual median and mean TRCs remained between 3 and 3.7 mg/L. Most of the distribu-

Continued on page 46

Figure 3: Utility Distribution Network Routine Monitoring Water Quality – TRC

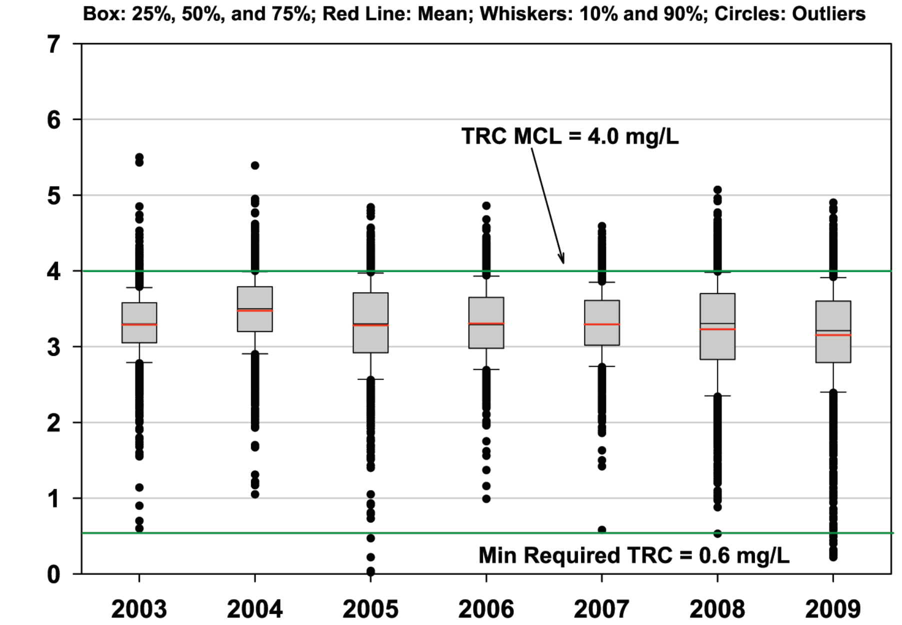
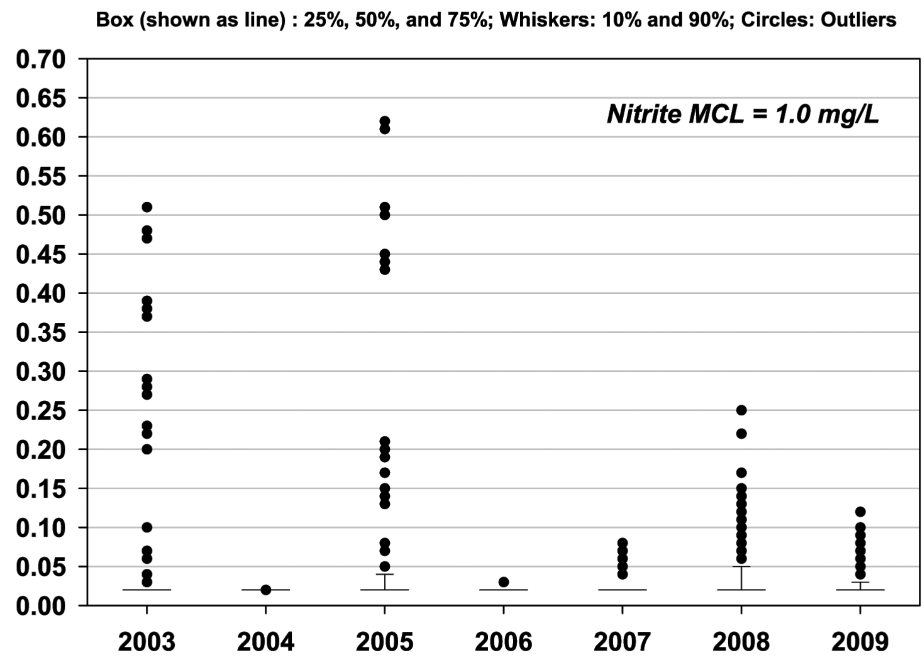


Figure 4: Utility Distribution Network Routine Monitoring Water Quality – Nitrite



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tion network TRCs (10 and 90 percentiles) were between 2.2 and 4 mg/L. Only 19 out of 16,973 samples showed TRC concentrations lower than 0.6 mg/L. Some of these samples occurred during free chlorine maintenance events when free chlorine was present in the system. In summary, historical TRC data suggest that the Utility maintains TRC levels above 0.6 mg/L in the entire distribution network.

The spatial analysis of the Utility's water system distribution network water quality suggests that the South Beach area and the North Beach area in the southern system present the most challenges for the Utility to maintain TRC in the distribution network. The chlorine residual loss in the southern system is primarily caused by the long water age, nitrification, and other water quality issues.

Nitrite is the first byproduct of ammonia oxidation by AOB. Therefore, the nitrite level is one of the most important indicators of nitrification in a system. Any nitrite occurrences exceeding the background levels may suggest the presence of nitrification. Figure 4 presents the nitrite concentrations of the routine monitoring sites from 2003 to 2009. More than 90 percent of the nitrite monitoring results were equal to or less than 0.02 mg/L. However, the nitrite concentration increased to as high as 0.6 mg/L in the distribution network as a result of nitrification.

Figure 5 shows the monthly average nitrite of each routine site in 2008 and 2009. No apparent trend in monthly nitrite concentrations was observed. There were significant variations in the nitrite levels before free chlorine maintenance. Nitrite levels reduced to baseline condition (0.02 mg/L) during free chlorine maintenance. Elevated nitrite was not observed within two months after the maintenance, however, elevated nitrite levels occurred in the system after that. This result agrees with the literature that free chlorine maintenance is effective at inhibiting nitrification, but nitrification is likely to return within several months after the return to chloramines, particularly in systems having warm temperatures throughout the year (Carrico et al, 2008).

Figure 6 presents the TRC concentrations at different nitrite ranges for the routine monitoring results from 2003 to 2009. The median TRC was 3.2 mg/L when nitrite was less than 0.02 mg/L, 2.6 mg/L when nitrite was between 0.02 and 0.04 mg/L, and 2.0 mg/L when nitrite was higher than 0.04 mg/L. The 10 to 90 percentiles of TRC also showed a substantial reduction when the nitrite level was higher than 0.04 mg/L. This result suggests that maintaining appropriate TRC levels in the distribution network can help inhibit AOB and prevent severe nitrification episodes. The data presented in Figure 6 indicate that the Utility needs to maintain a TRC level of 2.5 mg/L to help control severe nitrification episodes in the main pipes of the system.

The Utility performed a nitrification study from July 2008 to October 2009. The TRC, monochloramine, free chlorine, nitrite, and free ammonia were monitored biweekly for selected distribution sites and storage tanks. Figure 7 presents the TRC distribution at various nitrification conditions for the data collected during the nitrification study. The data were classified into two groups: the non-nitrifying samples and the nitrifying samples. *Nitrifying samples* were defined as those samples with positive field nitrite analysis, whereas *non-nitrifying samples* represented those samples with negative nitrite analysis. The median

Figure 5: Utility Distribution Network Routine Site Monthly Average Nitrite (2008–2009)

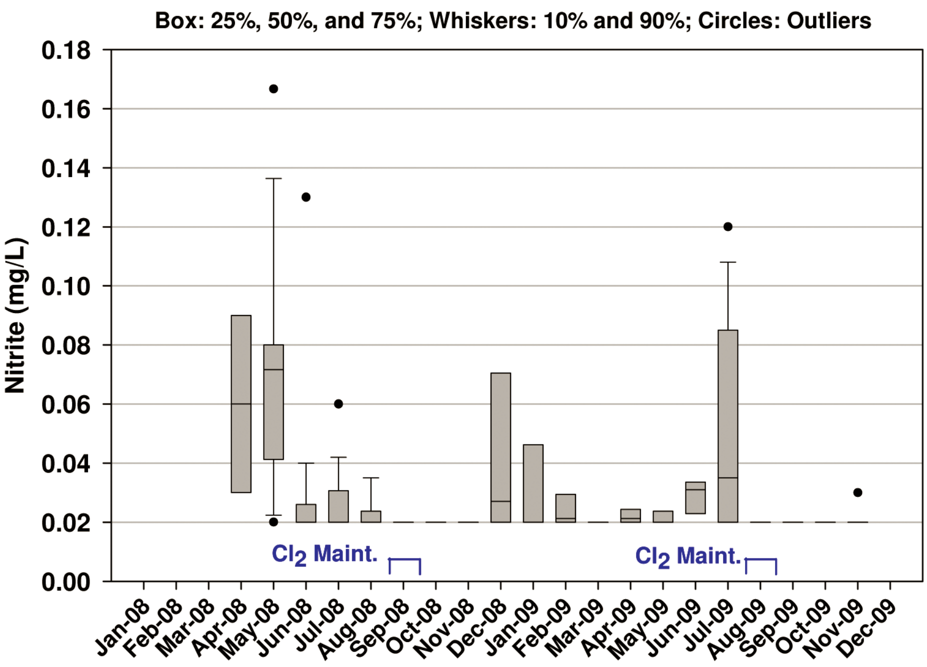
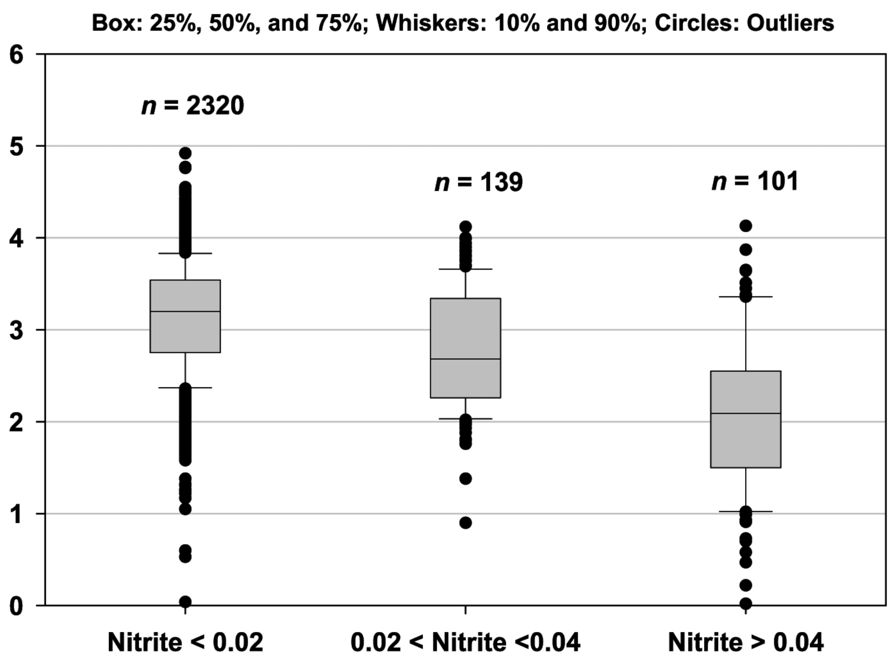


Figure 6: Utility Distribution Network TRC Distribution at Various Nitrite Ranges



TRC concentration of all non-nitrifying samples was 2.5 mg/L. Ninety percent of the non-nitrifying samples showed TRC levels higher than 2.0 mg/L. The median TRC of all nitrifying samples was 1.8 mg/L. Ninety percent of the nitrifying samples showed TRC levels less than 2.7 mg/L. The nitrifying samples were further grouped into three categories: <0.02 mg/L, 0.02 to 0.04 mg/L, and >0.04 mg/L. The median TRC was 2.2, 2.1, and 1.2 mg/L for these three groups. TRC was less than 2.0 mg/L for nitrifying samples with nitrite higher than 0.04 mg/L. This data analysis indicates that the system may need to maintain TRC above 2.0 mg/L to limit the occurrence of medium and severe nitrification episodes.

Figure 8 shows the NH_3/TRC ratio distribution at various nitrification conditions. For non-nitrifying samples, the median and 90 percentile NH_3/TRC ratios were 0.10 and 0.18, respectively. The median and 90 percentile NH_3/TRC ratios for all nitrifying samples were 0.16 and 0.30, respectively. The median NH_3/TRC ratio for nitrifying sample with nitrite less than 0.04 mg/L was between 0.1 and 0.15. A substantial increase in NH_3/TRC ratio was observed for nitrifying samples with nitrite higher than 0.04 mg/L. The median ratio was 0.18. These results suggest that NH_3/TRC ratio is a useful indicator for nitrification potential. Chloraminated systems should control the free-ammonia-to-total-chlorine ratio to reduce the nitrification potential in the distribution system.

Summary And Recommendation

The nitrification control experience at the Utility suggests that sound distribution system operation, monitoring, and maintenance play an essential role in managing water quality from multiple sources of supply. Comprehensive system monitoring and remedial actions are necessary for successful distribution system nitrification control.

Nitrification occurrences in the Utility's water system distribution network have followed the typical response patterns of TRC loss accompanied by decreases in free ammonia and increases in nitrite. The TRC levels and NH_3/TRC ratios showed strong correlations with nitrite levels in the system. High free-ammonia-to-total-chlorine ratios resulted in high nitrification potential in the Utility's distribution network and the water quality data indicate that maintaining TRC levels above 2.5 mg/L helps prevent the occurrence of severe nitrification episodes. Free chlorine maintenance was effective at inhibiting nitrification in the Utility's water system distribution network, but nitrification typically returned within several months after the return to chloramines.

Figure 7: Utility Nitrification Study TRC Distribution at Various Nitrification Events

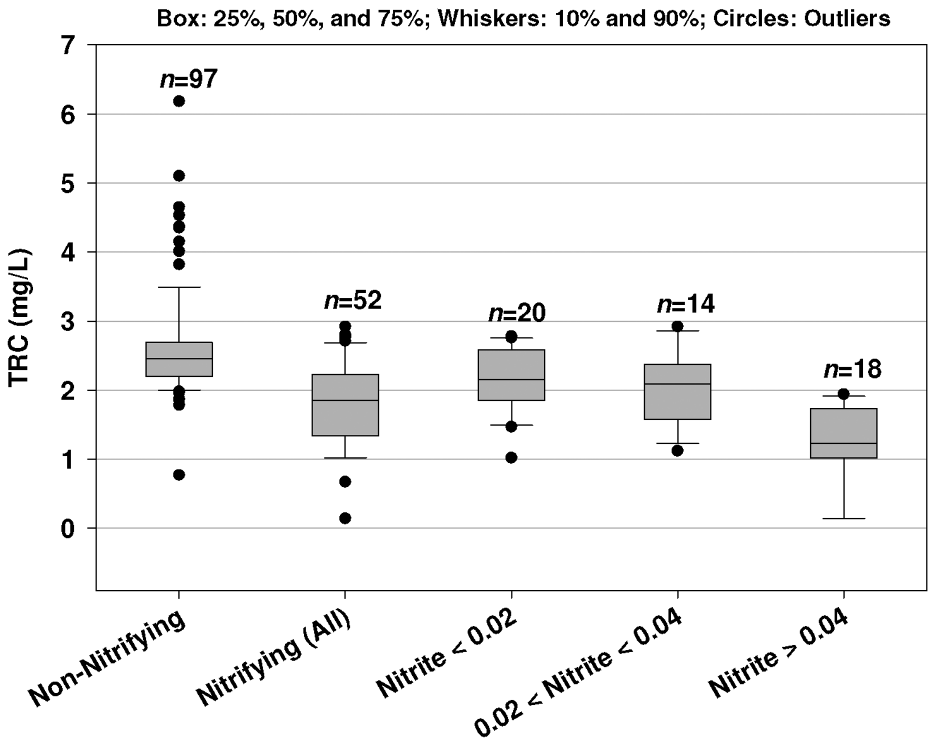
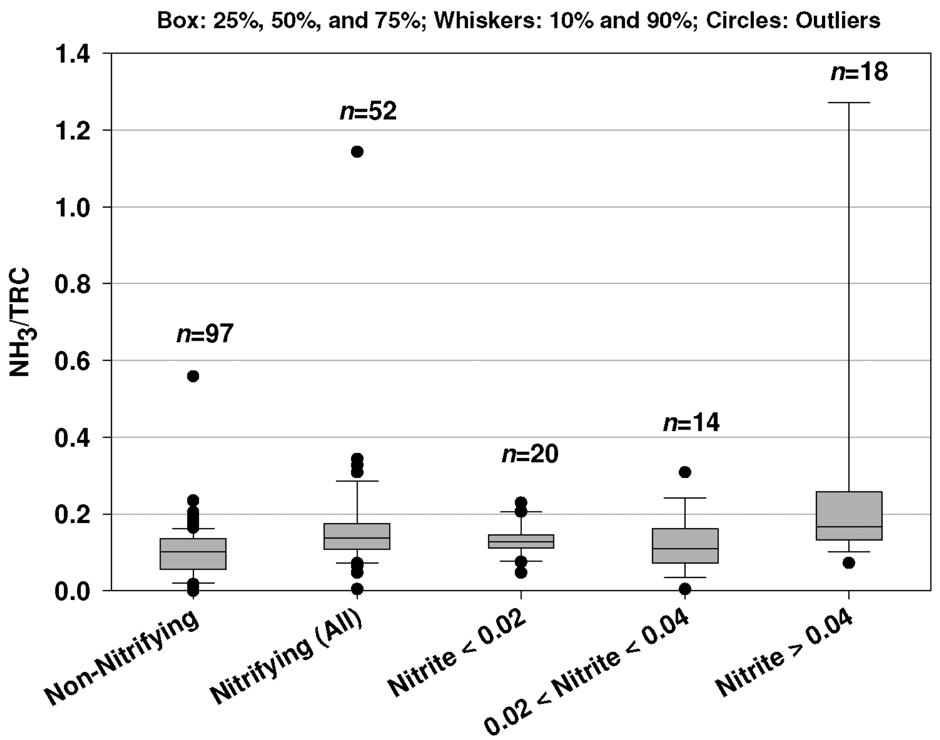


Figure 8: Utility Nitrification Study NH_3/TRC Ratios at Various Nitrification Events



To improve water quality and reduce the flushing volume, the Utility's water system model was upgraded using the updated distribution network information. The model results were used to help develop recommended corrective actions to mitigate persistent nitrification issues. The following major improvements were proposed to improve the Utility's water quality:

- Combine the two water sources (groundwater and regional blend) into one water source to eliminate the water quality interface in the northern system.

Continued on page 48

Continued from page 47

- Provide total chlorine boosting at the Utility's major distribution pump stations.
- Provide re-circulation pump stations at low-flow areas to improve the hydraulic conditions.

The TRC model results showed that these improvements significantly increase the distribution network TRC levels and reduce the required flushing volume (Jones Edmunds, 2010). Pinellas County Utilities is implementing these recommended improvements to help maintain the system water quality and improve the system operation.

Acknowledgements

The authors would like to thank the engineering and environmental services, laboratory, operation, and maintenance staff of Pinellas County Utilities 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.

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