In: Proceedings of the 2011© American Water Works Association AWWA WQTC Conference (Nov. 13-17, 2011, Phoenix, AZ)

Navigating Uncharted Waters: Assessing Geosmin Occurrence in a Colorado Rocky Mountain Source Water River

Jill Oropeza, Watershed Specialist
City of Fort Collins Utilities, Fort Collins, Colorado

Judith A. Billica, Water Quality Specialist
Northern Colorado Water Conservancy District, Berthoud, Colorado

Keith Elmund, Environmental Services Manager
City of Fort Collins Utilities, Fort Collins, Colorado

ABSTRACT

Geosmin is a naturally occurring, organic compound that imparts an earthy odor to water. Geosmin is produced by some species of cyanobacteria (blue green algae) and actinomycetes (a filamentous bacteria) and is difficult to remove during the treatment process. Customers are very sensitive to the odor, with some individuals noticing the odor at extremely low concentrations, from 4-5 ug/L. While it does not pose a threat to public health, its detectable presence can give rise to customer concerns about the quality the drinking water.

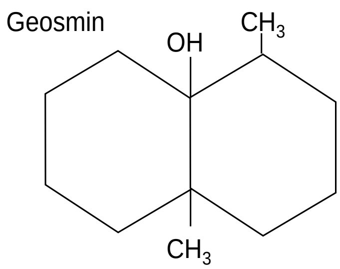
The presence of geosmin in water supply lakes and reservoirs in the U.S., Australia and Europe is well documented, although factors leading to outbreaks are often not well understood. The presence of geosmin in high quality, cold, turbulent, nutrient-poor Rocky Mountain headwaters is unexpected based on the reported experiences of others. The Cache la Poudre (Poudre) River originates in Rocky Mountain National Park on the east side of the Continental Divide and is one of two water sources for the City of Fort Collins, Colorado, Water Treatment Facility (FCWTF). Routine monitoring for geosmin in both FCWTF raw waters began in 2003 and has revealed episodes of elevated geosmin in the City's Poudre River water supply.

For utilities that experience episodes of geosmin in source water supplies, an early warning detection and monitoring program for geosmin is a critical tool for protecting drinking water quality, minimizing associated treatment costs and maintaining customer satisfaction. An understanding of geosmin occurrence, sources, transport and fate is essential before watershed activities can be implemented for its control.

Following a geosmin outbreak in early 2010, the City of Fort Collins Utilities initiated a geosmin monitoring program on the Mainstem of the Poudre River above the FCWTF intake. This paper outlines the FCU monitoring approach, the key findings, and the factors that have contributed to the program's success to date.

BACKGROUND

Geosmin is one of the most common, naturally occurring, taste and odor (T&O) producing organic compounds found in drinking water supplies. It imparts an earthy odor to water that can be detected by the most sensitive people when present at extremely low concentrations (<5 ng/L, or <5 parts per trillion (ppt)). The City of Fort Collins Utilities can expect "earthy" odor complaints if geosmin levels are above 4.0 ng/L in its finished water. Geosmin is produced by some species of cyanobacteria (blue-green algae) and actinomycetes (a filamentous bacteria). It is released after cell lysis and death and, depending on the species, it may also be actively excreted by healthy cells into the water column (e.g., Graham et al, 2008).



Geosmin does not pose a public health risk, but its detectible presence in treated drinking water can cause serious concerns in the eyes of the public about the aesthetic quality of the water supply. Utilities around the country receive high numbers of customer complaints whenever a geosmin outbreak occurs in the water supply. Geosmin is one of the most difficult T&O compounds to remove during water treatment.

The FCWTF receives raw water supplies from two main sources, Horsetooth Reservoir and the Mainstem of the Poudre River. One of FCU's most powerful strategies for minimizing the presence of geosmin in drinking water is to adjust the blend ratio of the two source waters in favor of the non-affected source, thereby lowering geosmin concentrations prior to treatment, when possible. The co-occurrence of elevated geosmin concentrations in both source waters would severely limit the effectiveness of this approach, and treatment operations could be forced to rely on less effective and more expensive options. While there are some potential water treatment fixes for geosmin odor control (Westerhoff et al., 2002; Paradis and Hofmann, 2006) watershed-based solutions for controlling geosmin provide a lasting, reliable and more economical approach to protecting drinking water quality. However, an understanding of geosmin occurrence, sources, transport and fate is essential before watershed activities can be implemented for its control.

The Fort Collins Utilities monitors water quality of the Poudre River through the collaborative Upper Cache la Poudre River Water Quality Monitoring Program (Billica et al., 2008). In most water quality monitoring programs, including the Fort Collins program, geosmin is not a routine monitoring parameter, and must be addressed with a separate monitoring plan.

Geosmin data for the Poudre water supply at the FCWTF are available from 2003 to present, and indicate periodic episodes of elevated geosmin concentrations (> 4 ng/L) (Figure 1). Between November 2009 and January 2010, an abrupt increase in geosmin concentrations was observed at the FCTWF. During this period, concentrations increased from around 2 ng/L to a maximum observed concentration of 7.53 ng/L. Concentrations at the FCWTF remained near or above 4 ng/L through the beginning of May, and then dropped below the 4 ng/L threshold for the duration of 2010, with one exception (at 4.4 ng/L) in July.

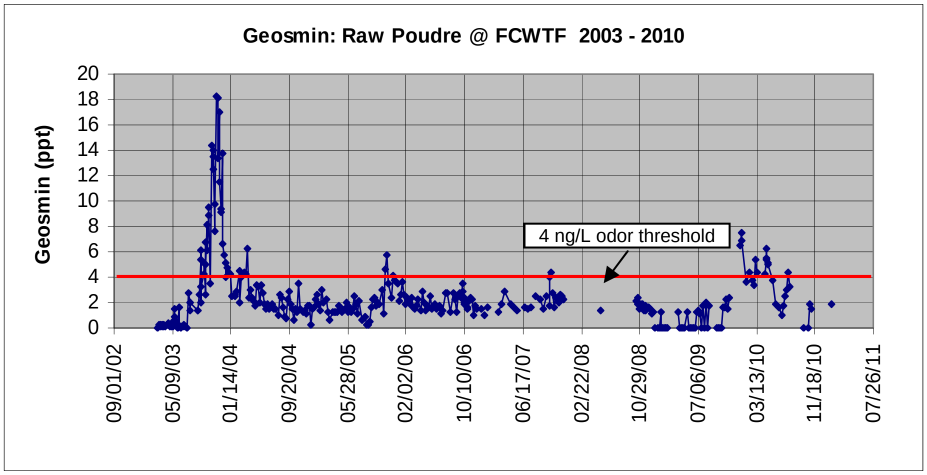


Figure 1. Geosmin concentrations in raw Poudre River water supply at the FCWTF from 2003-2010.

Geosmin sampling activities on the Mainstem of the Poudre River were initiated following the January 2010 outbreak to gain a better understanding of the spatial and temporal occurrence of geosmin in this river system. The work detailed in this paper is part of a broader effort to improve our understanding of geosmin dynamics in FCU's water supply reservoir and source watersheds (see also Billica et al., 2010).

Unlike lake and reservoir systems, there is currently little guidance in the literature for assessing spatial and temporal occurrence or monitoring approaches for understanding and predicting geosmin outbreaks in river systems. Therefore, it was important to continuously adapt and refine our monitoring activities based on our observations and lessons learned about geosmin dynamics on the Poudre.

Geosmin monitoring activities on the Poudre River focused on the following objectives:

- Identify the areas on the Poudre River with high geosmin concentrations that are sources of geosmin to the FCWTF.
- Identify spatial and seasonal geosmin and nutrients trends in areas of geosmin production.
- Evaluate potential sources of nutrients to the target areas.
- Characterize the periphyton community and identify known geosmin-producing species, when possible.

Ultimately, the monitoring activities aim to identify opportunities within the watershed to mitigate or reduce geosmin production and to assist in the development of an early warning monitoring program that enables water treatment operators to minimize the presence of geosmin in treated drinking water supplies.

SITE DESCRIPTION

The Mainstem of the Poudre River originates in Rocky Mountain National Park, on the east side of the Continental Divide and serves as one of two water sources for the City of Fort Collins Water Treatment Facility. From its headwaters, the Mainstem Poudre travels approximately 65 miles through the Poudre Canyon, descending approximately 5,500 feet from its starting elevation of 10,800 feet. It then flows through the City of Fort Collins, and meets the South Platte River on the agricultural plains, near Greeley, Colorado. The City of Fort Collins raw Poudre River water intake facility is located on the Mainstem of the Poudre River above the confluence with the North Fork Poudre approximately 5 miles above the mouth of the Poudre Canyon.

The upper Poudre watershed (above the canyon mouth) encompasses approximately 361,300 acres (565 square miles) mountain terrain, dominated by coniferous forest; developed land represents less than 0.7% of the total watershed. Within this upper basin, there are a total of 30 miles of river designated under the Wild and Scenic Rivers Act (1968) as “wild” and another 46 miles with a “recreational” designation. These designations underscore the pristine conditions of these river segments and protect against any activity that threatens the water quality or the outstanding natural, cultural, and recreational values on these segments. Furthermore, the Colorado Department of Health & Environment (CDPH&E) has designated the Mainstem Poudre a Class 1 – Cold Water Aquatic Life water body, indicating that it is capable of sustaining a wide variety of cold water biota, including sensitive species and has set forth the water quality standards for its protection.

The primary tributaries of the Mainstem Poudre are the South Fork Poudre and Joe Wright Creek. Within the upper watershed, there are nine water supply reservoirs and five trans-basin diversions that deliver water from the Colorado River, Michigan River and Laramie River basins; however, the Mainstem Poudre remains free of impoundments. Water quality at the FCWTF intake, therefore, reflects the cumulative contributions of these sources in addition to the land use activities within the watershed.

The hydrology of the Mainstem Poudre is driven predominantly by mountain snowmelt runoff. Peak stream flows occur mid- to late-June and are followed by a return to much lower flows by late summer and through the winter months (Figure 2).
The period of high spring runoff on the
Mainstem Poudre is characterized by cold temperatures, low conductivity and hardness, and relatively high turbidity and total organic carbon (TOC) concentrations. Nutrient concentrations experience some seasonal effects, but are generally low year-round. Sources of nutrients in the Upper Poudre include, but are not limited to, sediment transport, feces from wildlife and livestock, potentially leaking septic systems, atmospheric nitrogen deposition, reservoir releases within the Upper Poudre watershed, and the breakdown of organic matter.

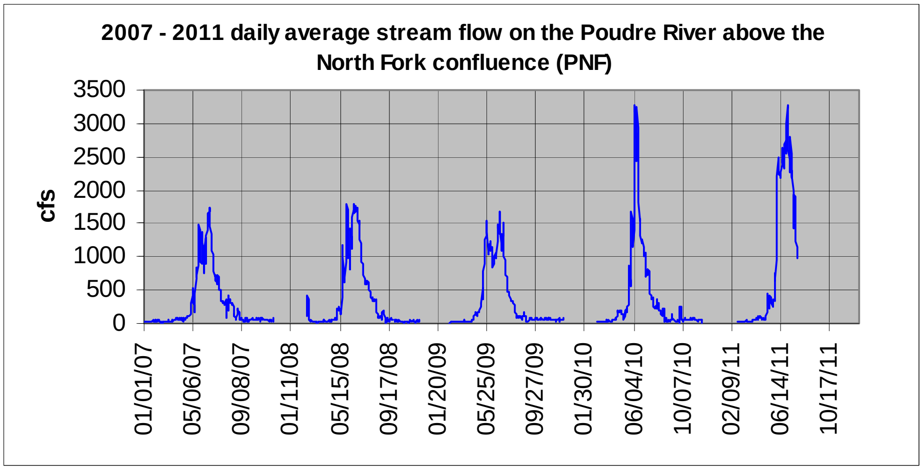


Figure 2. 2007 - 2011 daily average stream flow on the Poudre River above the North Fork confluence (PNF).

MONITORING ACTIVITIES

Intensive sampling on the Mainstem of the Poudre River began in January 2010 in direct response to the elevated geosmin concentrations observed in the raw water supply at the FCWTF (Figure 1).

Initial sampling activities focused on characterizing the geosmin concentrations in the river and identifying areas of high geosmin production that could be potential sources of geosmin to the FCWTF intake. Reconnaissance geosmin sampling focused on the areas area upstream and downstream of Rustic, Colorado, located approximately 25 miles upstream of the FCWTF intake. This area was targeted based on the prevalence of permanent seasonal and year-round housing and camping facilities in the area as well as the upstream State of Colorado Division of Wildlife Poudre River Fish Hatchery. The fish hatchery does not currently operate at full capacity, but does routinely discharge water from a limited number of ponds into the Poudre River.

Reconnaissance sampling spanned nearly 29 miles, extending from the outlet of Joe Wright Reservoir (on Joe Wright Creek) downstream to Kelly Flats Camping area (Figure 3). The area of highest geosmin concentrations was found to extend from approximately one-quarter mile above Rustic, near the Poudre Canyon Chapel downstream to the Eggers Fishing area.

Phase I Monitoring. Phase I monitoring activities consisted of monthly geosmin samples collected at four routine sites within this area of highest geosmin concentrations around Rustic from February, 2010 to April, 2011. The selected monitoring sites were *Poudre above Rustic* (near Poudre Canyon chapel), *Poudre Canyon Fire Station* (mile marker 90), *Poudre below Rustic* (PBR) and *Poudre at Eggers* fishing area (Figure 3). Initial sampling at these four sites revealed geosmin concentrations ranging from 20.61-38.14 ng/L. It is notable that this area of high geosmin production corresponds to the stretch of river where an attached green algae bloom (*Ulothrix sp.*) occurred in the summers of 2009 and 2010. This study took the preliminary steps to determine whether geosmin occurrence and the *Ulothrix* bloom were related, although it was recognized that *Ulothrix* itself is not a geosmin producer.

Nutrient testing was added to the routine monitoring program in February 2010 to determine whether elevated concentrations of nutrients were available to stimulate geosmin-producing algae growth. Samples were analyzed for Total Kjeldahl Nitrogen (TKN), nitrate, nitrite, ammonia, total phosphorus (TP) and ortho-phosphorus. The outflow from the Poudre River Fish Hatchery was sampled for nutrients in February 2010 and again in February 2011. Periphyton samples were collected monthly beginning in July, 2010 at the four routine monitoring sites near Rustic. Periphyton sample collection was limited to periods of time when the river was free of continuous ice and water levels allowed safe access to the river. Because geosmin production is species specific, it was critical to identify algae samples to the species level. All periphyton samples were identified by private consultant, Richard Dufford, to the species level, when possible, and qualitatively ranked for abundance.

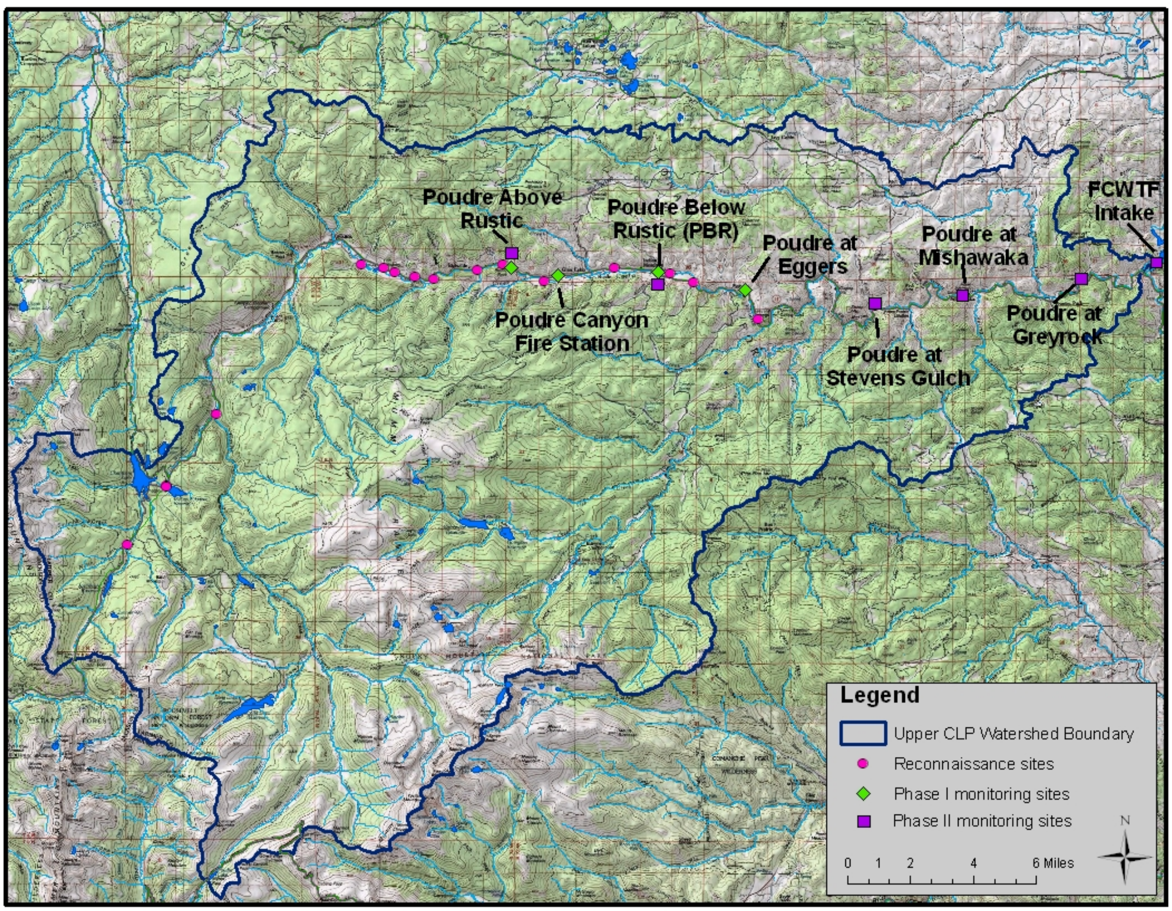


Figure 3. Map of Upper Poudre geosmin monitoring sites.

Total coliform and *E.coli* analyses were added to the sampling program in August, 2010 and serve as potential indicators of animal and human fecal contamination. The co-occurrence of these bacteria with elevated nutrient concentrations could potentially serve as an indicator of leaking septic systems and vault toilets associated with homes, campgrounds and rental cabin properties as a source of nutrients to the river. All available individual sewage disposal system (ISDS) permits for the area of interest were obtained from the Larimer County Department of Health and Environment and mapped where possible. Twenty ISDS permit locations were identified for this area (Figure 4). Three additional sites that were upstream and downstream of permanent and seasonal residential developments were sampled in August 2010. These sites included above and below Home Moraine residential area and below the Glen Echo Resort.

A timeline of the program development in provided in Figure 4.

Phase II Monitoring. The second phase of geosmin monitoring (Phase II) began in May, 2011 and can be characterized by two important changes to the sampling program: a reconfiguration of sample sites to include sites closer to the FCWTF intake and the adoption of new quantitative periphyton sampling protocols. To maintain data continuity with Phase I sampling, two of the original sample sites were retained and three new downstream sites were added (Figure 3). In addition, a sample from the raw Poudre water at FCWTF was collected on the same day as the Poudre river samples, to help determine which sites are potentially contributing to geosmin at the FCWTF intake. All other sampling parameters remained the same. Phase II sampling will continue through the spring of 2012.

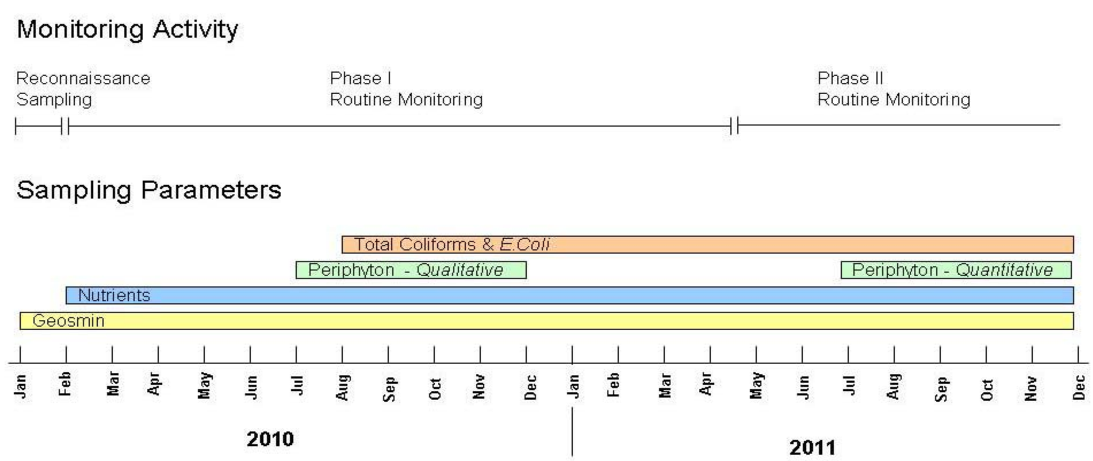


Figure 4. Timeline of 2010-2011 geosmin monitoring activities on the Upper Poudre River

Field sampling methods. All samples were collected by FCU staff. Grab samples for geosmin, nutrients, periphyton and bacteria were collected from the main channel flow using a telescopic pole with a clean, attached sample bottle. The sample volume collected in the bottle attached to the pole was immediately transferred to amber glass bottles for geosmin testing, and to plastic sample containers for nutrients and bacteria testing. All nutrient, bacteria and geosmin samples were analyzed by the City of Fort Collins Water Quality Lab (Table 1).

Parameter	Method	Reporting Limit	Preservation	Holding Time
Total Coliform, E.coli - QT	SM 9223 B	0	cool, 4C	8 hrs
Ammonia - N	Lachat 10-107-06-2C	0.02 mg/L	H_2SO_4	28 days
Nitrate	EPA 300 (IC)	0.2 mg/L	cool, 4C (eda)	48 hrs
Nitrite	EPA 300 (IC)	0.1 mg/L	cool, 4C (eda)	48 hrs
Total Kjeldahl Nitrogen	EPA 351.2	0.1 mg/L	H_2SO_4 pH<2	28 days
Phosphorus, Total	SM 4500-P B5,F	0.01 mg/L	H_2SO_4 pH<2	28 days
Phosphorus, Ortho	SM 4500-P B1,F	0.005 mg/L	filter, cool 4C	48 hrs

Table 1. Analytical methods, reporting limits, sample preservation and sample holding times for analyses conducted by the City of Fort Collins Water Quality Lab.

Qualitative periphyton samples (Phase I) were collected by scraping algae and biofilms from the surface of rocks. Samples were composited in plastic bottles and preserved with a 4% formalin solution upon return to the lab. A change in methods was implemented in May 2011 to provide an estimate of algae abundance as well as species identification. Quantitative periphyton samples (Phase II) were collected from a known surface area from three selected cobbles from the streambed. The stream area type (pool, riffle, or run) were identified for each cobble. The algae sample was isolated by removing algae from the rock surface around the outside of the PVC cylinder using a wire brush and spray bottle. The PVC cylinder was then removed, and the algae from under the cylinder were scraped and washed into a plastic sample container. This procedure was repeated for each sample cobble. Algae samples from similar stream areas were composited and preserved with a 4% formalin solution upon return to the lab. All samples were refrigerated until analysis.

Geosmin analysis. Geosmin occurs in surface waters as cellular (cell-bound) and dissolved fractions (Juttner and Watson, 2007). For the Fort Collins monitoring program, samples were unfiltered and tested for total geosmin concentrations. However, protein-bound geosmin may be underestimated using current extraction techniques (Juttner and Watson, 2007). Geosmin analysis were conducted by the City of Fort Collins Water Quality Laboratory using solid phase microextraction as described in Standard Method 6040D (2005) by gas chromatography/mass spectrometry. Geosmin data were generally available within two days of sample collection.

RESULTS

Geosmin. Reconnaissance sampling of the Upper Poudre indicated that geosmin concentrations were highest in the area surrounding Rustic, ranging from 15.43 ng/L to 38.14 ng/L.

Phase I geosmin concentrations, as shown on Figure 5, exhibit a seasonal pattern of high concentrations in the winter months, and low concentrations during the summer months. This seasonal pattern in geosmin concentrations was evident at all sites.

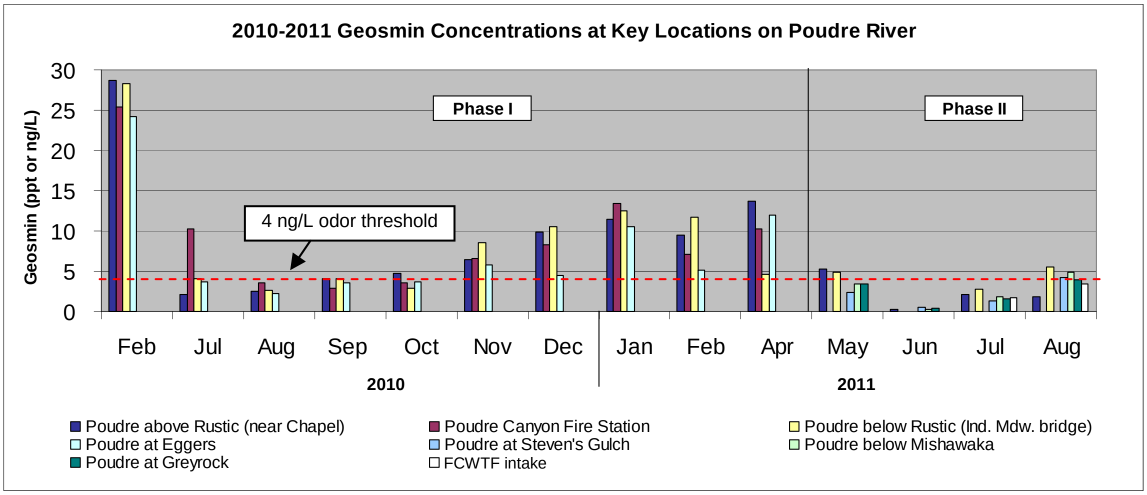


Figure 5. Geosmin concentrations at key Phase I and Phase II monitoring locations on the Poudre River from 2010 to 2011.

A comparison of stream flows at the FCWTF intake and geosmin concentrations at the nearest upstream monitoring location (Poudre below Rustic) shows an inverse relationship between geosmin concentrations and stream flows (Figure 6); high concentrations were observed during low flows (winter) and lower concentrations were observed during periods of higher flows (summer).

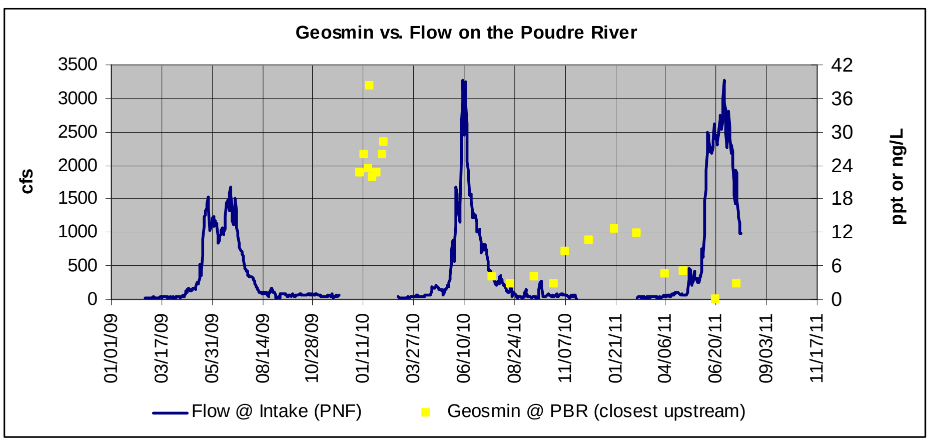


Figure 6. Flow at FCWTF intake (PNF) versus geosmin concentrations at Poudre below Rustic (nearest

Phase II monitoring sites appear to exhibit a similar seasonal trend, however, data is still limited for many of the sites. While it is possible that stream flow affects the seasonal pattern in geosmin results in part through concentration (low flows) and dilution (high flows), the seasonal pattern of geosmin concentrations may also result from changes in rates of cellular geosmin production in response to changes in water temperature, photoperiod, or other biological, physical or chemical factors not addressed by this study.

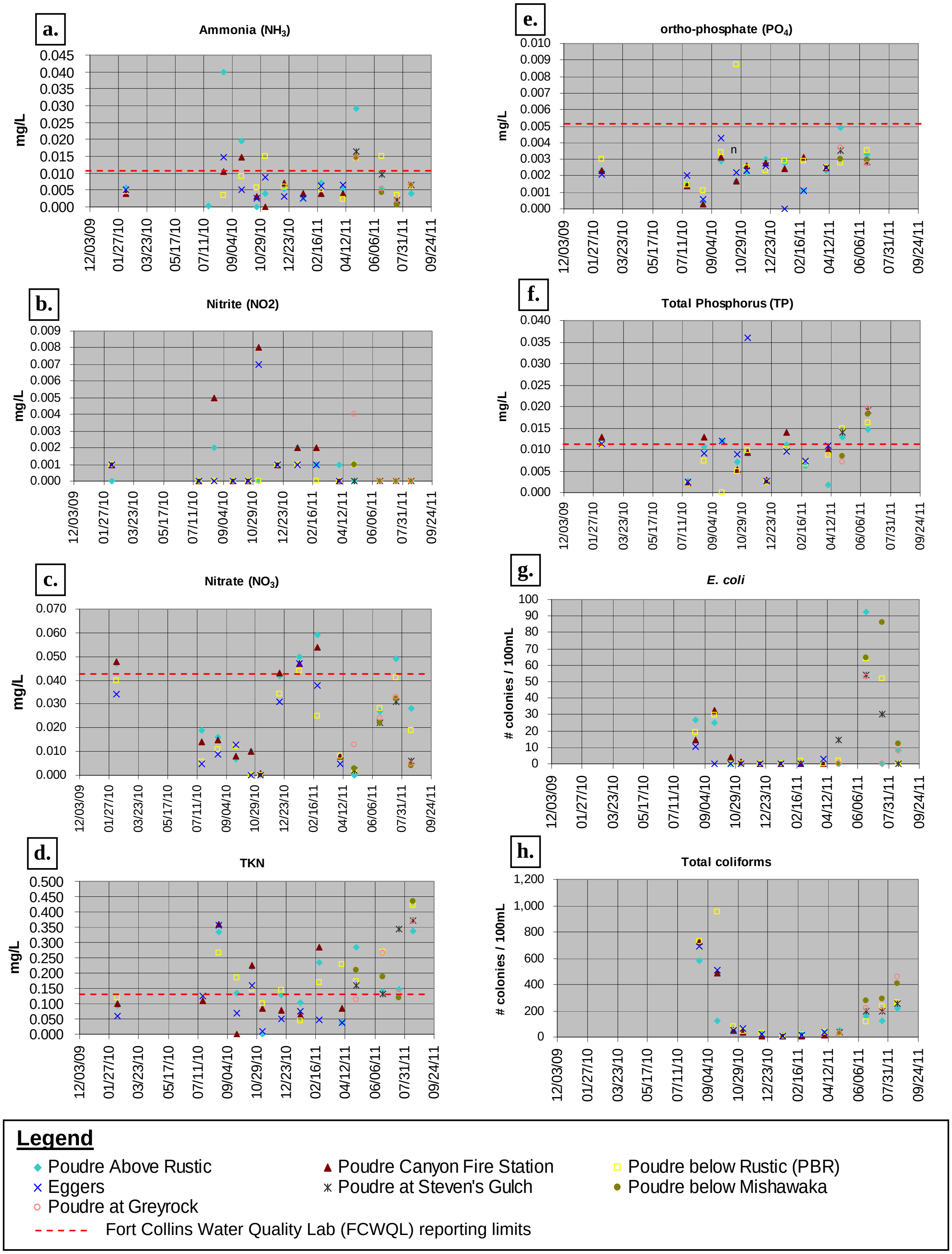
There were no consistent upstream to downstream trends in geosmin, and concentrations often varied considerably between sites for a given sampling date within this 7 mile stretch of river. The lack of spatial trends in geosmin suggests that for a given site, concentrations are influenced as much or more by local, site-specific conditions than proximity to a single source. Factors that potentially influence geosmin concentrations at a given site include production and degradation rates as well as environmental factors that affect the volatility of geosmin, including water temperature and the amount of turbulence to which it is exposed. Based on the variability in geosmin concentrations within the 7 mile stretch of river, it was concluded that, while the Rustic area may be a regional "hot spot" of geosmin on the Upper Poudre, elevated concentrations at the FCWTF likely result from production sites closer to the intake. Current monitoring at the three new (Phase II) sites between Rustic and the FCWTF intake is designed to address this possibility.

Observed geosmin concentrations at Phase I sites differed between years as well. Peak observed concentrations were significantly higher in 2010 (24.2 – 28.6 ng/L) than in 2011 (10.5 – 13.45 ng/L). In 2010, the high geosmin concentrations on the Upper Poudre corresponded with a period when concentrations exceeded the geosmin odor threshold (4 ng/L) at the FCWTF, whereas there were no observed exceedances at the FCWTF in 2011 (Figure 1). Reasons for the differences between years are unknown.

Nutrients. Concentrations of all total and dissolved nutrient fractions were extremely low in the study area and were frequently below reporting limits (Figures 7 (a-f). Like geosmin, there was considerable variability in concentrations between sites for a given sample date and no evidence of upstream to downstream trends for any measured parameter. The site *Poudre below Rustic* consistently had the highest ortho-phosphate concentrations, although concentrations at this and other the Phase I monitoring sites, were within the range of concentrations observed on the Mainstem as part of the Upper Cache la Poudre Cooperative Water Quality Monitoring Program (Oropeza and Billica, 2011). It is possible that nutrient concentrations from an effluent source could occur within the natural range of variability for this area. However, if sustained, an increase in the seasonal mean concentration would be expected over time. The periods of record for these sites are generally less than 2 years and are not currently sufficient to identify any trends in nutrient concentrations.

There were no correlations between nutrient parameters and geosmin concentrations at *Poudre above Rustic*, *Poudre Canyon Fire Station* or *Eggers*. The site *Poudre below Rustic*, did however, show a significant positive relationship between geosmin and nitrite ($r = 0.662$; $p=0.023$) and a significant negative relationship between geosmin and TKN ($r = -0.592$; $p=0.055$).

Figure 7 (a-h). Nutrient and bacteria concentrations for Phase I and Phase II monitoring sites on the Upper Poudre.



Total Coliforms and *E.coli*. Total coliforms and *E.coli* samples serve as potential indicators of animal and human fecal contamination. Figure 7(g-h) presents monitoring data since August 2010. Both indicator bacteria exhibit relatively high summer concentrations and very low concentrations in the winter and early spring months. Total coliform concentrations are an order of magnitude greater than *E.coli* concentrations, with peak levels of total coliforms ranging from 121 to 953 colonies/100 mL. Similar to the patterns observed with geosmin and nutrients, neither bacterial indicator show any upstream to downstream trends. The relatively high summer concentrations are likely a result of increased presence of livestock and recreational activity within the watershed. The noticeable rise in total coliforms and *E. coli* concentrations beginning in June 2011 corresponds with the onset of spring snowmelt runoff, a period when relatively large amounts of sediments and organic matter are transported into the river from the surrounding landscape. Subsurface flows also increase during the period of spring runoff. These have the potential to intercept drainage from septic leach fields or possible leaks from impaired vault toilets in the area. *E.coli* did not show any significant correlation to geosmin concentrations at any of the study sites. Total coliforms showed a significant *negative* relationship with geosmin at *Poudre below Rustic* (r = -0.663, p=0.026).

Periphyton. Phase I periphyton (attached algae) data from August through November 2010 were reported as dominant species by rank. The limitation of this approach is that is does not give specific information about the overall size of the periphyton community or the abundance of individual groups of algae over time, but it does indicate which divisions of algae were most (or least) dominant by rank. Results show that green algae and diatoms were the most prominent groups of algae at all sites throughout the 2010 fall-winter season. Various species of blue-green algae, or cyanobacteria, were also present throughout the monitoring period. Figure 8 provides a representative example of the relative rankings of these major groups of algae. These results are consistent with algal community assemblages in other streams in the northern Colorado region (Vavilova and Lewis, 1999).

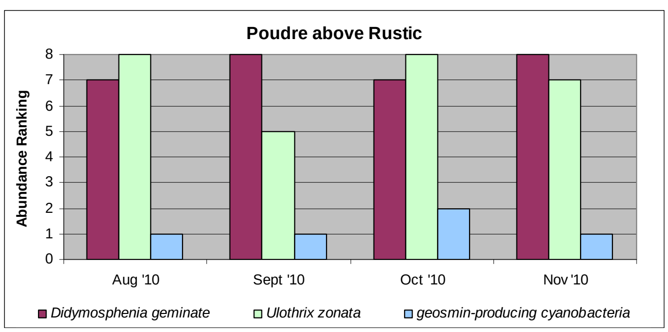


Figure 8. Periphyton dominance ranking for the most commonly identified species of green algae, diatoms and geosmin-producing cyanobacteria for Poudre above Rustic monitoring site. (Rankings: 8 Dominant; 7 abundant; 6 Common-abundant; 5 Common; 4 Occasional-common; 3 Occasional; 2 Rare-occasional; 1 Rare.)

Ulothrix zonata, an attached filamentous green algae and *Didymosphenia geminate* (also known as didymo) an invasive diatom, were the most commonly identified species from August to November of 2010, and in general, were ranked as "common-abundant" to "dominant". Known geosmin producing species of cyanobacteria were present in most samples. The known geosmin producers included *Pseudanabaena limnetica, Pseudanabaena catenata, Pseudanabaena sp.* (Juttner and Watson, 2007) and *Oscillatoria* *tenuis* (Wu and Juttner, 1988) and were ranked as "rare" to "occasional-rare". This finding is consistent with other studies in which geosmin producing species represent a relatively very small portion of the total algae population (Taylor et al, 2006, Billica et al., 2010).

Potential Sources of Contamination. Three sites that were considered potential sources of nutrients and geosmin to the area of interest around Rustic were sampled on August 3, 2010 in addition to the routine Phase I monitoring sites. Sites included above and below the residential development at Home Moraine and below the Glen Echo Resort, which had a high concentration of individual sewage disposal system (ISDS) permits. Geosmin concentrations were low at these sites, ranging from 1.52 ng/L below Home Moraine and 3.68 ug/L at Glen Echo. Results showed that nitrate concentrations at these locations were somewhat higher than those observed at the nearest downstream monitoring locations; however concentrations were within the range observed in the upper watershed, as measured by the Upper Poudre water quality monitoring program (Oropeza and Billica, 2011). The upper and lower Home Moraine sites also had significantly higher *E.coli* concentrations than the other downstream locations (Figure 9). Total coliform concentrations as well as ammonia, nitrite, TKN, dissolved and total phosphorus concentrations were similar to or lower than concentrations at downstream locations.

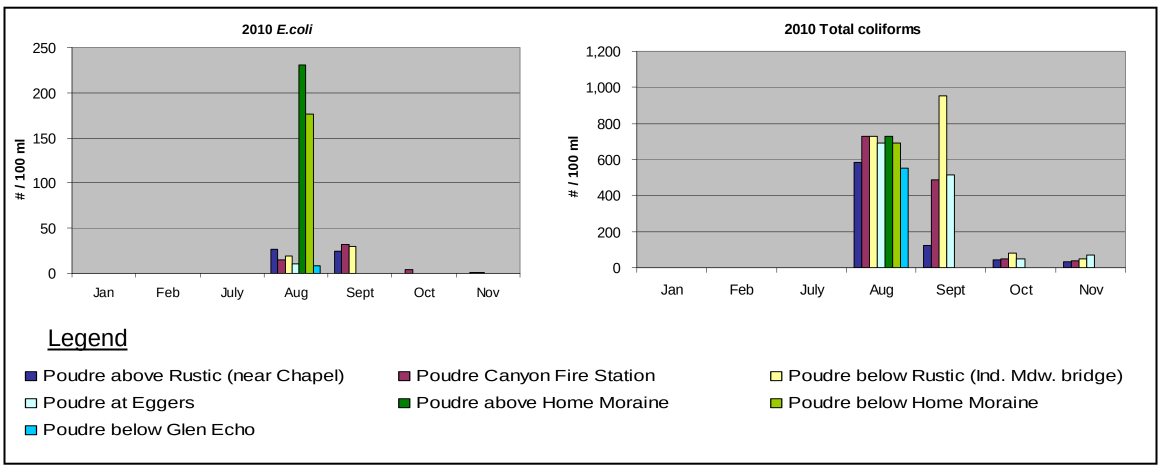


Figure 9. Comparison of August 2010 *E.coli* and Total coliform concentrations at Phase I monitoring sites and at *Poudre below Home Moraine*, *Poudre below Glen Echo Resort* and *Poudre above Home Moraine.*

The outflow from the Poudre River Fish Hatchery was sampled once during the reconnaissance sampling and twice during the Phase I monitoring period for geosmin. On all three occasions, geosmin concentrations were lower at this site than at the nearest downstream site sampled; concentrations ranged from 4.70 – 5.35 ng/L. Nutrients were sampled at this site once in 2010 and once in 2011. Results show that all nutrient parameters were below or near reporting limits and did not differ substantially between the two years. *E.coli* and total coliforms were only sampled in 2011. *E.coli* was not detected and total coliform concentration was very low, 24.4 colonies/100 mL, respectively.

FINDINGS AND CONCLUSIONS

A geosmin outbreak in raw drinking water supplies presents special challenges for traditional water quality monitoring programs because the sources and events leading up to an outbreak are not well understood or easily monitored. Without an adequate early warning system for geosmin in source waters, water treatment plant operators have little time to respond, resulting in an increase in customer T&O complaints and a negative perception of treated drinking water quality. And without an understanding of temporal and spatial variability, concentrations, production sites, transport, and fate of geosmin within source watersheds, watershed managers are unable to identify potential control strategies.

This paper outlines the geosmin monitoring program used by the FCWTF and highlights some of the key findings to date. The area of highest geosmin concentrations on the Upper Poudre was a 7 mile area near Rustic, Colorado, approximately 25 miles above the FCWTF intake. Within this area, geosmin concentrations showed strong spatial and temporal (seasonal and annual) variation; however, monitoring activities as described in this paper, were unable to determine the factors that account for the observed differences in concentrations. Changes were made in the configuration of sampling sites in May 2011 in order to identify sites further downstream that are more likely to affect concentrations at the FCWTF water supply intake. At the time of this paper, there was not enough available data to determine any relationships between geosmin concentrations at the new sites and the FCWTF intake.

Nutrients were generally very low within the study area. At the nutrient concentrations observed on the Upper Poudre, it is expected that periphyton abundance (and potential geosmin producing cyanobacteria) are more strongly limited by factors not addressed in this study like elevation, temperature and length of growing season (Lewis and McCutchan, 2010). The switch to quantitative periphyton sampling (Phase II) will allow us to track changes in the periphyton community composition and determine if and how geosmin production is related to the abundance of geosmin producing cyanobacteria species and to the overall abundance of the periphyton.

Many questions remain, and it is expected that several years of monitoring will be required to better understand the factors that influence geosmin production, degradation, transport and fate and to identify geosmin occurrence patterns within the Upper Poudre. Currently, no opportunities have been identified within the watershed to mitigate geosmin production.

The ability to develop a responsive and early-warning monitoring plan for geosmin outbreaks relies on our ability to closely track geosmin trends within the watershed and monitor the presence of known-geosmin producing species of cyanobacteria. Therefore, the most critical elements to the success of this monitoring effort are the availability high quality geosmin data with short turn-around times, and scheduling flexibility provided by the Fort Collins Water Quality Laboratory as well as the available expertise to identify algae to the species level.

Future monitoring will build on the following findings of the geosmin monitoring program conducted to date:

- Geosmin concentrations exhibit a seasonal pattern of highest concentrations in the winter and lowest concentrations during spring snowmelt runoff.
- Peak geosmin concentrations on the Poudre River were significantly higher in 2010 than in 2011.
- Geosmin concentrations at the FCWTF were not representative of concentrations on the Upper Poudre River for either year.
- There were no consistent upstream to downstream trends in geosmin concentrations within the study area.
- The filamentous green algae, *Ulothrix zonata* and the invasive diatom, *Didymosphenia geminate* were the dominant algae species within the Upper Poudre River study area.
- Geosmin producing cyanobacteria were frequently present in the periphyton community, but were relatively rare at the Poudre River monitoring sites.
- Nutrient concentrations near the fish hatchery, above and below Home Moraine housing developments, and below the Glen Echo Resort were generally low, and often below reporting limits.
- Geosmin concentrations for a given location on the Upper Poudre are not well predicted by nutrient concentrations, proximity to upstream sources of geosmin, the presence of known geosmin producing cyanobacteria species or concentrations of the bacterial indicators, *E. coli* and total coliforms.

ACKNOWLEDGEMENTS

Judith A. Billica contributed to the development of the content for this manuscript while employed by the City of Fort Collins Utilities, Fort Collins, Colorado**.**

REFERENCES

Billica, J., J. Loftis and J. Moore, 2008. *Design of a Collaborative Water Quality Monitoring Pogram for the Upper Cache la Poudre River.* Prepared for the City of Fort Collins Utilities. July 14, 2008.

Billica, J., J. Oropeza, and K. Elmund, 2010. *Monitoring to Determine Geosmin Sources and Concentrations in a Northern Colorado Reservoir*, In: Proceedings of the National Water Quality Monitoring Council and NALMS 2010 National Monitoring Conference (April 25-29, 2010, Denver).

Graham, J.L., K.A. Loftin, A.C. Ziegler, and M.T. Meyer, 2008. *Guidelines for Design and Sampling for Cyanobacterial Toxin and Taste-and-Odor Studies in Lakes and Reservoirs.* U.S. Geological Survey Scientific Investigations Report 2008-5038.

Jiuun-Tzong Wu and Friedrich Jüttner, 1988. *Differential partitioning of geosmin and 2-methylisoborneol between cellular constituents in Oscillatoria tenuis*. Archives of Microbiology, Volume 150, Number 6, 580-583, DOI: 10.1007/BF00408253

Juttner, F. and S. Watson, 2007. *MiniReview: Biochemical and Ecological Control of Geosmin and 2-Methylisoborneol in Source Waters*, Applied and Environmental Microbiology, Vol. 73, No. 14, July 2007, p. 4395-4406.

Lewis, William M. and James H. McCutchan, 2010. *Ecological responses to nutrients in streams and rivers of the Colorado mountains and foothills*. Freshwater Biology, 55, 1973-1983.

Oropeza, J. and J. Billica. 2011. *City of Fort Collins Utilities 2010 Annual Report for the Upper Cache la Poudre River Collaborative Water Quality Monitoring Program*, Internal Water Production Report, May 2, 2011, 86 pages plus appendices.

Paradis, N. and R. Hofmann, 2006. *Mitigation of Taste and Odor Compounds by UV/H2O2 Advanced Oxidation*, In: Water Quality Technology Conference Proceedings, (November 2006).

Paul Westerhoff, Milton Sommerfeld, Larry Baker, 2002. *Reducing 2-Methylisoborneol (MIB) andGeosmin in the Metropolitan-Phoenix Area Water Supply.* A Cooperative Research and Implementation Program by City of Phoenix, Salt River Project and the Central Arizona Project, July 2002.

Taylor, W.D., R.F. Losee, M. Torobin, G. Izaguirre, D. Sass, D. Khiari, and K. Atasi, 2006. *Early Warning and Management of Surface Water Taste-and-Odor Events*, AWWA Research Foundation, Denver, CO.

Vavilova, V., and W. Lewis, 1999. *Temporal and altitudinal variations in the attached algae of mountain streams in Colorado.* Hydrobiologia, 390: 99-106.