Monitoring to Determine Geosmin Sources and Concentrations in a Northern Colorado Reservoir

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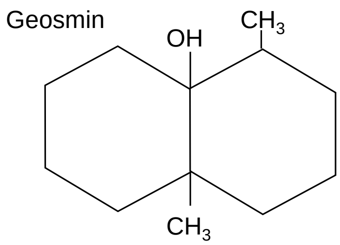
ABSTRACT

Geosmin is a naturally occurring organic compound produced by some species of cyanobacteria and actinomycetes that imparts an earthy odor to water when present at extremely low concentrations (<5 nanograms/L). In October 2008, a significant geosmin outbreak occurred in Horsetooth Reservoir, a reservoir that supplies water to northern Colorado communities served by three drinking water treatment plants, including the City of Fort Collins Water Treatment Facility (FCWTF). 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. The City of Fort Collins initiated geosmin monitoring within Horsetooth Reservoir and upstream components of the Colorado-Big Thompson (CBT) Project in direct response to the 2008 outbreak. This paper outlines the geosmin monitoring program used by the FCWTF and highlights some of the key findings to date and factors that affect the success of the program. The reconnaissance monitoring conducted in 2008 revealed high geosmin concentrations throughout Horsetooth Reservoir, but geosmin production sites could not be determined. The expanded monitoring program in 2009 showed significant spatial and temporal variation in geosmin concentrations in the reservoir and in the upstream components of the CBT Project. The data suggest a very complex system with respect to geosmin, and varying levels of geosmin production, transport, and degradation throughout the system. Many questions remain and it is expected that several years of monitoring will be required to fully understand geosmin sources, transport, and fate, and to identify geosmin occurrence patterns.

BACKGROUND

In October 2008, a significant geosmin outbreak occurred in Horsetooth Reservoir, a reservoir that supplies water to northern Colorado Front Range communities served by three drinking water treatment plants, including the City of Fort Collins Water Treatment Facility (FCWTF). The event produced a record high geosmin concentration of 25 nanograms per liter (ng/L) at the FCWTF raw water supply intake. Customer complaints increased and the FCWTF responded by adjusting their treatment process for taste and odor control (including changing the raw water blend and feeding powdered activated carbon) and by initiating a monitoring program for Horsetooth Reservoir to determine the spatial distribution of high geosmin concentrations.

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 their water supply. Geosmin is one of the most difficult T&O compounds to remove during water treatment.

The Fort Collins Utilities has a long-term water quality monitoring program for Horsetooth Reservoir. In most water quality monitoring programs, including the Fort Collins program, geosmin is not a routine monitoring parameter. Recent publications (i.e., Taylor et al, 2006; Juttner and Watson, 2007; Graham et al, 2008) provide guidance for the design of reservoir monitoring programs to assess the spatial and temporal occurrence of geosmin produced by cyanobacteria. Studies conducted on U.S. reservoirs provide further guidance on monitoring approaches and data analysis tools related to understanding and predicting geosmin outbreaks (Christensen et al, 2006; Journey and Abrahamsen, 2008; Pan et al, 2002; Smith et al, 2002).

Juttner and Watson (2007) suggest that three zones in lakes should be investigated as possible sources of geosmin: 1) the epilimnetic water and associated plankton; 2) the hypolimnetic water (oxic or anoxic), and 3) the benthic littoral zone (i.e., shallow, near shore bottom regions). Taylor et al (2006) emphasize that geosmin producing species are frequently hard-to-find minor components of the aquatic community and, therefore, geosmin will usually be detected analytically before a T&O producer will be observed microscopically. Geosmin production is often strain specific, and phytoplankton data showing the occurrence of known geosmin producing cyanobacteria species or genera does not prove causation. Dissolved geosmin is relatively stable to chemical and biological degradation and can persist for significant periods of time depending on environmental conditions (water temperature, oxygen levels, etc); this must be considered when trying to understand and track the distribution, transport, and fate of geosmin in aquatic systems (Juttner and Watson, 2007).

SITE DESCRIPTION

Horsetooth Reservoir (elevation 5430 ft, length 6.7 miles, width 0.9 miles) is located directly west of the City of Fort Collins, Colorado. At maximum capacity, Horsetooth Reservoir has a storage volume of 156,735 acre-feet, a mean depth of approximately 80 feet (24 m), and a maximum depth of 188 feet (57 m). The reservoir was created by the construction of four dams in the 1940's by the U.S. Bureau of Reclamation as part of the Colorado-Big Thompson (CBT) Project. The CBT Project is operated and maintained by the Northern Colorado Water Conservancy District. Horsetooth Reservoir is a terminal reservoir on the CBT Project and stores water prior to being released for municipal, industrial, and agricultural uses. The hydraulic residence time of Horsetooth Reservoir is generally in the range of 1 to 1.5 years, depending on reservoir operations.

The CBT Project transports water from the upper Colorado River on the west slope of the continental divide to the east slope of the continental divide (Figure 1) through a series of reservoirs, canals, and pipelines. The CBT Project watershed area covers over 1,000 square miles compared to the natural local Horsetooth Reservoir watershed area of approximately 17 square miles. The CBT Project watershed area is primarily forested and includes national forest lands, Rocky Mountain National Park, and the towns of Winter Park, Granby, and Estes Park.

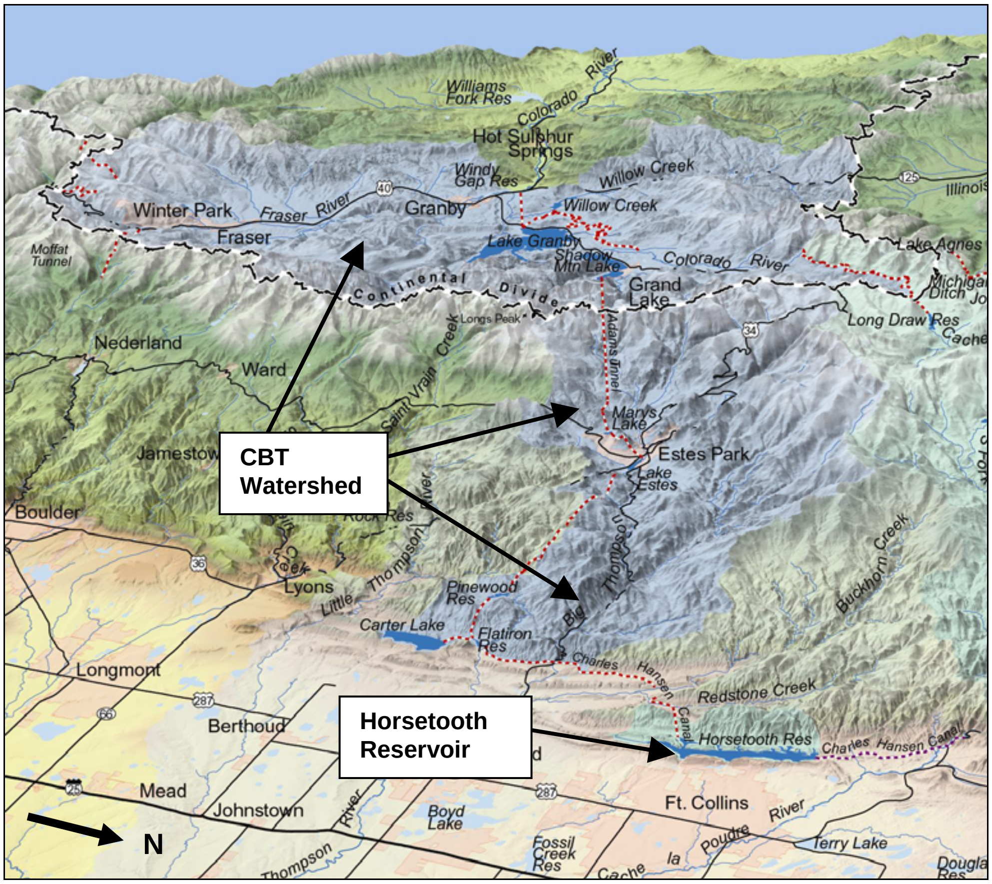


Figure 1. Horsetooth Reservoir and the Colorado-Big Thompson (CBT) Project watershed.

Water enters Horsetooth Reservoir at its south end via the CBT Project Charles Hansen Feeder Canal. Water entering Horsetooth via this canal is a mixture of water from the east slope Big Thompson River and water from the Colorado River headwaters (and associated reservoirs) that is transported through the continental divide via the Adams Tunnel. The travel time from the west portal of the Adams Tunnel to the inlet of Horsetooth Reservoir is on the order of about one week, depending on flow rates.

The Fort Collins Utilities long-term water quality monitoring program has provided information on the general limnological characteristics of Horsetooth Reservoir. Chlorophyll-a, total phosphorus, and Secchi disk transparency data all indicate that the tropic status of the reservoir is generally in the mesotrophic range. Horsetooth Reservoir is a dimictic reservoir, characterized by two mixing periods each year – one in the spring and one in the fall. Thermal stratification develops in the spring and strengthens throughout the summer and into the fall. Fall turnover occurs in October or November. However, due to the presence of pools behind each of the dams, the reservoir does not uniformly mix at the same time. During the period of thermal stratification, water entering the reservoir from the Hansen Feeder Canal is generally of a colder temperature than the epilimnion. As a result, a density current forms and temperature and specific conductance data indicate that an interflow exists within the metalimnion.

Horsetooth Reservoir Operations. Water quality in Horsetooth Reservoir is impacted by CBT system operation due to its influence on reservoir hydraulic residence times, water levels, and influent flow rates. The primary in-flow to Horsetooth Reservoir is the CBT Project Charles Hansen Feeder Canal. There are two outlets from Horsetooth Reservoir: the Charles Hansen Supply Canal at Horsetooth Dam, and the Soldier Canyon Dam Outlet. The Soldier Canyon Dam outlet structure is located near the bottom of the reservoir and provides a continuous (year round) supply of raw water to the FCWTF.

Horsetooth Reservoir water surface elevations annually fluctuate 35 to 50 feet in response to water entering the reservoir from the Hansen Feeder Canal and water being released from the reservoir at the Soldier Canyon Outlet and to the Hansen Supply Canal. Water levels are lowest in the late fall after the end of the irrigation season and rise over the winter during the reservoir filling period. The annual drop in Horsetooth Reservoir water level results in large areas of exposed sediments. The sediments of rivers, lakes, and reservoirs have been reported as potential sites of geosmin production by actinomycetes (Wood et al, 1983). Although actinomycetes may be found in large numbers in sediments covered by water, they are likely relatively inactive in that environment due to the lack of oxygen. The aerobic conditions required for the production of geosmin prevail only when the sediment is exposed and dried during a drop in the water level (Wood et al, 1983). The sediments could then become a source of geosmin, particularly when the water level rises or fluctuates. In Horsetooth Reservoir, it is possible that geosmin is produced within the exposed sediments as the water level drops, and then subsequently enters the reservoir as the water level rises. No actinomycetes data have been collected for Horsetooth Reservoir sediments. However, water levels in Horsetooth Reservoir begin rising each fall *after* the on-set of seasonal taste and odor events, so it could be concluded that actinomycetes present in the sediments are likely not a significant source of geosmin.

GEOSMIN MONITORING PROGRAM

Geosmin monitoring within Horsetooth Reservoir began in Fall 2008 in direct response to the record high geosmin levels measured at the FCWTF intake. The initial monitoring program was a reconnaissance study to evaluate spatial distributions and concentrations of geosmin within the reservoir. Because the 2008 sampling plan was initiated after the on-set of the geosmin episode, sampling did not provide data to address the location of production sites and fate of this compound. In 2009, sampling efforts were expanded to meet the following long-term objectives:

- Provide for a better understanding of the spatial and temporal distributions, concentrations, and potential production sites of geosmin within the reservoir and the canal inflow, considering the impacts of reservoir stratification, interflow, and CBT system operations.
- Improve early-warning capabilities by sampling earlier, more often, and at more key sites within the CBT system.

- Evaluate the physical, chemical, and biological factors affecting geosmin occurrence, transport, and fate in Horsetooth Reservoir.

Since cyanobacteria are considered to be the chief source of geosmin in aquatic systems where photosynthetic growth is possible (Juttner and Watson, 2007), the monitoring program currently assumes that the geosmin detected in Horsetooth Reservoir and the upstream components of the CBT system is due to the presence of cyanobacteria (phytoplankton and/or periphyton). However, this working hypothesis will be re-evaluated as data collection and analysis progresses over time.

Sampling Locations. The geosmin sampling locations are established sampling sites in long-term water quality monitoring programs conducted by the City of Fort Collins, the Big Thompson Watershed Forum, the Northern Colorado Water Conservancy District, and/or the U.S. Geological Survey. The geosmin sampling locations (Figure 2) include four sites within Horsetooth Reservoir (R20, R21, R30, and R40), three sites along the 13 mile length of the Hansen Feeder Canal (C30, C40, and C50), one site at the east portal of the Adams Tunnel (C10), and one site on the Big Thompson River (M70) where diversions from the river to the Hansen Feeder Canal can occur. Geosmin samples are also collected of raw Horsetooth Reservoir water at the FCWTF. The intake is located at the bottom of Horsetooth Reservoir at Soldier Canyon Dam (R40) so samples of raw Horsetooth Reservoir water at the FCWTF are representative of hypolimnetic conditions at Soldier Canyon Dam.

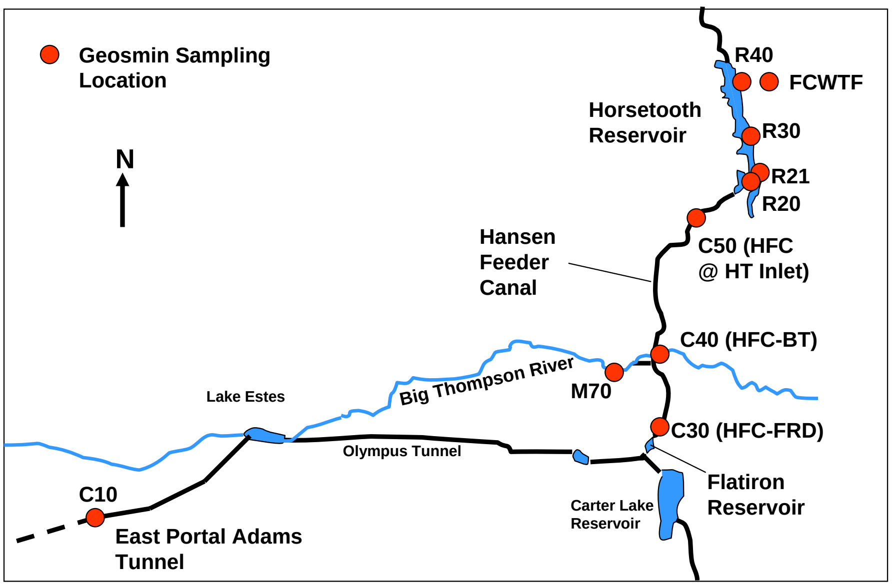
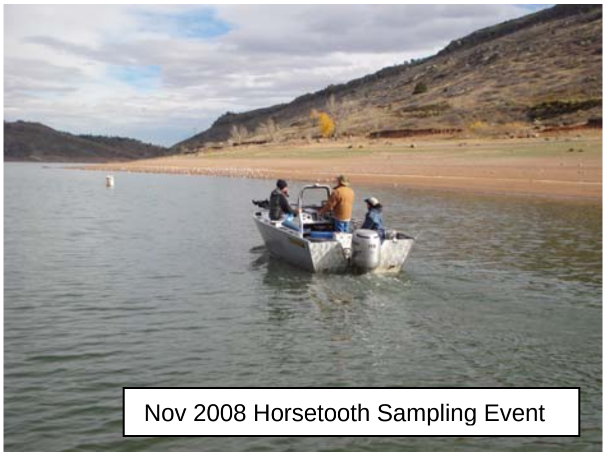


Figure 2. Geosmin Monitoring Program Sampling Locations.

Field sampling methods. All geosmin samples were collected by City of Fort Collins Utilities staff. The reservoir sample sites were accessed using the City of Fort Collins sampling boat. All reservoir samples were discrete depth grab samples collected using a Van Dorn sampler. Each collected sample was immediately transferred to an amber glass bottle and placed on ice in sample coolers. Reservoir water column grab samples were generally collected at two depths: a near surface sample at a depth of 1 meter, and a bottom sample at 1 meter above the reservoir bottom. Because data analysis indicated the occurrence of interflow from the Hansen Feeder

Canal, grab samples were also collected from the metalimnion as the 2009 sampling season progressed. The canal, river, and Adams Tunnel grab samples were collected from the center of the main flow with sampling aided by the use of a telescopic pole. The sample volume collected in the bottle attached to the pole was immediately transferred to an amber glass bottle and placed on ice in sample coolers.



Nov 2008 Horsetooth Sampling Event

Geosmin Sampling Frequency. Reservoir geosmin sampling began in Fall 2008 with one sampling event in November and one in December; the 2008 sampling did not include the sites upstream of Horsetooth Reservoir. In 2009, the geosmin monitoring program was expanded to improve early-warning capabilities by sampling earlier, more often, and at more locations. The 2009 sampling frequency was reviewed and modified as the season progressed based on the results of the most recent sampling event. Both the sampling locations and frequencies had to be carefully optimized such that program objectives could be met within reasonable budget and time constraints.

Hansen Feeder Canal at Site C40

Horsetooth Reservoir geosmin sampling in 2009 was conducted twice in August, twice in September, once in October, and once in November. Sampling of the sites upstream of Horsetooth Reservoir was conducted beginning in August 2009, and conducted twice a month in August through November. Sampling of raw Horsetooth Reservoir water at the FCWTF (representative of conditions in the hypolimnion at Soldier Canyon Dam R40) was conducted once a week. This is the water that the treatment plant operators must respond to and treat to meet regulatory requirements and customer expectations for aesthetically pleasing water.

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 are not filtered prior to analysis so analysis is conducted for total concentrations. However, protein-bound geosmin may be underestimated using current extraction techniques (Juttner and Watson, 2007). Geosmin analysis is conducted by the City of Fort Collins Water Quality Laboratory using solid phase microextraction as per Standard Method 6040D (2005), and gas chromatography/mass spectrometry. Geosmin data are generally available within two days of sample collection. The high quality data, short turn-around times, and scheduling flexibility provided by the Fort Collins Water Quality Laboratory are key elements to the success of the Fort Collins geosmin monitoring program.

Routine sampling program. The reservoir geosmin samples were generally collected at the same time that the routine samples were collected. Data collected as part of the routine Horsetooth Reservoir monitoring program include Secchi depth, profiles for temperature, dissolved oxygen, and specific conductance, and water column discrete depth and composite samples for nutrients, chlorophyll-a, phytoplankton, total organic carbon, major ions, and metals. The field and laboratory methods for the routine monitoring program are outlined in Billica and Oropeza (2009). Data collected as part of the routine monitoring program provide for the evaluation of the physical, chemical, and biological factors affecting geosmin.

Phytoplankton analysis. As part of the routine Fort Collins program, samples are collected for phytoplankton enumeration (cells/mL) and identification within Horsetooth Reservoir (at a depth of one meter) and at the Hansen Feeder Canal at the inlet to Horsetooth Reservoir (C50). The routine monitoring program has historically included phytoplankton identification and enumeration to the *genus* level. However, since geosmin production is species (and sometimes strain) specific (Juttner and Watson, 2007; Taylor et al, 2006), the routine monitoring program was modified in 2009 to conduct phytoplankton enumeration and identification to the *species* level (when possible). Speciation was conducted by Richard Dufford (private consultant in Fort Collins) as outlined in Billica and Oropeza (2009).

RESULTS

Geosmin Data at the FCWTF. A plot of geosmin data for Horsetooth Reservoir samples collected at the FCWTF raw water sample tap is shown on Figure 3 for the period of record (October 2003 to December 2010). The FCWTF customer odor threshold for geosmin (4 ng/L) was exceeded in raw Horsetooth Reservoir water at the FCWTF in Oct-Nov 2003, Nov-Dec 2005, Oct 2006-Jan 2007, Oct-Dec 2007, and Oct 2008-March 2009. Although the data indicate the presence of recurring seasonal geosmin episodes, it wasn't until 2008, when the record high geosmin concentration of nearly 25 ng/L was measured in raw Horsetooth Reservoir water at the FCWTF, that the Fort Collins Utilities initiated their geosmin sampling program within the reservoir.

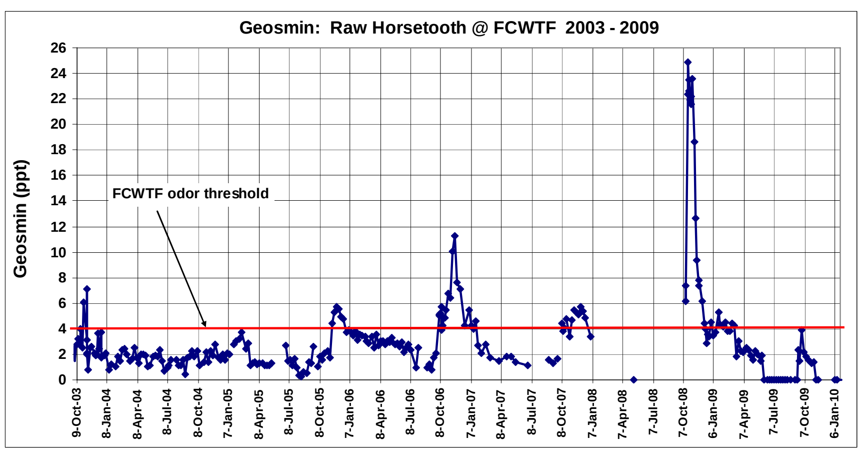


Figure 3. Horsetooth Reservoir geosmin concentrations at the FCWTF raw water intake.

2008 Horsetooth Reservoir Geosmin Data. Geosmin concentrations measured in samples collected within Horsetooth Reservoir are plotted on Figure 4. The geosmin concentrations in the November 4, 2008 Horsetooth Reservoir samples were the highest on record. The peak concentration was 53 ng/L, collected at 1 meter below surface in the pool at Spring Canyon Dam (R21). The samples collected on Nov. 4, 2008 do not show a clear geosmin gradient from upstream (R20, Inlet Bay Marina) to downstream (R40, Soldier Canyon Dam) in the top and bottom samples (Figure 4). However, the samples collected on Dec. 2, 2008 do show a gradient with the highest concentrations at the upstream (R20) end of the reservoir and the lowest concentrations at the downstream (R40) end of the reservoir.

A. TOP SAMPLES

B. BOTTOM SAMPLES

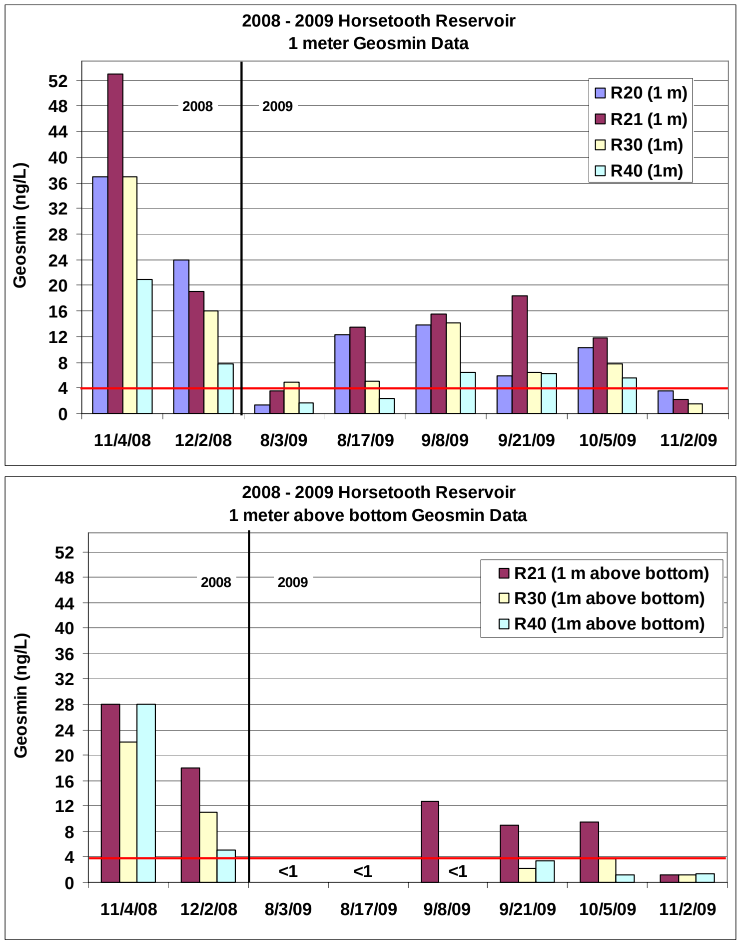


Figure 4. Geosmin concentrations measured within Horsetooth Reservoir in 2008 and 2009 at: A) a depth of a meter below the surface, and B) a depth of 1 meter above the reservoir bottom.

The pools at Spring Canyon and Dixon Canyon Dams were still weakly stratified on the Nov. 4, 2008 sampling date, resulting in significantly different top and bottom geosmin concentrations. By the December 2008 sampling date, the reservoir was completely mixed. The bottom geosmin concentrations (at depths of 32 m to 35 m) measured on Nov. 4, 2008 were all surprisingly high. High geosmin concentrations at the bottom of the reservoir prior to turnover is likely due to the settling of organic particulate matter that contains cell-bound geosmin (Juttner and Watson, 2007). Microbial digestion of this settled organic particulate matter in the hypolimnion results in the transfer of cell-bound geosmin into dissolved geosmin.

2009 Horsetooth Reservoir Geosmin Data. In 2009, the geosmin sampling season was begun early enough to follow the progression of increasing geosmin concentrations at various locations within the reservoir. The peak 2009 geosmin concentration of 18.4 ng/L, measured on 9/21 in the surface sample from Spring Canyon (R21), was significantly less than the 2008 peak

(Figure 4). The highest geosmin concentrations were measured at Spring Canyon (R21) top and bottom throughout the 2009 sampling season. Geosmin concentrations at the reservoir bottom at Spring Canyon (at depths of 35 to 40 meters) were also relatively high. During 2009, it was particularly revealing to observe that low concentrations can exist throughout the season at the FCWTF intake (all values were < 4 ng/L) while potentially problematic concentrations developed at various locations within the reservoir. Geosmin concentrations measured at the FCWTF intake are not representative of concentrations found within the reservoir.

2009 CBT System Geosmin Data. Geosmin concentrations measured in CBT Project components upstream of Horsetooth Reservoir are plotted on Figure 5. Geosmin concentrations at the Horsetooth Inlet (C50) indicate that geosmin is transported to the reservoir from upstream sources. Potential upstream sources include phytoplankton in the west slope reservoirs, phytoplankton in Flatiron Reservoir, and periphyton in the Hanson Feeder Canal. Large blooms of cyanobacteria are known to be present at times in August and September in the west slope Grand Lake and Shadow Mountain Reservoir (Lieberman, 2008).

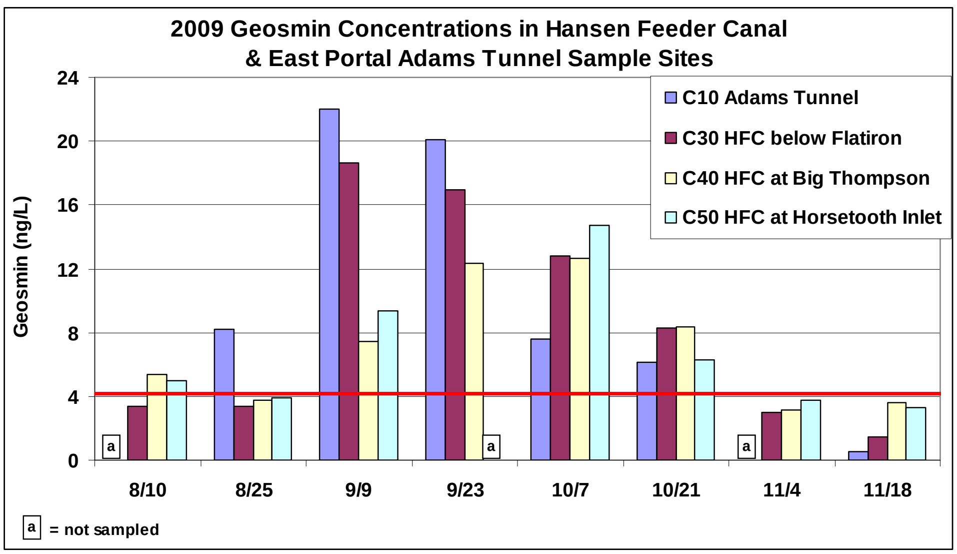


Figure 5. 2009 Geosmin concentrations in CBT Project components upstream of Horsetooth Reservoir.

The data plotted on Figure 5 suggest that at different times of the season, each of the possible geosmin sources may be more significant. Processes such as volatilization and biodegradation are also occurring at the same time and can cause net decreases in concentration from upstream sites to downstream sites. Finally, transport and fate is complicated by operation and maintenance of the various CBT Project components; in 2009 the Hansen Feeder Canal from C40 to C50 was off for maintenance from September 11 to 25, while flow through the Adams Tunnel was off or very low from August 13 to 26, and November 2 to 17. In addition to significant temporal variability, the monitoring program conducted to date has revealed wide spatial variability in geosmin concentrations as shown on Figure 6 for the September 8-9 sampling event.

Figure 7 compares geosmin concentrations in water flowing into Horsetooth Reservoir (C50) with reservoir water closest to the influent end (R20 Inlet Bay and R21 Spring Canyon). Concentrations at Inlet Bay (R20) and Spring Canyon (R21) are higher than the influent water

(C50) until early October. This indicates that at least a portion of the geosmin in Horsetooth Reservoir is being produced in Horsetooth Reservoir. Alternatively, cell-bound geosmin (not separately measured by the laboratory analysis) may be transported to Horsetooth Reservoir where it is subsequently released during microbial digestion. When the Hansen Feeder Canal was off (Sept. 11 to 25), the geosmin concentration at Inlet Bay decreased while the geosmin concentration at Spring Canyon increased. It is postulated that geosmin concentrations at the Inlet Bay are generally being sustained by the inflowing waters, and without that source, geosmin degradation exceeded geosmin production resulting in the drop in concentration. At Spring Canyon, geosmin production occurred independent of the inflow allowing geosmin concentrations to increase during this time.

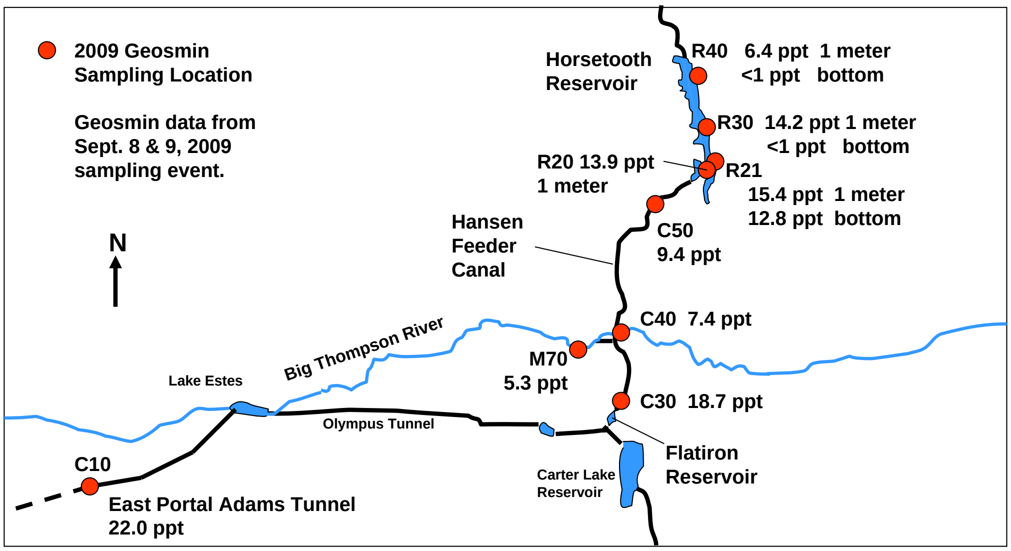


Figure 6. September 2009 geosmin concentrations in sampling sites upstream of Horsetooth Reservoir and sampling sites within Horsetooth Reservoir.

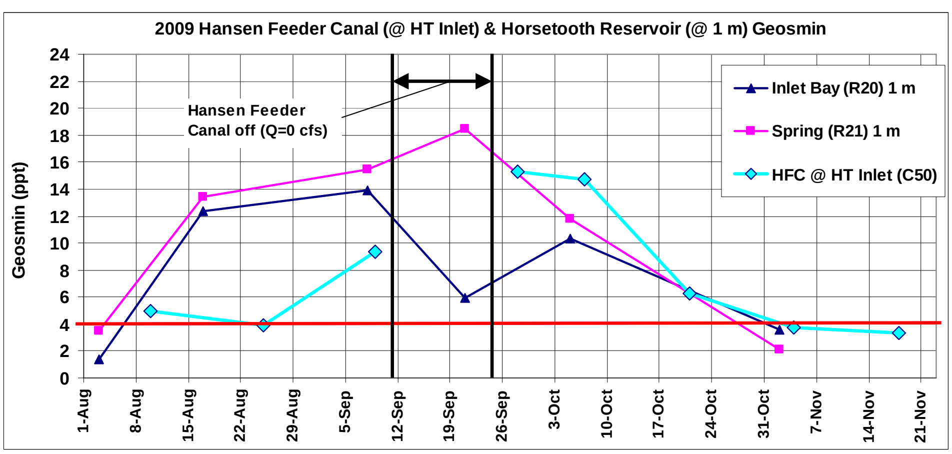


Figure 7. Comparison of geosmin inflow concentrations (C50) with concentrations at the upstream end of Horsetooth Reservoir.

Temperature data indicate that Hansen Feeder Canal water exists as an interflow in the metalimnion of Horsetooth Reservoir. Because of this, metalimnion samples were also collected for geosmin analysis beginning in late September. The reservoir geosmin data from the October 7 sampling event are shown on Figure 8. The geosmin concentrations within the bottom half of R20 (Inlet Bay) were higher than the surface due to the cold Hansen Feeder Canal water (with a geosmin concentration of 14.8 ng/L) plunging to the bottom of the relatively shallow (19 m) Inlet Bay. Some amount of mixing and entrainment of ambient Inlet Bay water into the Hansen Feeder Canal inlet water occurs when the canal water plunges below the surface of the reservoir. This results in intermediate geosmin concentrations and water temperatures at the bottom half the Inlet Bay water column (compared to those measured in the Hansen Feeder Canal and the top half of the Inlet Bay water column). It is postulated that this interflow continues moving through the reservoir metalimnion, with additional entrainment of ambient reservoir water causing the geosmin concentration in the metalimnion to decrease as the interflow proceeds downstream. Numerical modeling will be required to better understand the flow patterns in Horsetooth Reservoir and the impact of Hansen Feeder Canal interflow on geosmin transport.

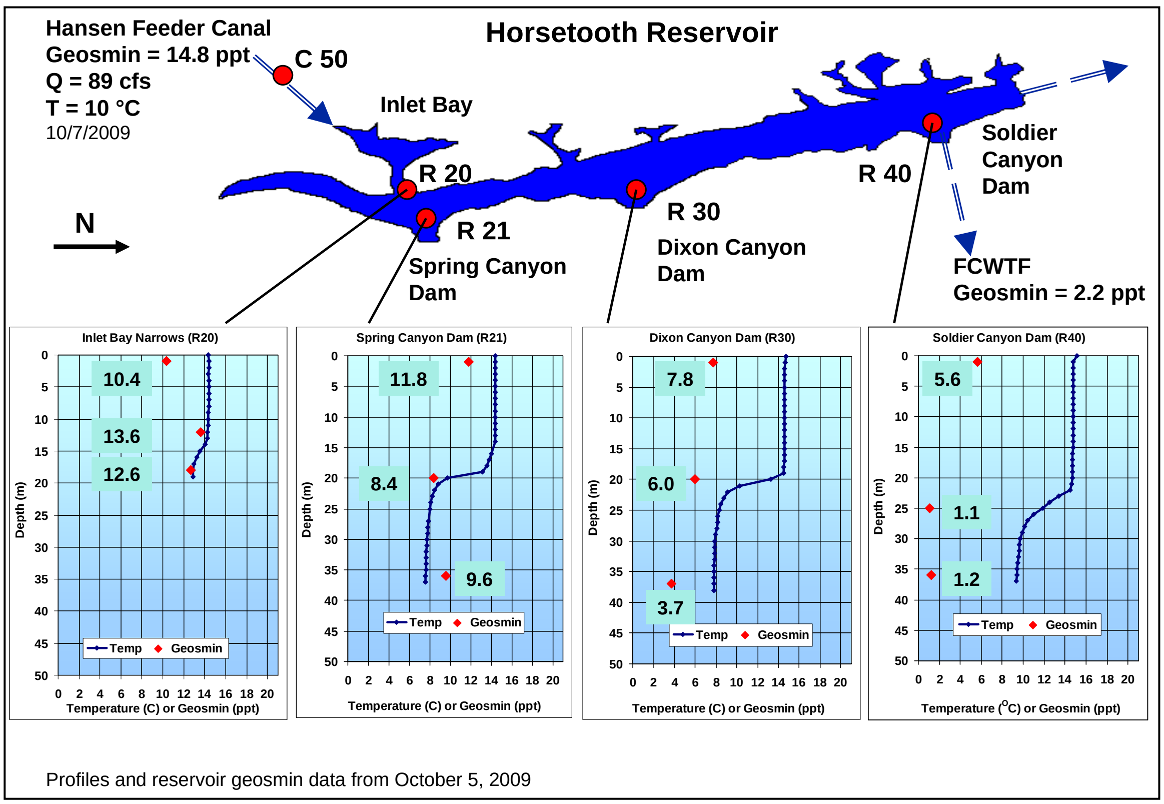


Figure 8. Temperature profiles and geosmin concentrations at sampling sites within Horsetooth Reservoir (collected October 5, 2009).

Chlorophyll-a and phytoplankton. Most monitoring programs attempt to establish correlations between geosmin concentrations and cyanobacteria densities and chlorophyll-a concentrations. In 2009, the total phytoplankton densities ranged from 4,201 to 39,348 cells per milliliter (cells/mL) in the 1 meter samples collected from Horsetooth Reservoir. The geosmin producing genera of cyanobacteria generally made up 5 percent or less of the total density. The most common cyanobacteria genera found in Horsetooth that include species of geosmin producers were *Anabaena* and *Synechococus*, with *Aphanizomenon* and *Pseudanabaena* making up very minor amounts of the total densities. *Synechococcus* are very small (bacterial dimensions) unicellular cyanobacteria that can be overlooked (Taylor et al 2006). Geosmin producing species identified in the 2009 samples include *Anabaena lemmermannii* and *Aphanizomenon gracile* (Juttner and Watson, 2007). The 2008 phytoplankton data indicated lower total densities within the reservoir, and lower densities of geosmin producing genera. Although the densities of potential geosmin producers was low in both years, it has been observed by others that the geosmin source may not be the predominant organism, but rather a minor or inconspicuous component (Taylor et al, 2006).

The 2008 and 2009 chlorophyll-a concentrations for the reservoir sites at a depth of one meter are summarized on Table 1. The data show that the August through November average chlorophyll-a concentrations in the reservoir in 2008 were higher than in 2009, indicating that conditions in the reservoir were different during the two years. However, observing this difference does not provide the necessary information to determine the cause(s) of the record setting high geosmin concentrations in 2008. The site with the highest 1 meter geosmin concentrations in both 2008 and 2009 - Spring Canyon (R21) - did not have the highest chlorophyll-a concentrations. Soldier Canyon (R40), which consistently had the lowest 1 meter geosmin concentrations in 2008 and 2009, had some of the higher chlorophyll-a concentrations in fall 2008 and 2009.

Table 1. Average of August through November chlorophyll-a data

Site	2008 Avg (ug/L)	2009 Avg (ug/L)
R20 Inlet Bay	3.6	2.2
R21 Spring Canyon Dam	2.9	2.2
R30 Dixon Canyon Dam	4.5	2.0
R40 Soldier Canyon Dam	4.2	2.6

Chlorophyll-a density is only a good predictor of geosmin if the geosmin-producing species make up a significant portion of the total algal biomass (Taylor et al, 2006). Since geosmin-producing genera were only minor contributors to the total phytoplankton density, the direct relationship between the 2008 and 2009 one-meter geosmin and chlorophyll-a data is poor as shown on Figure 9.

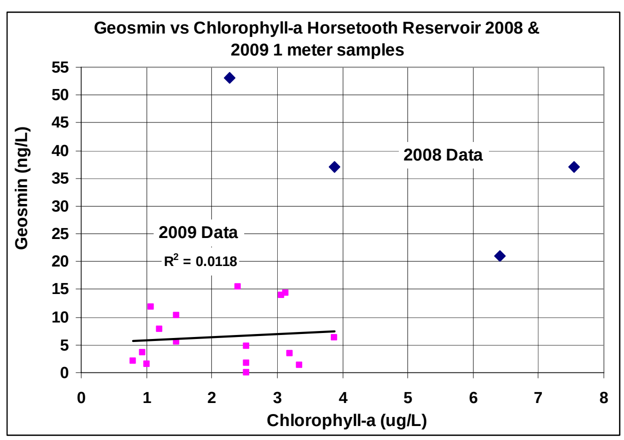


Figure 9. Geosmin versus chlorophyll-a (all Horsetooth Reservoir 2008-2009 1 meter samples).

Periphyton Data. Periphyton (attached algae) sampling was conducted in 2008 and 2009 by the Northern Colorado Water Conservancy District at the three locations on the Hansen Feeder Canal where geosmin sampling has been conducted (C30, C40, and C50 shown on Figure 2). One sample was collected at each site in each of the months of September 2008, June 2009, and August 2009. Algae speciation was conducted by Richard Dufford. The attached cyanobacteria

Phormidium autumnale made up 100 percent of the biomass at C30 (downstream of Flatiron Reservoir) in September 2008, and 45% of the biomass at C30 in August 2009. Attached cyanobacteria were not observed at the other two Hansen Feeder Canal locations. Several species of the genus *Phormidium* have been shown to produce geosmin. However, *Phormidium autumnale* has not been identified as a geosmin producer. Additional periphyton sampling will be required before it can be ruled out as a possible geosmin source.

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 outlined the geosmin monitoring program used by the FCWTF and highlights some of the key findings to date and factors that affect the success of the program. The reconnaissance monitoring conducted in 2008 revealed high geosmin concentrations throughout Horsetooth Reservoir, but geosmin production sites could not be determined. The expanded monitoring program in 2009 showed significant spatial and temporal variation in geosmin concentrations in the reservoir and in the upstream components of the CBT Project. The data suggest a very complex system with respect to geosmin. The watershed that makes up the study area is large and includes natural and constructed hydrologic features subject to biological, physical, and hydrodynamic processes and varying operational controls. The monitoring conducted to date indicates varying levels of geosmin production, transport, and degradation throughout the system.

Many questions remain and it is expected that several years of monitoring will be required to more fully understand geosmin sources, transport, and fate, and to identify geosmin occurrence patterns. Future monitoring will build upon the following findings of the geosmin monitoring program conducted to date:

- Significant spatial variation in geosmin concentrations exists within the reservoir and within upstream water bodies.
- Concentrations are highest in the epilimnion (as measured by the 1 meter samples).
- Significant geosmin concentrations can exist at the bottom of the reservoir even when the reservoir is stably stratified.
- Data suggest that geosmin is both transported into the reservoir via the Hansen Feeder Canal and produced within Horsetooth Reservoir
- Geosmin concentrations measured at the FCWTF intake are not representative of concentrations found within the reservoir.
- No correlation exists between geosmin concentrations and chlorophyll-a concentrations or the algal cell density of the potentially geosmin producing genera.

- More periphyton sampling of the canal will be required to evaluate the canal as a geosmin production site.
- A better understanding of geosmin transport and fate will require separate analysis of the dissolved and cell-bound fractions.
- Numerical modeling will be required to fully understand the flow patterns in Horsetooth Reservoir and the impact of Hansen Feeder Canal interflow on geosmin transport.

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