Adaptive Water Resource Management

for Taste and Odor Control for the Anderson Regional Joint Water System

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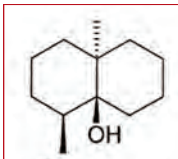
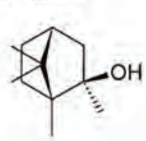
Introduction

Surface water provides potable water for most citizens in the United States. Although about 90% of the public water systems in the US obtain their water from wells, groundwater systems tend to be much smaller than those served by surface waters. Surface waters supply about 66% of the potable water consumed. Periodically, surface waters can be plagued by taste and odor problems. The two most commonly measured taste and odor compounds in water are geosmin and 2- methylisoborneol (MIB). These compounds are primarily produced by cyanobacteria (blue green algae), diatoms, and actinomycetes that may or may not grow to 'bloom' densities in water resources sufficient to cause taste and odor problems for operators attempting to treat the source water.

Geosmin and MIB are naturally occurring terpene alcohols produced by cyanobacteria, diatoms, and filamentous bacteria (actinomycetes) as well as myxobacteria. Geosmin (trans -1,10-dimethyl-trans-9-decalol) is an aromatic volatile metabolite with an earthy smell that is responsible for the characteristic odor of moist soil as well as off-flavors in drinking water and food such as fish. Methyl isoborneol is a volatile methylated monoterpene with an intense muddy odor that contributes to the characteristic musty or earthy smell in water and fish tissue. These organic compounds are usually found in ultra-trace levels (a few parts per trillion or less) in surface waters. The human nose can detect geosmin at concentrations as low as 5 to10 parts per trillion (ng/L) of water. Although geosmin and MIB are not known to be a public health problem, the olfactory sensitivity of consumers can create considerable concern prompted by foul smelling drinking water that can lead to complaints and misinterpretations of the odors as a water quality problem.



Geosmin



2-Methylisoborneol

"The costs of controlling the taste and odor problems can be substantial as can the costs of failing to control the problems as consumer complaints rise."

There are numerous producers of taste and odor compounds. Types of cyanobacteria including species of *Oscillatoria*, *Lyngbya*, *Phormidium*, *Planktothrix*, *Anabaena*, *Nostoc*, *Aphanizomenon*, *Synechococus*, and *Pseudanabaena* are common synthesizers of geosmin and MIB. Some examples of Actinomycetes that produce geosmin include genera such as *Streptomyces*, *Nocardia*, *Actinobacteria*, *Arthrobacter*, and *Fossombronia*, and some may produce MIB as well. Several other microbes (e.g., fungi, protozoa and eukaryotic algae) can also generate geosmin and MIB in aquatic systems on occasion.

Taste and odor compounds generated in source water must be treated to produce potable water. Since consumers of potable water generally rely on the taste of their water as the primary indicator of its safety, operators producing treated water are faced with the decision to deal with taste and odor compounds within the treatment facility or in the source water. The costs of controlling the taste and odor problems can be substantial as can the costs of failing to control the problems as consumer complaints rise. In-plant control involves dealing with taste and odor compounds upon arrival at the treatment plant. Treatment may include ozonation for oxidation of geosmin and MIB and granular activated carbon for sorption. Source water control involves managing the densities of taste and odor producers through strategic applications of appropriate algaecides. Some managers of critical water resources may need both in-plant and source water control options to achieve and maintain acceptable treated water quality. Decisions regarding the course of action are site-specific and involve several factors such as the frequency and intensity of production of taste and odor compounds, logistics, characteristics of the water resource, availability of water treatment equipment, consumer sensitivity, and costs.

When algae grow to the extent that the taste and odor compounds that they produce become problematic, water resource managers are often compelled to intervene. Many managers employ adaptive water resource management consisting of the following steps or considerations:

1. **Problem definition.** Determine the intensity, frequency, and location of taste and odor compounds and producers, as well as define the internal and external capabilities for addressing the problem.
2. **Plan development.** Develop a strategy to reduce and control taste and odor compounds. The plan may include where and how to treat taste and odor producers, obtaining permits, and securing contractors with specific capabilities, experience, and credentials.

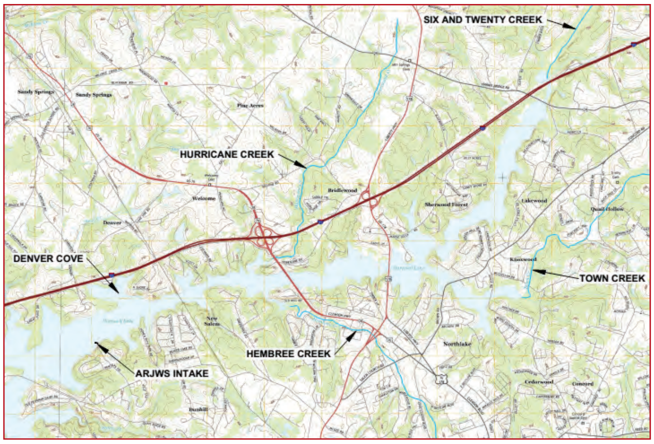


Figure 1. Six and Twenty Creek Cove of Hartwell Lake, South Carolina.

Figure 2. Anderson Regional Joint Water System intake structure on Hartwell Lake.

3. **Strategic monitoring.** Measure responses of target algae, considering safety for non-target species; evaluate the durability of a treatment for future planning.
4. **Economics.** Consider cost, return on investment, and savings associated with water resource management options.

This article provides an adaptive water resource management strategy for controlling taste and odor in source water of the Anderson Regional Joint Water System (ARJWS) using the considerations above. ARJWS is a partnership of rural and municipal water districts providing high-quality, clean, safe, reliable, economical flow of treated water to customers in Anderson and Pickens Counties, South Carolina. The ARJWS water treatment plant is supplied by surface water from the US Army Corps of Engineers Hartwell Lake. The plant operates 24 hours per day, every day of the year, with a current capacity of 48 MGD.

Materials and Methods

Hartwell Lake is a 55,900-acre US Army Corps of Engineers reservoir bordering Upstate South Carolina and Georgia. The reservoir is managed for hydropower, flood control, navigation, fish and wildlife, recreation, and drinking water supply. The Six and Twenty Creek cove of Hartwell Lake supplies South Carolina's Anderson Regional Joint Water System (ARJWS) water treatment plant (**Figures 1 and 2**).

ARJWS had experienced intermittent taste and odor problems in raw and finished water from the treatment plant on the Six and Twenty Creek cove of Hartwell Lake, making it difficult or impossible to provide the quality drinking water (odor-free) that customers expect.

To discern the proximate source of taste and odor compounds in the lake, water at various depths and sediment samples were collected near the ARJWS water intake structure on August 16, 2014. Samples were taken to the Clemson University ecotoxicology facility and analyzed by light microscopy to identify taste and odor producing organisms. The development of an adaptive management strategy began with identifying the source of taste and odor problems as terpene alcohols [2-methylisoborneol (MIB) and geosmin] produced by benthic algae (e.g., blue-green algae and diatoms). Clemson University also conducted laboratory assays using water and algae samples to determine effective algaecides and application concentrations. With MIB concentrations of over 2,000 parts per trillion in Hartwell Lake in the summer of 2014, an immediate algaecide application plan was developed based on the results from the laboratory study of responses of taste and odor producing algae to candidate algaecides.

Based on these initial laboratory results, a plan was developed to conduct a pilot study to determine the efficacy and cost effectiveness of chemical control of the putative taste and odor-producing organisms. A request for bids to conduct the algaecide application was issued on August 26, 2014. Aqua Services, Inc. performed the algaecide application on September 4 and 5, 2014

Parameter	Method	Method Detection Limit
pH	Direct Instrumentation: Orion Model 420A (Standard Methods 4500-H^+ B) (APHA, 2005)	0.01 SU
Temperature	Direct Instrumentation: Orion Model 420A	0.01 °C
Dissolved Oxygen	Direct Instrumentation: YSI Model 52	0.1 mg/L
Conductivity	Direct Instrumentation: YSI 30 (Standard Method 2510 B) (APHA, 2005)	0.1 µS/cm^2
Alkalinity	Standard Methods: 2320 B (APHA, 2005)	2 mg/L as $CaCO_3$
Hardness	Standard Methods: 2340 B (APHA, 2005)	2 mg/L as $CaCO_3$
MIB	Standard Methods: 6040 D (APHA, 2005)	5.0 ng/L
Geosmin	Standard Methods: 6040 D (APHA, 2005)	1.0 ng/L
PO_4	Standard Methods: 4500-P E (APHA, 2005)	0.08 mg/L
NH_3	Standard Methods: 4500- NH_3 F (APHA, 2005)	0.05 mg/L

Table 1. Analytical methods for explanatory water characteristics and environmental parameters

under South Carolina Department of Health and Environmental Control's (SCDHEC) National Pollutant Discharge Elimination System (NPDES) General Permit.

Prior to and following the pilot algaecide application, water and sediment samples were collected throughout the study area for analysis to confirm effectiveness of treatment. Analyses included explanatory parameters (**Table 1**), copper (graphite furnace atomic absorption spectrometer, Perkin-Elmer 5100 PC, Waltham, MA) and hydrogen peroxide (SpectraMax®M2 Microplate Reader, Molecular Devices Corporation, Sunnyvale, CA; Klassen et al. 1994) residuals, microscopy to determine presence/absence of taste and odor producers, and fish and invertebrate toxicity (US EPA 2000; 2002). Taste and odor compound monitoring continued weekly through November 2014, then decreased in frequency as concentrations naturally diminished at the onset of winter.

During the 2014-15 winter, in anticipation of the return of taste and odor producers in the spring or early summer, new laboratory assays were performed to refine algaecide and application recommendations for effective taste and odor control. Additional toxicity studies were conducted to establish margins of safety for non-target animals (fish and invertebrates) potentially exposed to algaecides. To refine plans for future algaecide applications (in 2015), a regimen of toxicity tests of Hartwell Lake water and sediments were conducted using sensitive, sentinel fish and invertebrate species to establish margins of safety for non-target species potentially exposed to algaecides. In addition, a hydrological study of the watershed upstream of the ARJWS intake structure was conducted for the purpose of understanding the areas of the lake that influence the ARJWS intake and time of travel from upstream to the intake.

Five tributaries and inlets upstream of the ARJWS intake were selected for the hydrological study; (1) Six and Twenty Creek, (2) Town Creek, (3) Hurricane Creek, (4) Hembree Creek, and (5) an unnamed tributary designated Denver cove. These tributaries comprise approximately 78% of the entire watershed that supplies water to the main water body above the ARJWS intake. To determine if water from each inlet enters the main water body, fluorescent tracer dyes were deployed to 'track' the water flow paths. Rhodamine WT and Fluorescein dyes were used to track flow. The dyes are National Sanitation Foundation (NSF) International certified safe for drinking water. Prior to dye deployment, water samples were collected in each cove to determine potential background fluorescence that may have affected the analysis. Each dye was introduced at a concentration of 500 parts per trillion.

Water samples, both at the surface (i.e., ≤ 6 inches deep) and at depth (i.e., ≤ 2 feet above the lake bottom), were collected at predetermined locations at approximately 20, 44, 68, 116, and 164 hours after deployment. The samples were placed in a cooler on ice (i.e., 4°C) during the sample collection period and delivered to the laboratory at Clemson University for analysis on the day of collection. Samples were analyzed following modified methods from Dierberg and DeBusk (2005) and Corbett et al. (2005) for Rhodamine WT and Fluorescein, respectively. Methods were modified by conducting a spectral scan to determine excitation and emission maxima specific for Hartwell Lake water. Relative fluorescence units (RFUs) were converted to dye concentrations using a linear regression calculated from dye standards.

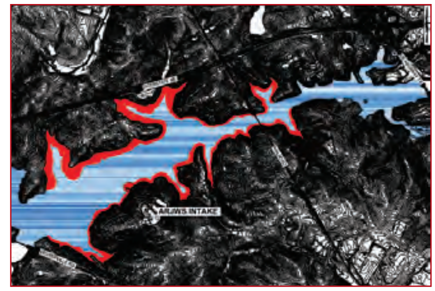


Figure 3. Source water treatment area (red shading), September 4-5, 2014.

Based on results of the pilot study, including effectiveness of algaecides to control taste and odor production and responses of non-target organisms to algaecide exposures, additional laboratory algal assay and toxicity tests conducted over the winter, and results from the hydrological study, a refined and adaptive source water treatment plan for 2015 was developed and implemented. Algaecide application procedures, monitoring, and laboratory analysis methods were the same or similar to those employed during the pilot study.

Results

Field observations and samples collected on August 16, 2014 in the vicinity of the ARJWS intake structure on Hartwell Lake indicated that taste and odor compounds were originating from benthic and epiphytic sources.

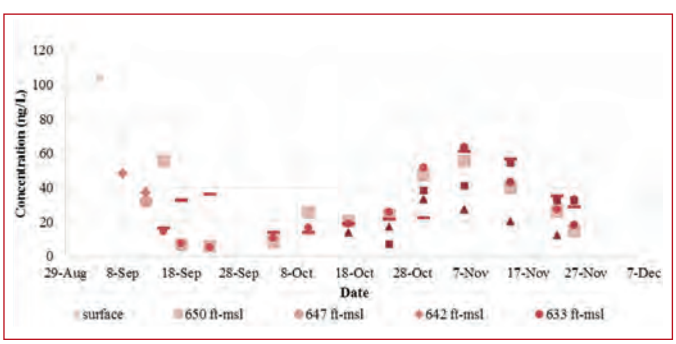


Figure 4. MIB concentrations in source water prior to and following algaecide application, September 4-5, 2014. Samples collected at various depths at the ARJWS intake, the Honea Path Park landing, an untreated area near the Highway 76 bridge, and finished water at the ARJWS treatment plant.

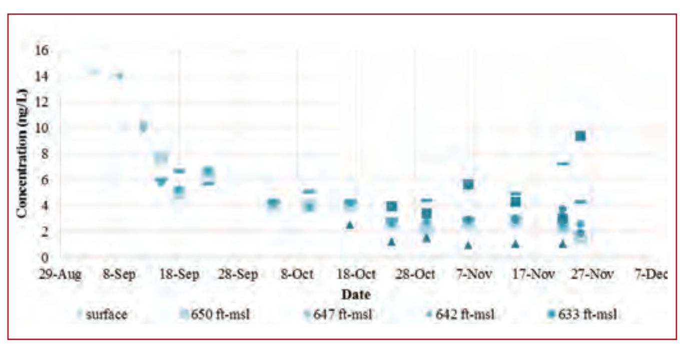


Figure 5. Geosmin concentrations in source water prior to and following algaecide application, September 4-5, 2014. Samples collected at various depths at the ARJWS intake, the Honea Path Park landing, an untreated area near the Highway 76 bridge, and finished water at the ARJWS treatment plant.

2015 Algaecide Applications	Product	Area of Application	Acreage
May 14	Phycomycin SCP	Intake structure vicinity	6.5
May 26-27	Algimycin PWF Phycomycin SCP	Lake littoral zone and intake structure vicinity	82 43
July 21	Phycomycin SCP	Intake structure vicinity	6.5
August 5-6	Algimycin PWF Phycomycin SCP	Lake littoral zone and intake structure vicinity	82 43
August 27	Phycomycin SCP	Intake structure vicinity	6.5
September 10-11	Algimycin PWF Phycomycin SCP	Lake littoral zone and intake structure vicinity	105 37

Table 2. 2015 Hartwell Lake treatment algaecide applications for taste and odor control

Light microscopy revealed the presence of the blue-green algae *Oscillatoria*, *Anabaena*, and *Planktothrix* and the diatoms *Tabellaria* and *Fragilaria* as putative sources of MIB and geosmin.

Based on laboratory assays to determine efficacy of various algaecides, the copper-based Algimycin®-PWF applied at 1 mg copper per liter and the peroxide-based Phycomycin® SCP applied at 100 pounds per acre-foot were selected for the pilot study. The algaecides are registered for application to surface water by the US EPA and are certified for use in potable waters by the NSF.

On September 4-5, 2014, Algimycin and Phycomycin were applied to the bottom two acre-feet of approximately 160 acres of the Hartwell Lake littoral zone (from the shoreline to the 25' depth contour) and approximately 4 acres around the ARJWS water intake structure (**Figure 3**).

Within days, MIB and geosmin concentrations declined significantly in the treatment area, eliminating taste and odor problems in the raw water for several weeks (**Figures 4 and 5**). Results from water samples collected October 30, 2014, indicated MIB concentrations were beginning to increase in comparison with concentrations from previous weeks. Benthic putative taste and odor producers were observed upstream in an untreated area macroscopically and microscopically, in addition to a noticeably potent odor. It was likely that these untreated waters (where algaecides were not applied) were influencing the increase in MIB concentrations at the ARJWS intake.

During sampling on November 6, 2014 near the intake structure (parts of the algaecide treated area), putative taste and odor producers were observed both visually and microscopically. These benthic algae were beginning to grow in low densities on submerged structures (rocks, logs, tree branches, etc.). The onset of winter conditions in November limited colonization and growth of algae, although monitoring continued through the winter.

Results of the watershed hydrological investigation indicated that portions of the water from each of the studied inlets entered the main water body within one day. Additional sampling at the ARJWS intake revealed that water originating in Hurricane and/or Hembree Creeks reached the intake in less than three days. The results suggested that a portion of the lake water has the potential to travel from the easternmost reaches of the main water body to the ARJWS intake within one week. There are likely preferential paths or short circuiting occurring in the main water body that account for these observations. Samples collected at the intake did not provide evidence that water from the Denver cove reached the intake under the conditions present during this study.

Source water monitoring indicated geosmin concentrations began to increase in February 2015, significantly rising in late April and early May, peaking at over 25 ng/L (**Figure 6**). Based on results of the pilot study, additional laboratory assays, and source water monitoring through the winter and spring, a refined algaecide application plan was developed consisting of Algimycin®-PWF applied at 0.5 mg copper per liter and Phycomycin® SCP applied at 100 pounds per acre foot applied to the bottom two acre feet of littoral zone as previously described. Algaecide applications were conducted in May (**Table 2**), resulting in a decline of

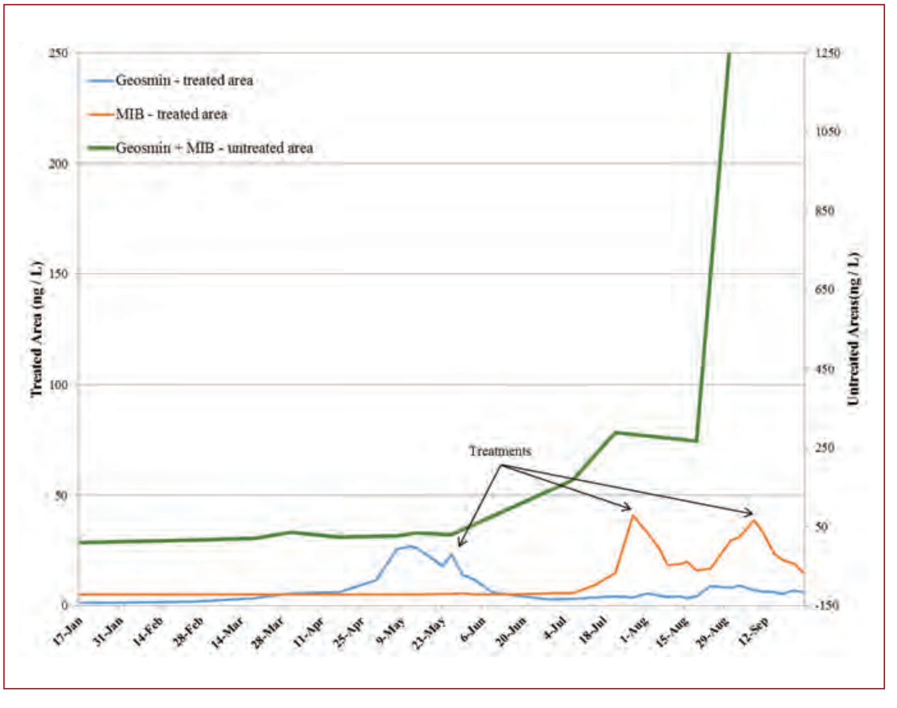


Figure 6. Geosmin and MIB concentrations in source water, 2015.

geosmin to below detection (<5 ng/L). MIB concentrations remained stable during this time (<10 ng/L), then began increasing in July, exceeding 60 ng/L by late July (Figure 6). A second lake treatment was conducted August 5-6, resulting in a decline of MIB to approximately 15 ng/L. Within four weeks of treatment, MIB and geosmin increased to unacceptable levels, triggering a third treatment of the lake September 10-11. Following the third treatment, MIB and geosmin concentrations declined to <15 ng/L and <10 ng/L, respectively, and have remained to date (**Figure 6**).

Discussion and Conclusions

Adaptive management of ARJWS source water has resulted in control of taste and odor in drinking water, essentially eliminating customer complaints, allowing the treatment plant to operate with minimal modification, and maintaining valuable aquatic resources of Hartwell Lake. The adaptive approach was initiated by identifying the source of taste and odor compounds. This case was unique in that the putative taste and odor producers were largely benthic and epiphytic, attaching to the lake bottom and other substrates around the ARJWS intake structure where sunlight could penetrate. Had that not been determined initially with an assumption that the problematic algae were planktonic, taste and odor control would have been ineffective.

Identification of taste and odor-producing organisms in the laboratory allowed for assays to evaluate responses to various algaecides to determine the most effective products and rates of application. This information was then scaled to the field as a treatment plan, upon which solicitations could be issued to qualified contractors to conduct full-scale algaecide applications. In this case, it was critical to select a South Carolina certified aquatic herbicide applicator with the capability to apply algaecides with precision to the lake bottom at specified depths and locations (**Figure 6**).

The watershed hydrological investigation informed the management strategy by focusing treatment on specific areas and avoiding areas that did not impact the intake structure. Thus, it was possible to restrict algaecide use to only where needed, saving time and cost, and limiting exposure of non-target aquatic species to algaecides.

Monitoring water resources is not a management tactic in and of itself; however, strategic monitoring can be used to inform management decisions. In this case, monitoring of taste and odor compounds and the organisms responsible for their production, both temporally and spatially, informed the outcome and durability of algaecide applications. Results from the monitoring program were used to predict the need for subsequent algaecide applications, providing adequate time to acquire necessary permits and schedule the certified applicator.

In 2014, ARJWS worked to control taste and odor in-plant with powder activated carbon (PAC) at a cost of approximately $500,000. The PAC system proved marginally effective against taste and odor at the levels experienced in source water. The combination of source water treatments and PAC in 2015 has cost $250,000 (i.e., 50% cost savings from the previous year), with significant effectiveness controlling taste and odor.

Adaptive source water management can be a viable option for drinking water supplies and used in concert with in-plant capabilities and compatible with other designated water resource uses (e.g., propagation of fish and wildlife, recreation, industrial). By 'adaptive,' the water resource management plan can be designed to fit existing operations of the water utility, factoring in cost and return on investment.

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Figure 7. Deployment of algaecides for bottom application.

Acknowledgements

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