Biological pretreatment: An innovative approach to addressing taste and odor

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Abstract
The presence of objectionable taste-and-odor (T&O) compounds in surface water supplies is a common problem facing drinking water utilities across the country and worldwide. While there are several viable T&O treatment options, including adsorption, biotransformation, and advanced oxidation, no single option fits all applications or is without potential limitations. Through bench- and pilot-scale testing, this work developed and evaluated high-rate biological roughing filtration as a promising alternative for geosmin and 2-methylisoborneol abatement to help utilities minimize T&O complaints without straining their annual operating budgets. Testing showed that biological roughing filtration can effectively treat a wide range of raw water T&O levels using short contact times, and the intermittent presence of T&O compounds did not appear to appreciably affect removal efficacy. Pilot-testing results were used to develop the design criteria for a full-scale 54-mgd biological roughing filter that is currently treating surface water in Manatee County, Florida.

Keywords
biofiltration, biological pretreatment, geosmin, MIB, taste and odor

1 INTRODUCTION

The occurrence of objectionable taste-and-odor (T&O) compounds in drinking water represents significant concerns for water utilities. An AWWA survey found that 43% of 800 utilities surveyed in the United States and Canada reported T&O complaints lasting more than 1 week, and treatment strategies for episodic T&O events amounted to an average of 4.5% of the annual utility budget (Suffet, Corado, Chou, McGuire, & Butterworth, 1996). Although a majority of the T&O compounds do not pose health risks, their presence can result in public skepticism that utilities can produce safe drinking water (Baker, 1949; S. B. Watson, 2004; S. Watson et al., 2007; S. B. Watson, Monis, Baker, & Giglio, 2016).

Of particular importance are the cyanobacteria- and actinomycetes-derived microbial metabolites 2-methylisoborneol (MIB) and trans-1,10, dimethyl-trans-9-decalol (geosmin), which can impart earthy–musty odors at concentrations as low as 1.3 ng/L (Mackey, Suffet, & Booth, 2013; Sklenar, Westrick, & Szlag, 2016). MIB- and geosmin-concentrations often decrease to between 100 and 200 ng/L in surface water supplies, although concentrations as high as 40,000 ng/L have been observed (Srinivasan, Sorial, Ononye, Husting, & Jackson, 2008; S. Watson et al., 2007).
Because of their chemical structure and polarity, geosmin and MIB are recalcitrant and undergo incomplete removal in conventional water treatment processes, such as coagulation, sedimentation, filtration, and chlorination (Mackey et al., 2013; Srinivasan et al., 2008; S. B. Watson et al., 2016). Adsorption-based processes involving powdered activated carbon (PAC) and granular activated carbon (GAC) can be effective for treating MIB and geosmin, exhibiting adsorption capacities between 1.3 and 4.6 µg for T&O compound/g adsorbent (Cook, Newcombe, & Sztajnbok, 2001; Gillogly, 1999). Given the seasonal variability of cyanobacterial events, PAC can be an attractive treatment solution, as it can be dosed on an as-needed basis. However, during intense and/or lengthy T&O events, PAC dosing can rapidly drive up operations and maintenance (O&M) costs and may not remove sufficient T&O to avoid consumer complaints. Alternatively, GAC can be used as conventional filtration media or within a postfilter contactor, although efficacy is subject to sorption capacity and the resulting replacement frequency (Corwin & Summers, 2012).

Advanced oxidation processes such as ozone/H2O2 and ultraviolet (UV)/H2O2 are capable of oxidizing recalcitrant compounds including geosmin and MIB and can be used on an as-needed basis (Kim, Moon, Kim, & Zoh, 2016; Liang, Wang, Chen, Zhu, & Yang, 2007; Nerenberg, Rittmann, & Soucie, 2000; Rosenfeldt, Melcher, & Linden, 2005; Westerhoff, Nalinakumari, & Pei, 2006; Xie et al., 2015). Although rate constants for •OH with the geosmin and MIB approach diffusion-controlled rates, the presence of radical scavengers such as natural organic matter and alkalinity reduces process efficiency and may require considerable UV and/or peroxide doses to achieve suitable T&O removal (Peter & Von Gunten, 2007; Xie et al., 2015). Furthermore, as with any oxidation process, byproduct formation must be fully characterized to avoid adding toxicity.

More recently, biofiltration using slow sand filtration, fluidized-bed contactors, and rapid filtration with GAC to promote the proliferation of contaminant-degrading bacteria has been increasingly used as a low-cost alternative to remove T&O compounds, metals (e.g., Fe, Mn), and trace organic contaminants (e.g., pesticides, solvents) (Zoschke, Engel, Börnick, & Worch, 2011). Biofiltration has also been augmented with upstream ozonation, which concomitantly oxidizes MIB and geosmin and creates more hydrophilic and biodegradable organic matter to stimulate microbial degradation during downstream biofiltration (Nerenberg et al., 2000).

In short, although several viable T&O treatment options exist, no single option fits all applications or is without some potential limitations. Escalating nutrient loading and warmer temperatures are expected to increase the frequency of cyanobacterial blooms and associated T&O-derived events (Jeppesen et al., 2009; Wells et al., 2015). Given the large, and growing, number of utilities affected by MIB and geosmin, additional treatment options are necessary to help utilities reliably minimize T&O complaints without straining their annual operating budgets. To that end, this article describes the development and scale-up of one of those tools: biological roughing filtration.

Biological roughing filters (BRFs), which operate at the head of a treatment plant (Figure 1), have been used since the early 1800s in the form of slow sand filtration (Baker, 1949). However, to the authors' knowledge, rapid rate BRFs (i.e., treating water at ≥2 gpm/ft² [4.9 m/hr]) have never been applied for T&O abatement in surface water. The principal benefit of treating T&O-laden raw water through biofilters is to take advantage of the biodegradable organic carbon and nutrients that would otherwise be removed through conventional treatment. If T&O removal using a BRF is effective and robust, a utility could consider eliminating or decreasing other T&O control methods such as PAC addition or oxidation, thereby realizing some O&M cost benefits. To evaluate this concept, bench- and pilot-scale studies were performed that examined geosmin and MIB removal across BRFs at the Manatee County Water Treatment Plant (Bradenton, Florida). The bench-scale study was performed only to demonstrate proof of concept, while the pilot study evaluated bioacclimation time, media selection, empty bed contact time (EBCT) requirements, and the resilience of BRFs to intermittent T&O presence. Results from the pilot study were used to develop full-scale design criteria and cost estimates.

2  |  MATERIALS AND METHODS

2.1  |  Experimental apparatus and design

For bench-scale testing, raw water from Lake Manatee was supplied to a 20-gal (76-L) stainless-steel tank, spiked with 100 ng/L MIB and geosmin (Supelco through Sigma
Aldrich, Natick, MA) and pumped (Watson Marlow, Wilmington, MA) upflow through a 2 inch-diameter glass column containing 9 in. of virgin, F-400 bituminous GAC (effective size 0.55–0.75 mm; uniformity coefficient 1.9 max; Calgon Carbon Corporation, Pittsburgh, PA). Flow rates ranged from 15 to 92 mL/min, corresponding to EBCTs ranging from 30 to 5 min, respectively. The column was wrapped in aluminum foil to prevent phototrophic growth in the GAC bed, and the system was operated for 54 days.

For the pilot study, raw water from Lake Manatee was pumped directly to a 63-gal (238 L) stainless-steel postmix tank, which then flowed by gravity through three parallel 6-inch-diameter filter columns (Figure 2). BRF 1 was packed with 59 in. of F816 GAC (effective size 1.3–1.5 mm; uniformity coefficient 1.4 max; Calgon Carbon Corporation). BRF 2 was packed with 29 in. of anthracite (effective size 0.95–1.05 mm) over 4 in. of sand, over 12 in. of support gravel. BRF 3 was packed with 59 in. of F820 GAC (effective size 1.0–1.2 mm; uniformity coefficient 1.5 max; Calgon Carbon Corporation). All filters were acclimated and carbon adsorption exhausted, as measured by UV-254 breakthrough, before odorant dosing to the raw water. Geosmin (≥97% Sigma-Aldrich) and MIB (≥98% Sigma-Aldrich) were spiked into the pilot feedwater from an 18-L stock tank with a peristaltic pump (Watson Marlow). Odorant removal was assessed over a range of raw-water concentrations (100–3,000 ng/L) and BRF EBCTs (1–20 min), and odorants were spiked individually and concomitantly. The impacts of intermittent odorant presence and the effect of nitrogen supplementation (0.18 mg/L NH₄Cl-N) were also evaluated.

### 2.2 Sampling and analytical methods

For the bench study, daily samples were taken from the tank and column effluent and stored at 4 °C until MIB and geosmin analyses (Method 6040D, APHA 1998) could be performed in the Manatee County lab on site. Daily samples were also taken for UV-254 absorption (Shimadzu UV-1601 spectrometer, Marlborough, MA). Weekly samples were taken for total organic carbon (TOC) and preserved with concentrated hydrochloric acid and stored at 4 °C until analysis (Method 5310B, APHA 1998) in the Manatee County lab on site. During the pilot study, influent and effluent samples were collected between one and five times per week, depending on the testing phase, and were analyzed on site for geosmin and MIB (Method 6040D, APHA 1998), temperature (Method 2550B, APHA 1998), pH (Method 4500H+B, APHA 1998), dissolved oxygen (Method 4500O, APHA 1998), TOC (Method 5310B, APHA 1998), and dissolved Mn and Fe (Method 3113B, APHA 1995). Columns were backwashed as needed based on daily measurements of column flow and loss of head or filter run time.

Using R, all data were fitted using locally estimated scatterplot smoothing (LOESS) to produce smoothed trendlines. Briefly, LOESS is a nonparametric approach that combines multiple least-squares regressions over localized subsets of data.

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**FIGURE 2** Lake Manatee pilot process flow. MIB, 2-methylisoborneol; GAC, granular activated carbon.
2.3 | Cost model development

A cost-sensitivity model was developed and used to evaluate design and operating scenarios for full-scale biological pretreatment at the Manatee County Water Treatment Plant. Model input variables included surface water flow, biofilter location, chemical addition options, EBCT (3, 6.3, and 10 min), biofilter bed depth, roughing-filter redundancy, and cost-estimating assumptions. Model outputs were capital costs, annual O&M costs and usage rates associated with biofilter operation, and payback period. Payback was calculated using historical PAC usage and solids disposal costs. Based on historical odor-ant occurrence and pilot performance, geosmin removal to meet finished water target concentrations was chosen as the control basis for the cost sensitivity model. An EBCT of 3 min would enable the water treatment plant to meet the target 92.1% of the time (reliability). Increasing the EBCT to 6.3 min resulted in 95.3% reliability, and a 10-min EBCT resulted in 97.6% reliability. Estimates were considered when planning level costs (Class 4).

3 | RESULTS AND DISCUSSION

3.1 | Bench-scale testing

Breakthrough curves for MIB, geosmin, TOC, and UV-254 are shown in Figure 3. Raw water TOC (~13–18 mg/L), geosmin (5–160 ng/L), and MIB (5–160 ng/L) were removed via adsorption onto fresh GAC at the beginning of the study. TOC and UV-254 breakthrough occurred after approximately 8 days as adsorption capacity diminished, while low-level MIB and geosmin breakthrough was not observed for approximately 2 weeks. Consistent removal of between 10% and 19% UV-254 and TOC over the last 3 weeks of testing suggest that biological activity had developed in the BRF, and this was supported by the visual observation of biomass at the bottom portion of the GAC bed. Effluent geosmin and MIB concentrations leveled off at ~5 and ~10–20 ng/L, respectively. When combined with the presence of visible biofilm on the GAC and the TOC/UV-254 removal trends, the geosmin and MIB breakthrough/removal curves suggest that a biological mechanism was at least partially responsible for the observed odorant removal approximately after day 40, when the initial adsorption capacity had been exceeded. Therefore, the proof-of-concept objective had been met, and the project team concluded that a pilot study was warranted to confirm the bench-scale results and to develop design criteria for a full-scale BRF.

3.2 | Pilot-scale testing

3.2.1 | Biological acclimation

Throughout the acclimation period, an EBCT of 10 min was used, which corresponds to a hydraulic loading rate of 3.7 gpm/ft² (9.0 m/hr) for BRFs 1 and 3 and 2.1 gpm/ft² (5.1 m/hr) for BRF 2 (i.e., EBCT is calculated only using the anthracite and sand depth for BRF 2). TOC and UV-254 absorbance (Abs254) were used as surrogates to monitor biological acclimation of the fresh media (Figure 4). Breakthrough trends for the GAC-based BRFs were consistent with the bench study,
with rapid exhaustion of adsorption capacity followed by steady removal of TOC and Abs254, although to a lesser extent. As expected, a negligible quantity of organic matter was initially removed across anthracite BRF. Over the final 100 days of acclimation phase testing, the average UV-absorbance removal was 4.1% ± 1.4%, 2.2% ± 1.6%, and 3.8% ± 1.3% for BRF 1, BRF 2, and BRF 3, respectively (in all instances, the ± represents the standard error of the mean). Similarly, the average TOC removal was 3.8% ± 1.8%, 2.8% ± 4.4%, and 5.1% ± 8.1% for BRF 1, BRF 2, and BRF 3, respectively. Greater removal across the GAC-based BRFs is likely because of the higher external surface area of GAC, allowing for greater bacterial colonization. After 283 days of continuous operation, biological acclimation testing was deemed complete, and odorant-spiking experiments were initiated.

### 3.2.2 Continuous odorant spiking

Continuous odorant-spiking experiments were performed at a 10-min EBCT over the initial 52 days of testing (Figure 5). Influent geosmin and MIB concentrations ranged from 8 to 35 and 20 to 44 ng/L, respectively, and consistent removal of both odorants to below the Manatee County treatment goals (7 ng/L geosmin, 12 ng/L MIB) was achieved. Percentage of odorant removal was typically greater than 95% regardless of the media used, feed odorant concentration, and raw water temperature, which ranged from 11.7 to 22.1 °C. The anthracite BRF performed as well as the GAC BRFs, thus isolating biological odorant degradation.

### 3.2.3 Challenge testing

Following the continuous odorant-spiking tests, a 225-day challenge-testing phase began (Figure 6). Spiked raw water MIB and geosmin concentrations ranged from 131 to 230.8 ng/L, but there were also extended periods (33–95 days) when geosmin and MIB were not present in the raw water, simulating seasonal presence/absence. Furthermore, MIB and geosmin were spiked simultaneously during some portions of this testing, while only one odorant was spiked to the raw water during other periods. A 10-min EBCT was maintained throughout the challenge-testing phase, and raw water temperature ranged from 16 to 31 °C. Effluent MIB levels were below the 12-ng/L treatment goal for all three BRFs throughout challenge testing. Except for a single instance, effluent geosmin for BRF 3 (820 GAC) and BRF 2 (anthracite) was below the 7-ng/L target during challenge testing. BRF 1 (816 GAC) also demonstrated effective odorant removal, showing only three instances of breakthrough above 7 ng/L. No particular impact of temperature on odorant removal was observed during these tests. In general, challenge testing demonstrated that BRFs can handle increased and intermittent odorant loading, providing Manatee County some treatment protection against T&O episodic variability.

### 3.2.4 EBCT testing

Because odorants were removed to consistently below-action levels in all tests and over all conditions in the initial phase of testing, a second phase was conducted to
FIGURE 5  2-Methylisoborneol (MIB), geosmin, and temperature during the continuous odorant-spiking phase. All experiments were performed at a 10-min empty bed contact time. BRF, biological roughing filter; GAC, granular activated carbon

FIGURE 6  2-Methylisoborneol (MIB), geosmin, and temperature during the challenge-testing phase. All experiments were performed at a 10-min empty bed contact time. Gray shading corresponds to the 90% confidence interval (relative to the rest of the plot, this was pronounced, as temperature data were limited between days 75 and 125). BRF, biological roughing filter; GAC, granular activated carbon
evaluate and quantify the effect of EBCT on odorant removal. Based on the distribution of the historical occurrence of odorants (2001–2010), various benchmark raw water levels were chosen for testing. The second phase of pilot testing sought to determine the EBCT required to remove odorants at the 95th percentile, 99th percentile, and maximum historical levels observed at the plant intakes (2001–2010). One GAC column (BRF 3—F820) was modified with sample ports at various depths along the filter column. During spiking experiments, depth-wise samples were collected at the filter influent, six sample ports, and filter effluent to determine the odorant removal at seven EBCTs/media depths in a single spiking experiment. Odorant concentrations up to 180 ng/L MIB and 2,477 ng/L geosmin were spiked. By varying flow rates through the column, EBCTs from 0.52 to 20.6 min were evaluated. Figure 7 shows odorant concentration with increasing EBCT for various initial raw water geosmin and MIB concentrations. EBCTs required to meet target limits for MIB and geosmin are plotted in Figure 8 and summarized in Table 1. The 10-year maximum observed MIB concentration (165 ng/L) was removed at a 6.3-min EBCT; the maximum geosmin concentration (2,432 ng/L) was removed at a 12-min EBCT.

3.2.5 | Nitrogen spiking

Water from Lake Manatee is high in phosphorus and carbon and limiting with respect to nitrogen. Therefore, experiments were performed to see if nitrogen supplementation would improve filter performance. Nitrogen (NH₄Cl) was added to the raw water for 45 days at a concentration of 0.18 mg/L N to achieve a molar nutrient ratio of 100:10:1 bioavailable carbon:ammonia-N:orthophosphate-P in the feedwater. No improvements in filter performance, determined by backwash frequency, head loss, or odorant removal percentages, were observed over this time. Geosmin removal was 80.6% at a 2.8-min EBCT before the start of nitrogen supplementation and was 82.4% on day 43 after the supplementation (data not shown). At a 5.2-min EBCT, the removal was 95.4% and 95.6%, respectively, for before and on day 43 after supplementation (data not shown). While ammonia was the only nitrogen source monitored, other sources of nitrogen (e.g., nitrogen fixers in the BRF biological community) may explain why no performance improvement was observed during this test.

4 | MANATEE COUNTY FULL-SCALE SYSTEM

Varying the cost model inputs described in the Materials and Methods section, the model was run to achieve a range of reliabilities and design conservativeness. EBCT was shown to have the greatest impact on cost, and the model estimated capital costs and pay-back period at between US$14M and $41M and between 11 and 33 years, respectively.

Factoring the cost-sensitivity model, a full-scale BRF for removing T&O compounds from Lake Manatee water was designed and subsequently constructed. Six new BRFs operate as constant level/constant rate influent flow-splitting units. The filters are elevated and provide flow to the two rapid-mix basins by gravity. Flow splitting...
to each rapid-mix basin is controlled by 42-in. magnetic flowmeters and modulating valves. The filters are sized to treat up to 54 mgd with a 3-min EBCT, with one filter out of service for backwashing. Backwashing is initiated either manually or automatically based on head loss or filter runtime limits. Backwash waste is currently sent to a storage pond and then returned to the BRF inlet, with the option of returning it directly to the rapid-mix basins.

A 3-min EBCT, with one filter out of service, treating 54-mgd design was chosen based on performance and cost efficiency. While 95% reliability would have required a 6.3-min EBCT, the 3-min EBCT provides 92% reliability. The 3% difference in reliability would have increased cost by 63%. Using a 10-min EBCT and gaining an additional 3% in reliability would have increased cost by 150%. For at least the next 20 years, water demands are projected to require less than 54 mgd from Lake Manatee Water Treatment Plant, thus increasing the EBCT and reliability. Also considered was the relatively infrequent need to treat high concentrations from the 92nd to 100th percentile and the ability to use the existing PAC system episodically to “peak shave” these high levels.

The BRF was placed in service in June 2018. Because of the early arrival of rain in May 2018 and sustained occurrence through August, no T&O episodes occurred in Lake Manatee in 2018 when the BRF was online. Full-scale odorant-removal results in 2019 have been limited to one episode in May and early June. Raw water geosmin levels were between 22 and 25 ng/L from May 8 to May 10, then below 6 ng/L until June 1, and then increased up to 244 ng/L before dropping below 5 ng/L on June 20. Raw water MIB levels were below 10 ng/L during this time, except for between May 16 and June 1, when they reached a peak of 35 ng/L. MIB in the BRF effluent was below 2 ng/L throughout this time period except for three detections at 2.5, 3.1, and 8.2 ng/L. The BRF removed geosmin to below the 7 ng/L target until raw geosmin spiked to 138 ng/L on June 5. PAC addition was initiated to shave peak geosmin concentrations on June 8 and was continued until June 15, during which time odorant removal was achieved through a combination of the BRF and PAC.

Quantification of odorant removal across the BRFs during the peak geosmin occurrence was difficult and

| Odorant | 95th percentile | 99th percentile | Maximum |
|---------|----------------|----------------|---------|
|         | Conc. (ng/L)   | EBCT (min.)    | Conc. (ng/L) | EBCT (min.) | Conc. (ng/L) | EBCT (min.) |
| MIB     | 35             | 1.5            | 74       | 5.2         | 165         | 6.3         |
| Geosmin | 129            | 6.5            | 564      | 10.0        | 2,432       | 12.0        |

Abbreviation: Conc., concentration; MIB, 2-methylisoborneol.
could not be fully characterized because (1) raw water geosmin levels were highly variable—this was caused by daily rainfall and the release of water through the primary spillway—and (2) the sampling protocols were not fully developed to account for treatment unit detention time or presence of PAC in the samples. The plant’s monitoring protocol has since been modified so that BRF performance during future odorant events can be quantified. Regardless, the BRFs removed MIB and geosmin to below target levels for a 25-day period during the 2019 odorant event before PAC use was required. As PAC would have otherwise been dosed on 20 of those days, BRF operation decreased the plant’s PAC usage and associated PAC solids handling.

5 | CONCLUSIONS

This study provides proof of concept and pilot-scale validation of biological pretreatment as an effective means for the removal of T&O compounds, geosmin and MIB, from surface water. Bench-scale and pilot-scale tests of BRFs conducted at the Lake Manatee Water Treatment Plant from 2008 to 2014 under various experimental conditions (i.e., raw water concentrations, seasonal temperature fluctuations, and EBCTs) provided promising results. Testing showed that BRF can effectively treat a wide range of raw water T&O levels using relatively short contact times, and the intermittent presence of T&O compounds did not appear to appreciably affect removal efficacy. The design and subsequent construction of BRFs at the head of the existing conventional surface water treatment trains was pursued at the Lake Manatee Water Treatment Plant. The BRFs were placed into service in June 2018. A subsequent T&O episode occurred in May/June 2019, and while BRF performance could not be fully quantified, the BRFs did remove odors to below target levels over an appreciable period.

As the occurrence and intensity of cyanobacterial blooms in surface waters will likely increase because of escalating nutrient loading to meet increasing food demand from population growth and warmer temperatures due to climate change, utilities will need expanded options to address high and variable concentrations of cyanobacterial metabolites such as MIB and geosmin. This work has demonstrated, for the first time, that biological pretreatment can be one of those options; it has also shown how a capital investment can be leveraged to realize O&M cost savings for T&O treatment.

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