Ultrasonic Treatment of Algae in a New Jersey Reservoir

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A system of ultrasonic buoys was installed in the Canoe Brook Reservoir 1 in Short Hills, N.J., to assess the impact of the system on controlling algae and cyanobacteria in the reservoir. The four buoys operated for five months in spring/summer 2014. The results of the study indicated that the ultrasonic system was effective for controlling algae when the correct ultrasonic program was used. During the testing period, geosmin and methyl isoborneol concentrations were well controlled. Additionally, the average alum dose used by the plant was reduced by 22% compared with the same period in 2013, with improved dissolved air flotation effluent turbidity and combined filter effluent turbidity and an 83% increase in unit filter run volumes. An economic assessment showed the buoys saved approximately $87,800 in operational costs, with a projected simple payback time of 1.8 years for the system.

Keywords: *algae, cyanobacteria, reservoir treatment, ultrasonic*

The Canoe Brook Water Treatment Plant, located in Short Hills, N.J., treats water from several off-stream reservoirs. Water from the Passaic River is pumped into Reservoir 2 except during summer months. Water from Reservoir 2 then drains by gravity into the adjacent Reservoir 1, which is also fed by the small Canoe Brook. Water from Reservoir 1 then feeds the treatment plant. Reservoir 1 covers approximately 200 acres and has storage of 757 mil gal with a maximum depth of 17 ft. Because of moderate-high levels of nutrients, the reservoir is considered eutrophic. This combination of factors leads to seasonally severe algal blooms. In the past, the reservoirs were treated with copper sulfate or a copper-ethanolamine complex[1] to eliminate the algae. The treatment plant was reconstructed in 2012 and includes preozonation, coagulation, dissolved air flotation, and granular activated carbon filters to deal with the algae and accompanying tastes and odors. Despite the presence of the new treatment processes, the raw water still has high concentrations of algae, which have led to excessive coagulant requirements and impaired filter runs.

LITERATURE REVIEW

As an alternative to copper-based algaecides, ultrasonic treatment is sometimes used to control algae. Ultrasonic treatment uses high-frequency sound waves to attack the algal cells. The treatment is widely used in commercial and residential applications, but it is relatively new for municipal drinking water reservoirs. Although a body of literature does exist related to ultrasonic treatment of algae, most of the studies have been conducted in laboratories using a small number of algal taxa under limited conditions (e.g., including controlled temperatures, short periods, stagnant water conditions, limited ultrasonic frequencies or power). The consensus of these publications is that ultrasonic systems work by concentrating sonic energy through cavitation, causing formation and collapse of bubbles that creates locally intense but short-duration heat (5,000°C) and pressure (2,000 atm) (Purcell et al. 2013a). When used for algal control, ultrasound causes the collapse of gas vesicles in the cell and inhibition of photosynthesis (Lee et al. 2001), production of free radical species (Purcell 2009), and destruction of the cell membrane (lysis) (Mason et al. 2003). A review of previous case studies seemed to indicate that the older ultrasonic algae control devices based on cavitation use relatively low ultrasonic frequencies but have a very high power output. Other devices, however, use low power output and high sonic frequencies that damage algal cells by collapsing gas vesicles in cyanobacteria or causing internal damage to other structures of true algae (Brand 2014).

Recent work by Purcell et al. (2013b) indicates that, for four cyanobacteria genera (two unicellular and two filamentous), the ultrasonic frequency used has a large impact on the removal of the different genera. This would seem to suggest that algae (or cyanobacteria) with different morphological features may have different optimum frequencies for cell removal and that increasing the power input to the water may not overcome an "incorrect" frequency for a specific genus. Hao et al. (2004) suggest that a correct frequency for ultrasonic treatment may be related to the size of the gas vesicle; the composition of the cell wall may also have an impact on the correct frequency (Brand 2014). Thus, different families (true algae or cyanobacteria) and genera may require different ultrasonic frequencies for successful treatment. Rajasekhar et al. (2012) provide an excellent discussion on the impact of ultrasonic frequency on bubble resonance and the subsequent destruction of gas vesicles in cyanobacteria. Three peer-reviewed field studies on ultrasonic treatment of water were reviewed by LaLiberte and Haber in 2014: Nakano et al. (2001), Ahn et al. (2007), and Purcell et al. (2013b).

In Nakano et al. (2001), the researchers used 10 single-frequency transducers in an 80-acre, very shallow (3 ft) recreational pond. The treatment units consisted of a combination jet circulator, aeration system, and ultrasonic transducer operating in a side-stream mode (water was pumped into a circulator module, with two 100-W, 200-kHz ultrasound transducers and approximately 5 s of contact time, and then ejected from the circulator). These ultrasonic systems were augmented by flushing of the lake using river water. Results were promising in the first two years of the study with decreased chlorophyll levels and increased transparency in the lake. However, in the final year of the study, the flushing rate was decreased (to less than the growth rate of *Microcystis aeruginosa*), and the cyanobacteria blooms reappeared. Because of the combination of ultrasound treatment and flushing, it is not clear which treatment had the highest impact on the organisms.

Ahn et al. (2007) tested an ultrasonic device for removing cyanobacteria from two neighboring ponds (1.8 and 2.3 mil gal, respectively) over a seven-week period from mid-August to the end of September. One pond was untreated and served as a control, whereas the other pond was treated with a combination of a single-frequency ultrasonic device (630 W, 22 kHz) and water pumps. While the system was operating, chlorophyll levels in the treated pond were reduced; however, the circulation pumps increased the turbidity of the water. When the treatment system was off, the chlorophyll levels quickly rose to the control levels and did not return to the lower levels when the system was turned back on. Cyanobacteria immediately became the dominant taxa when the apparatus was shut off in the treatment pond; diatoms became dominant when treatment resumed. This would suggest that the ultrasonic treatment was effective for the cyanobacteria but not the diatoms, possibly because of the incompatibility of the ultrasonic frequency and the diatoms. Because of the seasonal nature of the study, the growth of the diatoms at the end of the study period might have been related to decreases in the water temperature.

Purcell et al. (2013b) examined the use of ultrasonic devices in three drinking water reservoirs in the United Kingdom. Different ultrasonic devices were used in the different reservoirs, but each used either a fixed- (28 kHz) or narrow-frequency band (40–50 kHz). The authors concluded that ultrasound was selectively inhibitory toward specific algal groups on the basis of specific morphological characteristics, although the reductions reported were within normal variations in the lakes.

One common feature with these field studies is the use of single- or narrow-frequency devices. It has been suggested by Hao et al. (2004) and Purcell et al. (2013a) that different frequencies are required to treat different algal taxa. Therefore, the use of transmitters that can produce broad frequencies (either by multiple-frequency outputs or by cycling through single-/narrow-frequency bands) or are tunable to produce different frequencies may be required to treat natural systems in which algal population dynamics can shift seasonally (because of water temperature or nutrients) or in response to killing off a predominant taxon.

Ultrasonic treatment affects algal concentrations over a period of weeks. Therefore, because of the way the reservoir was treated, no side-by-side comparisons were possible. In addition, cycling the units on and off over a short period would not have a noticeable impact on the algal cell concentration. Thus, only comparisons to historical data could be used to assess the efficacy of the buoy system.

OBJECTIVES AND OPERATIONS

The primary objective of this study was to reduce algae concentrations in Reservoir 1. Secondary objectives were to reduce the concentration of taste and odor–causing compounds (geosmin and methyl isoborneol [MIB]) in the reservoir water and to increase the efficiency of the plant by decreasing chemical doses and increasing filter run times.

The study began on May 13, 2014, when four buoys[2] (one master, three slaves) were installed in the reservoir. The study ended on Nov. 12, 2014, when these buoys were removed for the winter. The buoys were located in the reservoir as shown in the photograph on this page, with the plant intake being located in the southern part (lower left) of Reservoir 1.

The plant and system were operated normally during the testing period. Because of a dry spring and summer that year, the inlet from Reservoir 2 was opened on August 13, allowing water to flow into Reservoir 1. This inlet was closed on August 26.

From the start of the testing program until August 25, the buoys operated using a generic program. On August 25, the program was changed remotely by the manufacturer to target cyanobacteria. On September 9, the program was changed yet again to specifically target the cyanobacterium *Aphanizomenon*.

DATA COLLECTION

Algal growth depends on several factors, including water quality (nutrients such as phosphate) and weather conditions (including temperature, precipitation, and solar radiation). Because this

Buoy locations for Canoe Brook Reservoir 1. *N.J. Map data ©2014 Google*

was a demonstration-scale study and only one reservoir feeds the plant, it was not possible to do a controlled side-by-side study. Therefore, all comparisons were made to previous years.

The data collected during the study fell into several categories, including weather data (rainfall and temperature), algal data (counts and characterizations), organic carbon measurements (geosmin/MIB, total organic carbon [TOC], and fluorescence excitation–emission matrix fluorometry [FEEM]), and plant operational data (chemical use, turbidities, and filter run lengths). The period of record for water quality data covered Jan. 1, 2008, through Dec. 31, 2013. These historical data included weather (e.g., air temperature, precipitation), algal count data from the reservoirs, and taste and odor compounds in the reservoirs. For plant operational data, only data from 2013 were used because that was the first summer the new plant was operational.

The water quality samples included grab samples (collected weekly) and continuous data from the onboard monitors on the master buoy, including phycocyanin (an indicator for blue–green algae), chlorophyll a (an indicator for green algae), oxidation–reduction (redox) potential, turbidity, dissolved oxygen, temperature, and pH. These data were collected at varying intervals throughout the test and downloaded using remote access.

On September 24, communication was lost with the master buoy and data were no longer collected. Following removal of the buoys on November 13, an investigation showed that the buoy was still operating, but communications (and data) were lost. Data from two of the slave buoys indicated that these were still operating until November, when the study ended. The third slave buoy (the southernmost and nearest to the master) stopped operating on October 8 because of battery power loss. This power drain was caused by fouling of solar panels by bird feces.

METHODS

Sample collection. Samples were collected on a weekly basis by local water quality staff at the Short Hills system. Water samples were collected by hand from the surface of Reservoir 2 near the inlet to Reservoir 1 and at the intake depth for Reservoir 1. Samples were sent to the American Water research laboratory in Delran, N.J., on ice via an overnight shipping carrier.

TOC. TOC was measured at the Delran laboratory using a TOC analyzer[3] in accordance with Standard Method 5310 B (APHA 2005). Triplicate injections were made and the average reported.

FEEM. FEEM fluorometry was performed at the Delran laboratory using a benchtop fluorometer.[4] A "peak picking" approach was used to identify separate components of the organic matter. The instrument scanned from 200 to 800 nm with a 5-nm bandwidth at 5-nm intervals. The readings were corrected against a distilled, deionized water blank and normalized to a quinine sulfate standard.

Humics were calculated using an excitation wavelength (λ_{Ex}) range of 370–390 nm and an emission wavelength (λ_{Em}) range between 460 and 480 nm (Henderson et al. 2009). Chlorophyll was calculated using an excitation wavelength of 431 nm and an emission wavelength of 670 nm (Moberg et al. 2001). Phycocyanin was calculated using an excitation wavelength range of 565–605 nm and an emission wavelength of 620–700 nm. Other identified peaks included

- fulvics (λ_{Ex} = 320–340 nm, λ_{Em} = 410–430 nm),
- labile humics (λ_{Ex} = 250–270 nm, λ_{Em} = 440–460 nm),
- humic-like organics (λ_{Ex} = 250–270 nm, λ_{Em} = 440–460 nm),
- humic-like terrestrial organics (λ_{Ex} = 330–350 nm, λ_{Em} = 430–450 nm),
- soil fulvics (λ_{Ex} = 380–400 nm, λ_{Em} = 490–520 nm),
- fluorescent dissolved organic matter (λ_{Ex} = 340–375 nm, λ_{Em} = 435–470 nm),
- tyrosine-like proteins (λ_{Ex} = 260–280 nm, λ_{Em} = 300–340 nm), and
- tryptophan-like proteins (λ_{Ex} = 260–280 nm, λ_{Em} = 340–380 nm).

The total fluorescence for each of these peaks was calculated by integrating the fluorescence signals over the bandwidths for the excitation and emission wavelengths. Humics are generally the most prevalent form of organics in surface waters and are associated with soil runoff. Chlorophyll and phycocyanin are algal pigments, with phycocyanin associated with blue-green algae (cyanobacteria) and chlorophyll associated with both green and blue-green algae. Thus, these values are indicators of the presence of algae.

Tastes and odors. Taste and odor compound (geosmin and MIB) results were measured at American Water's Central Laboratory in Belleville, Ill., using Standard Method 6040D (APHA 2005). The detection limits on these analyses were 2 ng/L. For the purposes of this study, any sample reported as below the detection limit was assumed to be 2 ng/L.

Algal counts. Algal counts were conducted using a dynamic particle analysis system.[5] Counts were conducted up to twice daily using water collected from the plant intake in Reservoir 1. Approximately once per week, the images in these samples were characterized using morphology to determine algal taxa. Counts in Reservoir 2 were taken on an as-requested basis.

Algal characterization data were generated using data acquired through the dynamic particle analysis system. This system isolates individual units, colonies, or cells as individual images. These images are then measured and quantified using particle analysis software.[6] Images were captured using the auto-image mode under a flow rate of 0.9 mL/min and an image capture rate of 20 frames/second. Boundary conditions for size limitations consisted of counting images between 20 and 400 µm using the particle analysis software–generated diameter measurement.

After image acquisition was complete, the collage files of all specimens within the size range were post-processed and sorted using the automated classification system available through the software. Images were then categorized by morphological feature identifications specific to their individual taxonomic genera and later grouped into five broader (nontaxonomic) classes:

- Diatoms: *Asterionella*, *Fragilaria*, and *Nitzschia*
- Chrysophytes: *Dinobryon*
- Green algae: *Oedogonium*, *Staurastrum*, and *Volvox*
- Cyanobacteria: *Aphanizomenon*, *Anabaena*, *Dolichospermum*, *Gomphosphaeria*, and *Lyngbya*
- Others: *Ceratium*, *Euglena*, *Mallomonas*, and unknown organisms

Algal number concentrations were then calculated on the basis of the amount of fluid imaged/amount of fluid processed.

RESULTS AND DISCUSSION

Weather data. Because algal growth is greatly influenced by weather, it was necessary to evaluate weather conditions during summer 2014 and compare them with the historical record. Weather data covering the testing period and the five previous years—including maximum and minimum temperature and precipitation—were collected from the National Oceanic and Atmospheric Administration for Short Hills (Table 1).

Based on this analysis, the average air temperature during 2014 was within the norm of the previous five years as compared with the same months in 2008–2013. The total rainfall during the testing period was 24.5 in., whereas the average total rainfall for the same months is 27.4 in. Thus, during the testing period, it was slightly dryer than typical. Assuming that the amount of rainfall is associated with the amount of cloud cover, it could be presumed that 2014 had slightly more sunlight than in previous years. Thus, conditions for algae growth during the test were at least representative of previous years, if not better for algal growth. Therefore, conclusions comparing the study period to previous years can be made with a high degree of confidence that the weather was not a confounding factor in algae control.

Algal counts. Historical total algal counts and counts for the filamentous cyanobacterium (blue-green alga) *Anabaena* in Reservoir 1 are shown in Figures 1 and 2. In these figures, the vertical lines represent the dates when the reservoir was treated with a copper-based algaecide. There were no copper treatments in 2012 and 2013 because the new treatment plant (which includes dissolved air flotation to remove algae as part of the coagulation/clarification process) became operational. In previous years, *Anabaena* was the most prevalent genus of cyanobacteria in Reservoir 1.

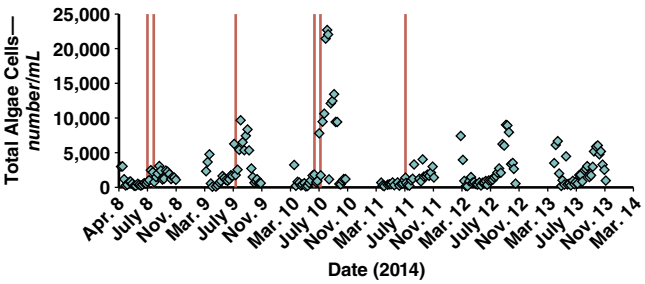
Algal counts in Reservoir 1 collected during 2014 are shown in Figure 3. As seen in these data, there was a progression of algae during the testing period. In early May, low levels of diatoms were prevalent. In late May, *Dinobryon* began to appear in low numbers. These then progressed to green algae, and then finally cyanobacteria increased in mid-August, reaching counts >20,000/mL. Before August 13, the total counts of all algae were <2,000/mL and most often <1,000/mL. As stated previously, on August 13 the inlet from Reservoir 2 was opened. This appeared to "seed" Reservoir 1 with higher levels of cyanobacteria, especially *Aphanizomenon*. This cyanobacterium was apparently resilient to the ultrasonic program that was in use at that time because of its morphological differences from *Anabaena* (the original target organism). On August 25, in response to the high algal counts, the ultrasound program was changed to target cyanobacteria in general. However, the *Aphanizomenon* counts continued to rise. On September 9 the program was changed yet again to target *Aphanizomenon*. Between September 17 and 24, the ultrasound began to have a substantial impact on *Aphanizomenon* on the basis of both cell counts (~93% removal) and fluorescence measures (~63% removal of phycocyanin and chlorophyll). Several weeks after the master buoy ceased communication on September 24 (Figure 3, vertical dashed black line), algal counts in Reservoir 1 began to increase. Algal counts for Reservoir 2 are compared with counts from Reservoir 1 in Figure 4. As seen in these data, cyanobacterial counts in Reservoir 2 were considerably higher (up to an order of magnitude) than in Reservoir 1 through early August. Importantly, it is clear that the decrease in algal counts in Reservoir 1 was due to the ultrasound and not weather conditions because, after the inlet was closed, the counts in Reservoir 2 remained higher than in Reservoir 1.

TABLE 1 Weather conditions for 2014 compared with 2008–2013

	Average Daily Air Temperature °C			Monthly Precipitation in.		
	Minimum Average	Maximum Average	2014	5-Year Minimum	5-Year Maximum	2014
May	10.1	23.2	16.7	3.9	5.1	7.0
June	15.6	28.2	22.0	2.5	6.6	2.3
July	18.3	31.3	23.8	2.8	5.8	6.7
August	17.0	29.3	22.1	4.7	18.1	3.4
September	13.4	25.5	19.4	2.2	6.3	1.5
October	6.2	18.6	13.5	4.0	6.6	3.7

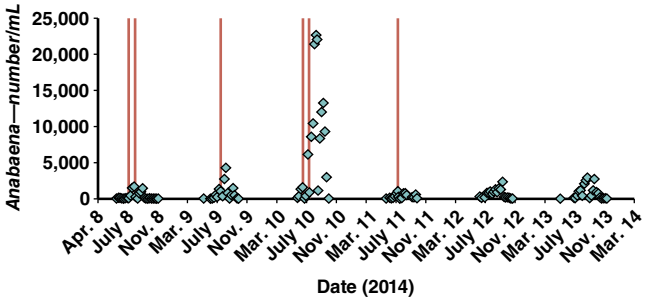
Source: www.ncdc.noaa.gov/cdo-web/datasets#GHCND

FIGURE 1 Canoe Brook, N.J., Reservoir 1 total algae counts



Vertical lines indicate copper treatment of Reservoir 1.

FIGURE 2 Canoe Brook, N.J., Reservoir 1 *Anabaena* sp. cell counts



Vertical lines indicate copper treatment of Reservoir 1.

In addition to the quantitative algal counts in Figures 3 and 4, the dynamic particle analysis system allowed for qualitative comparisons of algae before and after treatment. Even though the general blue–green ultrasonic program did not reduce *Aphanizomenon* counts, the dynamic particle analysis system showed that there was still an impact on these organisms. In Reservoir 2, *Aphanizomenon* existed as bundles or clumps of filaments. These bundles (which were also noted in images from Reservoir 1 in summer 2013) are thought to cause filter clogging. In Reservoir 1 during 2014, *Aphanizomenon* generally appeared primarily as single filaments and did not appear to cause filter clogging in the plant. Images of these two ways *Aphanizomenon* can exist are shown in the photograph on this page.

It is also possible that the increase in *Aphanizomenon* counts is due to this "disruption" of the bundles, and the higher counts were due to counting of single filaments instead of multiple cells in bundles. This "declumping" of *Aphanizomenon* by low-frequency ultrasonic waves was also alluded to by Purcell et al. (2013b).

Organic carbon. ***TOC.*** The historical raw water TOC generally ranged between 4 and 6 mg/L. One excursion occurred during July 2010, which corresponded to a period of high algal counts. This same pattern emerged with taste and odor compounds in which very high levels of geosmin and MIB were recorded in summer 2010.

Weekly TOC data collected during the study are shown in Figure 5. In general, the TOC in Reservoir 2 (shown in green) was higher than in the other reservoirs. However, in mid-August, the inlet from Reservoir 2 was opened to allow water into Reservoir 1. After this, there was an immediate increase in the TOC measured in Reservoir 1 (shown in red). Even after the inlet was closed later in August, the TOC in Reservoir 1 did not return to the level it was before the opening of the inlet, although the levels did fall from approximately 8 mg/L to approximately 6 mg/L. This is not different from the historical data.

Taste and odor compounds. Although overall TOC concentrations were not affected by ultrasound treatment, the concentration of taste and odor compounds in the water was apparently related to the level of algal cells: higher levels of algal cells resulted in higher taste and odor concentrations. The taste and odor compounds can either be dissolved within the water column or associated within the algal cells. Release of these compounds may occur when the algal cells are lysed (broken open) (Wert et al. 2014). If the compounds are held within the cells, by removing the cells by filtration or by killing (but not lysing), the compounds will not become dissolved in the water.

The historical record showed that during periods of higher algal activity, geosmin could exceed 30 ng/L; MIB was generally less of an issue with samples only occasionally exceeding 10 ng/L.

Weekly geosmin and MIB results for the reservoirs are shown in Figure 6. As seen in the figure, the geosmin levels in Reservoir 2 were generally higher than in Reservoir 1. After the inlet from Reservoir 2 was opened on August 13, there was a sudden increase in the geosmin level in Reservoir 1. However, this effect was present only for a single week. This would suggest that the geosmin remained within the algal cells and that it took one to two weeks (from sometime after August 13 to sometime before the samples were collected on August 26) for the ultrasound to have an impact on the cells in Reservoir 1.

FIGURE 3 Reservoir 1 total cell counts for all algal divisions

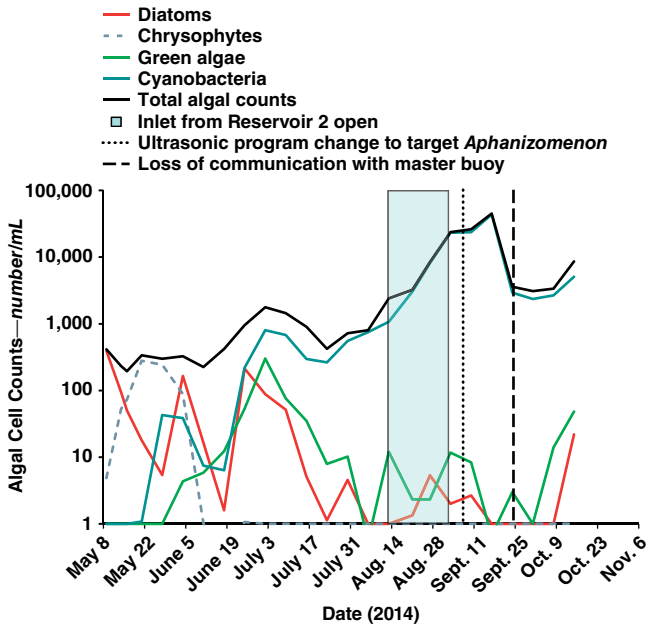
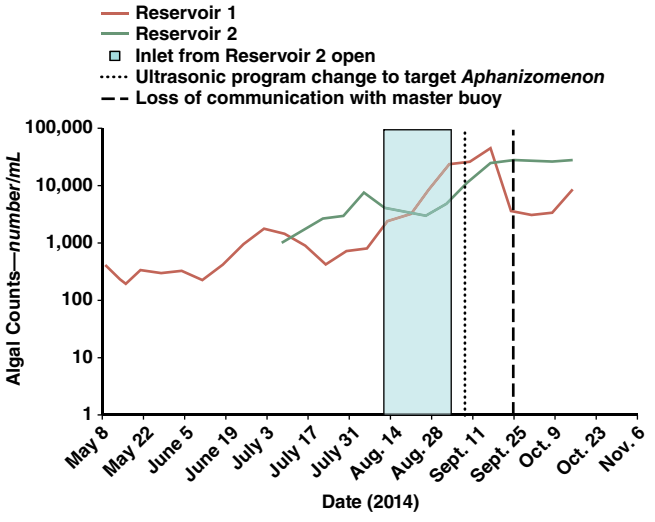


FIGURE 4 Comparison of Reservoirs 1 and 2 total algal counts

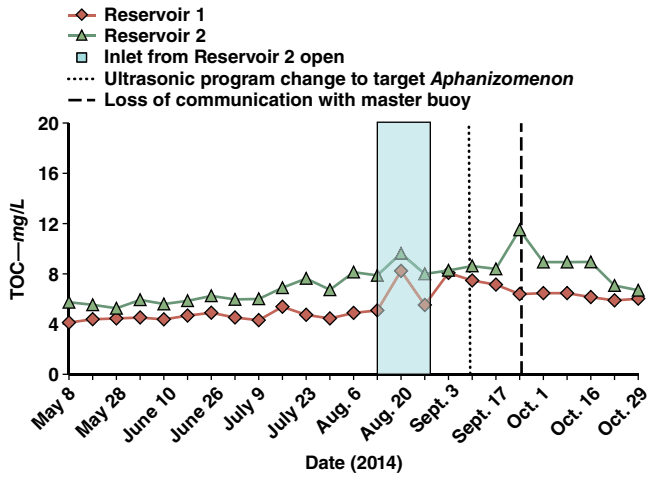


Images of *Aphanizomenon* as colonies (A) and single filaments (B)

Unlike geosmin, the MIB levels (shown by dashed lines) in the reservoirs were generally low (around the detection limit of 2 ng/L). At no time did MIB levels exceed 10 ng/L, and only two samples (one from each reservoir on different days) exceeded 5 ng/L. Because the MIB concentrations were low in both reservoirs, it is likely that MIB was not released by the algae present. Therefore, it is not possible to discern any effect by the ultrasonic treatment.

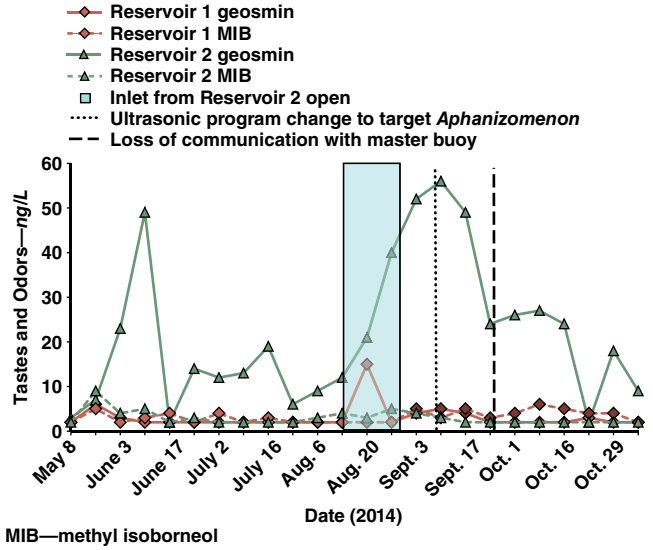
FEEM. FEEM analyses were conducted only during the testing period. As such, there are no historical data for comparisons. Weekly results for the parameters calculated using fluorescence are shown in Figures 7–9. In each figure, the period indicating when the inlet to Reservoir 2 was opened is shown by a shaded box.

FIGURE 5 Weekly total organic carbon results



TOC—total organic carbon

FIGURE 6 Weekly taste and odor results



MIB—methyl isoborneol

The weekly humic results shown in Figure 7 indicate that the level of humics in Reservoir 2 was higher than in Reservoir 1. During the course of the study, the humic level in Reservoir 2 decreased, whereas the level in Reservoir 1 remained relatively steady. When the inlet from Reservoir 2 was opened, the humic level in Reservoir 1 increased slightly but gradually recovered closer to its baseline.

The noticeable drop in humic levels for Reservoir 2 is puzzling. As shown in Figure 5, the overall TOC in Reservoir 2 increased, but the humic signal in Figure 7 shows a decrease. This decrease may be related to a "dilution" effect because a higher percentage of the total fluorescence signature results from algal pigments (the sum of the chlorophyll and phycocyanin signals increased from 0.5% of the total identified fluorescence peaks to 10.3% between the beginning and end of the study) or could be from an actual decrease in humic matter as it transformed into more biodegradable forms and was consumed (tyrosine and tryptophan-like protein signatures increased from 18.4% to 28.6% of the identified peaks over the course of the study).

The weekly chlorophyll results are shown in Figure 8. As seen, there are wide variations in the chlorophyll levels, indicative of algal growth, primarily in Reservoir 2. Following the opening of the inlet, a large increase in chlorophyll was seen in the Reservoir 1 samples. These Reservoir 1 levels showed sizeable variations during late August. On September 9, the ultrasonic program was changed to focus specifically on *Aphanizomenon* (shown by the dotted line in Figure 9). After this change, it took several weeks for the chlorophyll signal to diminish.

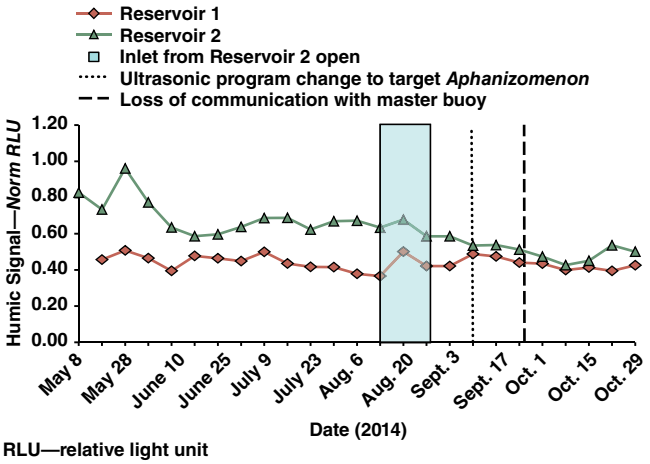
The weekly phycocyanin results are shown in Figure 9. Phycocyanin is a light-harvesting pigment complex ubiquitous among freshwater cyanobacteria (Vincent et al. 2004). The phycocyanin levels in Reservoir 2 started to increase in early July; it was not until the inlet was opened that high levels were seen in Reservoir 1. Following the second program change (indicated by the dotted line in Figure 9), it took several weeks for the phycocyanin signal to drop in Reservoir 1.

Several raw water samples containing algae were filtered through 0.7-µm glass fiber filters. Upon analysis, the filtration removed 65–90% of chlorophyll and phycocyanin, but almost no humic carbon (<10%). These results indicate the relative amounts of fluorescence associated with particles and the amounts that are dissolved in the water column. Because such high amounts of chlorophyll and phycocyanin were removed by a glass fiber filter, this indicates that these pigments were contained within algal cells and had not been released into the water column.

Buoy data. Data from the master buoy were measured by the onboard sensor package attached to the buoys. As such, there are differences because of both physical location and depth (~1.5 ft for the buoys and ~8 ft for the intake) between these two data sets.

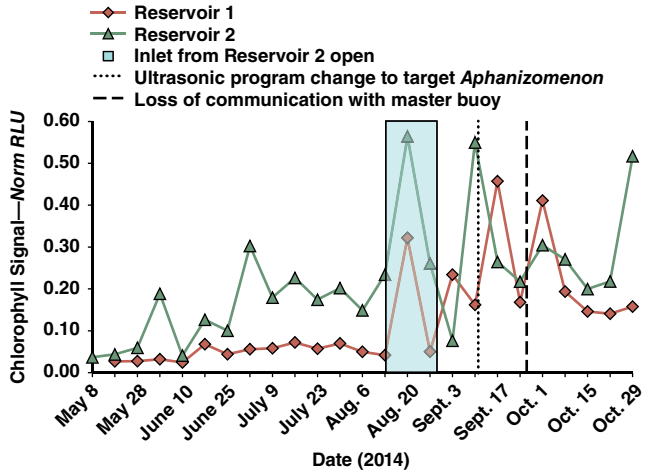
The data are separated into two groups: optical data (including turbidity, chlorophyll, and phycocyanin) and water quality data (including temperature, pH, redox, and dissolved oxygen). The optical data are shown in Figure 10; the water quality data are shown in Figure 11. As with the previous figures, the shaded area shows when the inlet to Reservoir 2 was open, and the

FIGURE 7 Weekly humic results



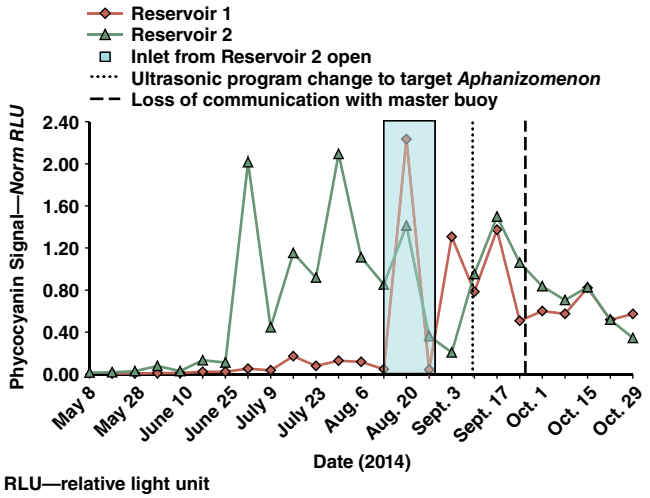
RLU—relative light unit

FIGURE 8 Weekly chlorophyll results



RLU—relative light unit

FIGURE 9 Weekly phycocyanin results



RLU—relative light unit

dotted line shows when the ultrasonic program was changed for the second time.

As illustrated in Figure 10, the optical data do not show any clear trends until early September, approximately 10 days after the inlet to Reservoir 2 was closed. At that point, the phycocyanin and chlorophyll concentrations rapidly rose. After the second program change on September 9, the chlorophyll and phycocyanin levels dropped almost immediately (daily averages were 72% and 78% lower for phycocyanin and chlorophyll, respectively, on September 10). This is in contrast to the data collected at the plant intake, where it took up to several weeks to see an effect on water quality. This difference in response time may be due to the difference in travel time between the buoy and the intake.

As shown in Figure 11, during the testing period the pH in the reservoir rose from approximately 7.8 to nearly 10.0. The redox potential in the water began to drop in early July, and daily minimum dropped below 200 mV; when the inlet from Reservoir 2 was opened, the minimum dropped to almost 100 mV. The dissolved oxygen levels remained higher than 100% saturation for much of the test; however, after the inlet from Reservoir 2 was closed, dissolved oxygen levels began to drop and by early September the minimum dissolved oxygen levels approached anoxia.

Similar to the optical data, the water quality data showed a rapid improvement in water quality after the second ultrasonic program change. Unlike the data collected at the intake, these improvements were almost immediate and were likely related to the water quality at the point of highest ultrasonic energy intensity. The difference in response to the program change at the intake (10–14 days) and at the buoy (~1 day) is likely due to the difference in travel time from the buoy to the intake. In addition, there was excessive aquatic vegetation growth near the plant intake (perhaps from increased light penetration resulting from the effectiveness of the buoys). These aquatic weeds could have shielded algae from damage by the ultrasound. In the future, these aquatic weeds will need to be controlled in some fashion to examine this hypothesis.

Although the data from the buoys and the data collected at the intake may show different response times, they show similar patterns and can be considered complementary. Thus, although additional extensive data collection and analysis are likely not necessary for future seasons, periodic water quality analyses at the plant intake should be performed to characterize the raw water. These analyses should include algal counts and TOC in addition to monitoring the data collected by the master buoy.

ECONOMIC ANALYSIS

Chemical use. Data for alum, sodium hypochlorite, and sulfuric acid use were collected from monthly production reports submitted to the New Jersey Department of Environmental Protection. Because the plant was redesigned in 2012, only data from 2013 were used for comparative purposes. Because the master buoy stopped communicating on September 24 and one of the slave units malfunctioned on October 8, only data through September were used for the economic analysis.

FIGURE 10 Optical data from the master buoy

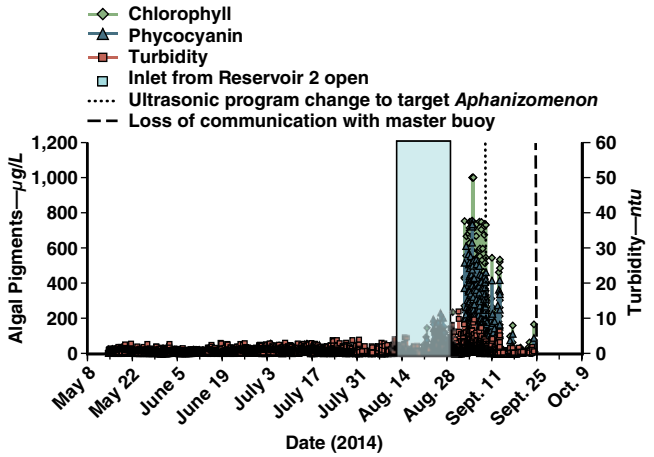
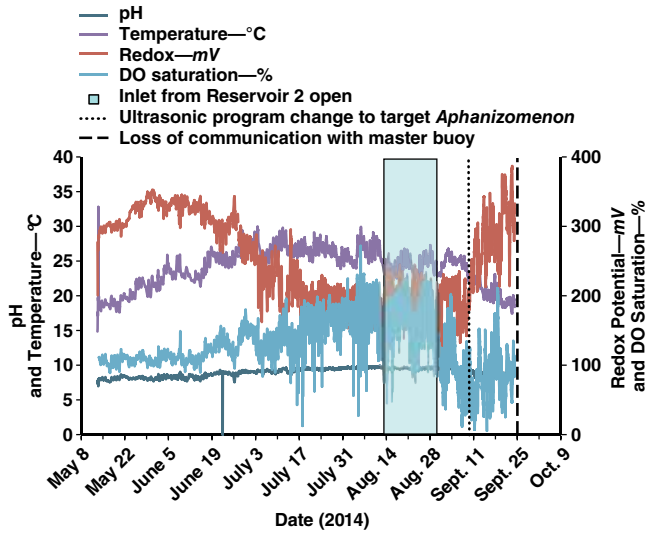


FIGURE 11 Water quality data from the master buoy



Pumping records indicated that the amount of water pumped by the plant in 2014 was approximately 20% greater than in 2013. Therefore, to account for this difference, chemical use data for 2013 were normalized to the 2014 pumping levels. Additionally, 2014 chemical prices were used to calculate additional costs and savings from the ultrasonic treatment. Using these normalization factors, the amount spent on treatment chemicals in 2014 was ~$18,000 less than in 2013. This represents approximately 16% saving for the five-month period.

Filter run length. Data on filter run length, combined filter effluent, and dissolved air flotation channel effluent were gathered from supervisory control and data acquisition data with 15-min intervals for the period May 1–September 30 for both 2013 and 2014. Median monthly values are shown in Table 2.

During 2014, the dissolved air flotation and filters operated with lower turbidities and higher run lengths than in 2013. In May 2013, the filter run lengths were greater than during the same period in 2014; however, the combined filter effluent turbidity was above the Partnership for Safe Water goal of 0.1 ntu. During summer 2013, the filter performance was especially poor, with median run lengths shorter than 15 h.

Average monthly unit filter run volumes were calculated on the basis of pumpage records and filter run lengths and showed that every month in 2014 except May (when the units were placed on-line) had higher unit filter run volumes than during the same months in 2013.

Economic comparisons. The Canoe Brook plant budgets approximately $60,000 for algal control using copper sulfate or a copper–ethanolamine complex. In addition, the plant spends approximately $25,000/year for reservoir monitoring. Thus, the operating-expenses cost is $85,000/year. On the basis of the analysis of chemical spending, using the buoys would save approximately $18,000/year in chemicals. This is balanced by an assumed cost of $15,000 for buoy maintenance. Thus, the overall operating expenses savings are approximately $87,800. The four buoys cost approximately $160,000 for purchase and installation. Thus, the simple payback on this system is approximately 1.8 years.

TABLE 2 Median DAF and filter operation data (May–September)

	DAF Effluent Turbidity *ntu*		Combined Filter Effluent Turbidity *ntu*		Run Length *h*		Unit Filter Run Volume *gal/ft²*	
	2013	2014	2013	2014	2013	2014	2013	2014
May	0.457	0.612	0.118	0.092	37.0	30.2	5,879	3,036
June	0.433	0.419	0.111	0.082	37.5	41.3	3,712	5,551
July	0.352	0.269	0.090	0.080	12.2	35.3	2,135	5,294
August	0.755	0.205	0.127	0.085	11.1	30.4	1,478	4,350
September	0.632	0.286	0.110	0.105	18.1	36.0	2,794	4,912
Average	0.524	0.329	0.108	0.088	15.1	34.3	2,488	4,548
Percent change	–37		–19		+127		+83	

DAF—dissolved air flotation

CONCLUSIONS AND RECOMMENDATIONS

During the initial part of the study, the buoys seemed to control the algae growth well. On August 13, when the inlet from Reservoir 2 was opened because of the need for additional water at the plant, the algae-laden water entered Reservoir 1 and seeded the reservoir with *Aphanizomenon*. Almost immediately, higher levels of algae, organic carbon, and tastes and odors were noted at the plant intake. *Aphanizomenon* then bloomed in the reservoir, reaching counts of 44,000/mL. In late August, because of the bloom conditions, the ultrasonic program was adjusted to treat *Aphanizomenon*. Once the correct ultrasound program was initiated, the values for algal counts, tastes and odors, and algal pigments returned to the baseline levels.

It is clear that the plant performance during the 2014 testing period was better than during the same period in 2013. The improvement in raw water quality allowed the plant operations staff to reduce alum doses by more than 20% compared with 2013 doses. These lower doses also resulted in the median dissolved air flotation effluent turbidity and median combined filter effluent turbidity being noticeably lower than in 2013; the median filter run length was nearly 20 h longer than in 2013.

The study concludes that the buoys were effective at treating algae. The key to future success is to rapidly identify the target genus *Aphanizomenon*. Once it is identified in Reservoir 1, it is imperative to shift to the correct ultrasound program before a bloom occurs. On the basis of a discussion with the buoy manufacturer (Brand 2014), the effective area of the buoys decreases when the *Aphanizomenon*-specific program is used compared with a generic algae or cyanobacteria program. Hence, the use of the *Aphanizomenon* program should be initiated only when needed, as opposed to it being the standard program.

The data from the buoys and data collected at the intake showed similar patterns and were considered complementary.

- The buoy data are useful for monitoring water quality in the immediate vicinity of the buoys but do not give a picture of what is happening with water entering the plant (or the rest of the reservoir).
- The FEEM data are useful for qualitatively determining the nature of the organic carbon in the water but do not give concentrations.
- The TOC data provide concentration numbers but do not give information on the nature of the organic carbon, which may drive the required alum dose.
- Taste and odor as well as algae count data and taxa characterizations are important parameters but are collected infrequently and thus do not provide actionable information for determining chemical doses at the plant.

Although another extensive study is likely not necessary for future seasons, some ongoing analyses will be required. These should include daily algal counts with weekly characterization of the algae along with weekly TOC measurements. These data will complement the data collected by the master buoy.

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ENDNOTES

[1]Cutrine-Plus copper–ethanolamine complex, Applied Biochemists, Germantown, Wis.
[2]LG Sonic MPC buoys, LG Sonic BV, Zoetermeer, Netherlands
[3]Shimadzu TOC-V_{CSH} combustion catalytic oxidation analyzer, Shimadzu, Kyoto, Japan
[4]Aqualog benchtop fluorometer, Horiba Scientific, Edison, N.J.
[5]FlowCAM Imaging Particle Analysis System, Fluid Imaging Technologies Inc., Scarborough, Maine
[6]Visual Spreadsheet (ViSp) software, Fluid Imaging Technologies Inc.

PEER REVIEW

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