Canal wall brushing—a control measure for taste and odour problems in drinking water supplies in arid environments

Qiang Hu, Milton Sommerfeld, Larry Baker and Paul Westerhoff

ABSTRACT

Canal wall brushing, accomplished by a tractor-mounted custom-designed rotating metal brush, was an effective means of removing nuisance periphytic cyanobacterial growth and consequently reducing MIB and geosmin production in the Arizona Canal, a major water conveying open channel in the metropolitan Phoenix (Arizona) water supply system. On average, *c.* 80% of the periphyton biomass was removed from the canal walls, resulting in immediate reduction in MIB and geosmin concentrations. Recolonization of periphytic cyanobacteria and other microalgae on the canal walls occurred following brushing, and algal biomass (chlorophyll *a* concentration) reached pre-brushing levels within 2 weeks. However, the production of MIB and geosmin was significantly reduced in the brushed section of the canal during this period of time. The extended duration of the effectiveness of brushing therefore did not appear to be due to the reduced total periphytic biomass, but rather the influence on species composition and population density of MIB and geosmin producers. Thus, slow recovery of MIB- and geosmin-producing cyanobacterial populations probably accounts for the reduced MIB and geosmin production. The brushing technique may be particularly applicable to open concrete-lined canal water supply systems and fish culture impoundments that contain point sources of periphyton-associated MIB and geosmin production.

Key words | canal wall brushing, cyanobacteria, drinking water, geosmin, 2-methylisoborneol (MIB), surface water supply

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INTRODUCTION

2-methylisoborneol (MIB) and geosmin are two major metabolites of microbial origin that contribute musty/earthy off-flavours to drinking waters in many regions of the United States, as well as in many other countries (Jüttner, 1995; Persson, 1996). Cyanobacteria are most often implicated as the source of the taste and odour metabolites. Earlier research focused mainly on planktonic cyanobacteria sources of these problems (Wnorowski, 1992). In recent years, however, periphytic species have received more attention (Berglind *et al.*, 1983; Burlingame *et al.*, 1986; Izaguirre & Taylor, 1995; Sugiura *et al.*, 1998).

MIB and geosmin are volatile terpenoids with extremely low odour threshold concentrations (a few parts per trillion) (Young *et al.*, 1996). Due to their tertiary alcoholic structures, MIB and geosmin are also highly resistant to oxidation (Bentley & Meganathan, 1981; Wnorowski, 1992). These features make it extremely difficult for conventional water purification processes to remove these compounds. Indeed, such oxidants as Cl_2, ClO_2, chloramines and $KMnO_4$, which are commonly applied in water purification, are either ineffective for MIB/geosmin removal or only partially effective on a case-by-case basis (McKnight *et al.*, 1983; Krasner *et al.*, 1986; Lalezary *et al.*, 1986; McGuire & Gaston, 1988; Peterson *et al.*, 1995). Frequently, the chlorine-type oxidants also impart tastes and odours of their own to the finished drinking water. Ozone seems to be an effective

oxidant of MIB and geosmin through direct oxidation by the ozone molecule or indirect oxidation by the hydroxyl free radical (Suffet *et al.*, 1995). Ozonation has been widely used in Europe and Asia, and is now being applied in the United States (Suffet *et al.*, 1995, 1996). On the other hand, the most frequently used technique for MIB and geosmin removal in the United States is activated carbon that removes taste and odour compounds from water by adsorption (Mallevialle & Suffet, 1987; Suffet *et al.*, 1996). However, in-plant control measures for water-borne taste and odour problems are performance variable, depending on the water chemistry and microbial populations. They are also very expensive. One survey showed that nearly 10% of the annual fiscal resources of water utilities was used to control taste and odour problems (Suffet *et al.*, 1996).

Since MIB and geosmin are primarily produced in surface waters by cyanobacteria (Casitas, 1987; Izaguirre & Devall, 1995; Jüttner, 1995; Persson, 1996), a more efficient and cost-effective measure may be the control of the culprit cyanobacteria in the source waters. A study conducted by Jüttner (1995) showed that a river bank and slow sand filtration approach was effective in removal of geosmin and some other odorous compounds from the River Ruhr in Germany. The most commonly adopted long-term control measure in the United States has been the application of copper sulphate to lakes and reservoirs to prevent odorous algae blooms (Means & McGuire, 1986; Sklenar & Horne, 1999). Some indirect measures have been proposed and implemented for source water control, such as artificial destratification and hypolimnetic aeration in deep lakes and reservoirs (Izaguirre & Devall, 1995). In addition, blending water tainted with odorous compounds with water from other unaffected sources to dilute off-flavour compounds to acceptable levels, or selective withdrawal of water from certain depths within a deep reservoir where the concentration of odorous compounds is minimal can also be effective control strategies (Burlingame *et al.*, 1986; Cooke & Carlson, 1989).

In this paper, we describe a physical brushing technique as a source control measure for reducing attached sources of taste and odour problems in a concrete-lined open canal. Brushing was accomplished with a tractor-mounted rotating metal brush that removes periphytic microorganisms, and particularly cyanobacteria, from submerged canal walls. This technique has been demonstrated to reduce the MIB and geosmin concentrations in the Arizona Canal, a major source water channel that conveys water to treatment plants in metropolitan Phoenix (Arizona), USA.

MATERIALS AND METHODS

Site description

More than 60 km long, the Arizona Canal is the main canal that transports water from the Salt and Verde Rivers, and their storage reservoirs, to all the other canals on the north side of the Salt River in the Phoenix metropolitan area. The average width of the canal is about 15 m, and the slope of the canal walls is *c.* 45°. Water depths in the canal range from 1.2 to 2.3 m. Flows in the canal typically vary from 14 to 56 $m^3 s^{-1}$ at the upper end to 1.4 to 10 $m^3 s^{-1}$ at the lower end, with higher flows in the summer and lower flows in the winter. Four water treatment plants (WTPs), including Squaw Peak and Deer Valley WTPs, are located near the canal, treat water and deliver it to over one million residents of the metropolitan Phoenix area, as well as to commercial and industrial users. Figure 1 provides a schematic of the Arizona Canal, WTPs, sampling sites and location of the experimental 3 km brushed section and adjacent 4 km unbrushed section of the Arizona canal.

Periphyton sampling

Algal samples were collected using a custom-designed periphyton sampler (Figure 2). The sampler was a rectangular chamber, measuring 25 cm long, 18 cm wide and 18 cm high. The upper part of the chamber was made of clear PVC, whereas the bottom was a metal template with a 10×15 cm open area (0.015 m^2). On the side of the chamber facing the top of the canal a small slot exists through which a wire pool brush inside the chamber is attached to a telescoping pole. The upstream side of the

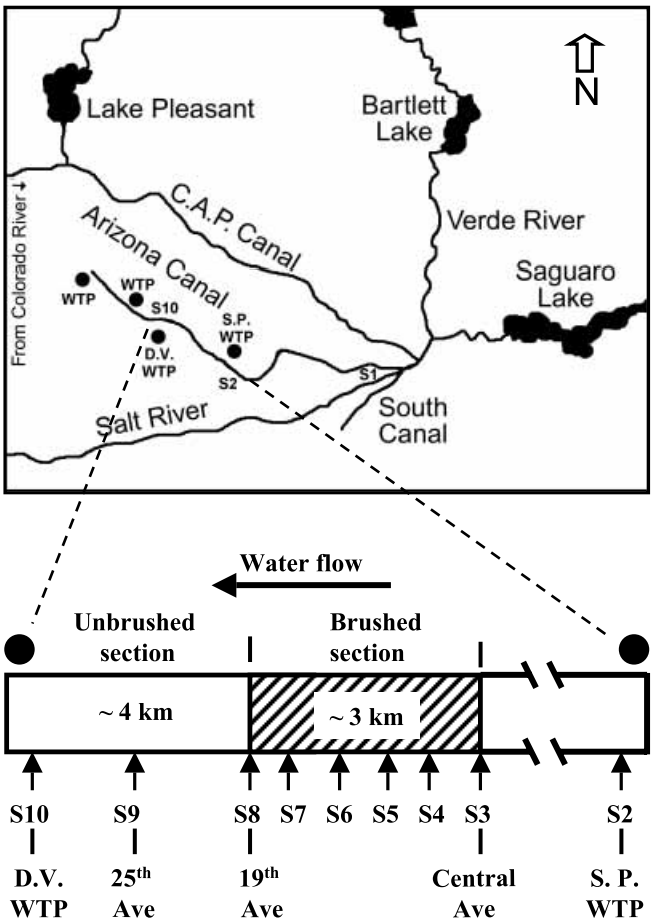

Figure 1 | Schematic of the Arizona Canal illustrating location of water treatment plants (WTP), the brushed and unbrushed canal stretches, and sampling sites along the canal. Black circles: water treatment plants; hatched bar: brushed section (*c.* 3 km, between Central Avenue and 19th Avenue); open bar: unbrushed sections (*c.* 4 km, between 19th Avenue and Deer Valley WTP); arrows: sampling sites (S2 through S10 on the Arizona Canal).

chamber has a 16 cm × 16 cm opening covered by a fine plastic screen that allows water to flow through the chamber. On the downstream side of the chamber is a circular opening (16 cm diameter) with a plankton-net (80 μm mesh) attached. Two people are required to collect samples. The sampler is placed by one individual on the canal wall and held in position with the telescoping pole. A second individual brushes the wall area exposed by the open template a specific number of times. As periphyton mats are removed from the canal wall within the template, they are carried by water flow into the plankton net.

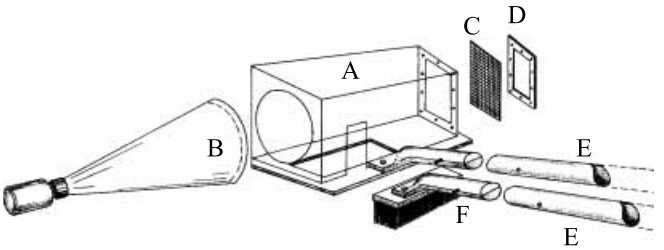

Figure 2 | Diagram of the periphyton sampler. Sampler consists of A, a rectangular chamber with an open window (10×15 cm) on the bottom plate; B, a plankton net; C, a plastic screen with metal frame, D; E, two telescoping poles; and F, a wire pool brush.

Sampling occurred at three depths: just below the surface, and at two additional depths at *c.* 40 cm intervals. The three samples were combined and stored in a sterile whirl-pak bag at 4°C.

Canal wall brushing

Both sides of the canal walls in a section spanning *c.* 3 km between Central Avenue and 19th Avenue of the Arizona Canal were subjected to brushing treatment. A tractor-mounted custom-designed metal brush developed by the Salt River Project, a local utility company, was employed. The brush measured 150 cm long and 80 cm in diameter. The rotation of the brush was about 60 rpm and speed of brushing operation was about 2 km/h. Figure 3 shows a Salt River Project designed tractor-mounted brushing system (Figure 3A) and a close-up photograph of the metal brush in operation (Figure 3B).

Sampling design

Within the 3-km canal stretch, six sampling sites were established for monitoring changes in periphyton biomass, and MIB and geosmin concentrations before and after brushing. For comparison, four sampling sites along a 4-km section downstream just below the brushed section were also monitored for the same parameters. Brushing was conducted once every 2 weeks from 21 September through 20 November 2000. Algal samples were taken at

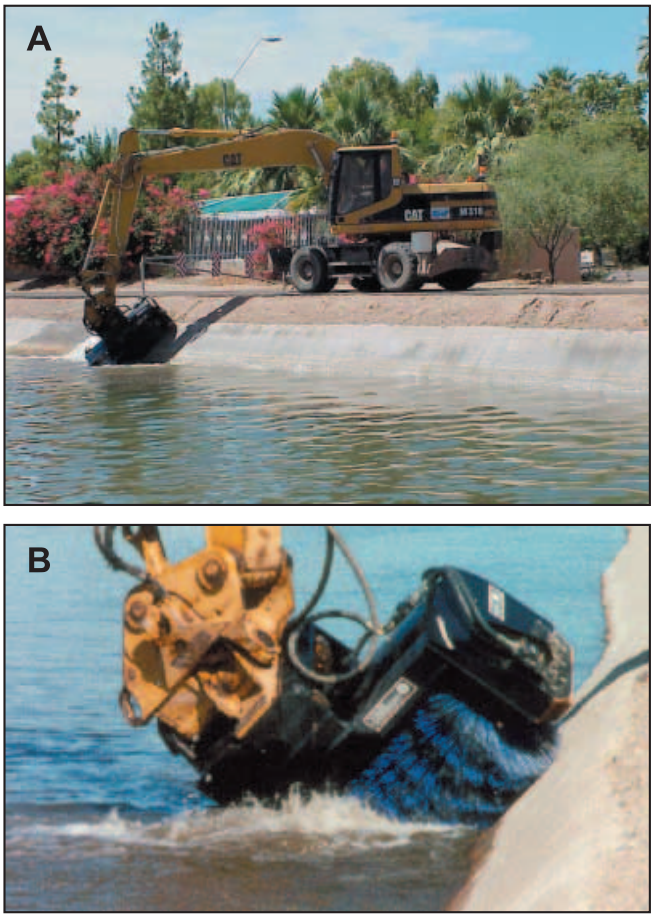

Figure 3 | A Salt River Project-designed tractor-mounted metal brushing system (A), and a close-up view of brushing in operation (B).

each of the sites after 1, 4, 7 and 14 days following brushing for chlorophyll analysis and light microscopic observation. Water samples were taken at the same time for MIB and geosmin analysis.

Chlorophyll measurement

Chlorophyll *a* is a major photosynthetic pigment present in cyanobacteria and other photosynthetic organisms. The chlorophyll *a* content of algal cells can range from 0.3 to 2% of the dry weight and is routinely used as a parameter to monitor changes in algal biomass (Rabinowitch, 1945). Chlorophyll *c* is an accessory pigment mainly occurring in the Division Chromophycota. Periphyton samples (160 ml) collected from the canal walls were homogenized at room temperature for 30 sec using a Waring blender (model: PB-5, Waring Products Corp. New York, NY). A 40-ml aliquot of homogenized sample was passed through filter paper (GF/C Whatman). Filter papers were then extracted in 10 ml methanol (100%) at 4°C in the dark for 24 h. Absorbance at 664 nm for chlorophyll *a* and 630 nm for chlorophyll *c* was determined on an aliquot of the methanol extract using a spectrophotometer (model DU-64, Beckman Instruments Inc., Fullerton, CA) (Greenberg *et al.*, 1992). Chlorophyll *a* and *c* concentrations were calculated on per square-metre surface area of the canal wall (mg chlorophyll m^{-2}).

Isolation and verification of MIB- and geosmin-producers

Enrichment, isolation and purification of cyanobacteria from water and benthic samples collected from the Arizona Canal were conducted according to Allen (1973). In brief, samples collected from the field were inoculated in either concentration or dilution series into both liquid and solid agar BG-11 growth medium. Enrichment cultures were placed in a Percival growth chamber (Percival Scientific Inc., Iowa, USA), illuminated with cool white fluorescent light of 20–30 μmol m^{-2} s^{-1} and at 30°C. Enrichment cultures were then used for isolation and purification of cyanobacteria. For unicellular species, the mixed algal suspension was streaked on BG-11 agar plates and incubated until appearance of well-separated cyanobacterial colonies. For filamentous cyanobacteria, their phototactic response on agar plates was utilized to separate them from other species. Supernatants from algal cultures and methanolic extracts of purified algal cells were subjected to gas chromatographic and mass spectrometric analysis for MIB or geosmin. Morphological features of isolated MIB- or geosmin-producers were observed using an Olympus light microscope (model: BH-2, Olympus Optical Co., Ltd, Japan). Taxonomic identification of the MIB- and geosmin- producing cyanobacteria was based on Anagnostidis & Komárek (1988) and Castenholz (1989).

Analysis of MIB and geosmin

Quantitative analysis of MIB and geosmin was performed on a Varian Star 3400 CX gas chromatograph and mass spectrometer (GC/MS). The water sample (25 ml) was placed into a 45 ml septum-capped vial containing 8.0 g of desiccated sodium chloride. An internal standard, 2-isopropyl-3-methoxy-pyrazine (IPMP), was added to the sample at a concentration of 10 ng l^{-1}. A solid phase microextraction (SPME) fibre (Supelco # 57348U) was introduced into the headspace of the vial through the septum. The sample was then incubated in a water bath at 50°C for 30 min with constant stirring. Compounds from the fibre were desorbed in the gas chromatograph and eluted from a column (MDN-5 capillary column, Supelco, Bellefonte, Pennsylvania) into the mass spectrometer for selective ion storage. MIB and geosmin concentrations were calculated from calibration curves generated from MIB and geosmin standards (Sigma, St Louis, MO, USA).

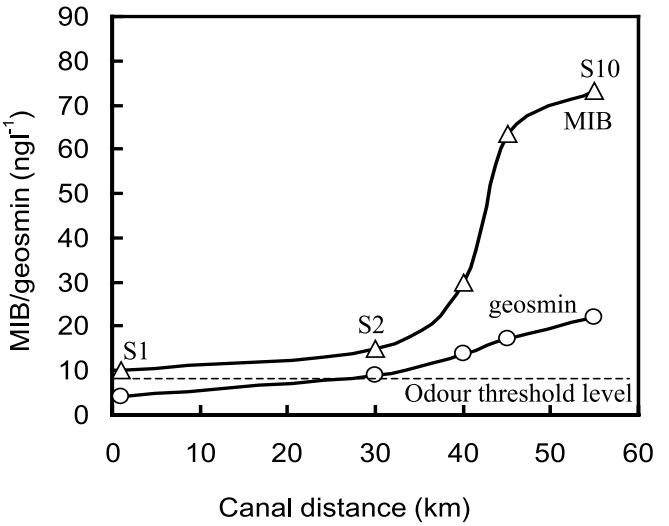

Figure 4 | Average MIB and geosmin concentrations along the Arizona Canal measured on 8/29/2000 and 9/6/2000, illustrating an increase in these taste and odour compounds between Squaw Peak and Deer Valley WTPs. S1 is the start of the Arizona Canal; S2 is the site at the inlet to the Squaw Peak WTP, and S10 is at the inlet to the Deer Valley WTP.

RESULTS

MIB/geosmin production in the Arizona Canal

During a baseline monitoring effort, we observed that the Arizona Canal experienced major episodes of MIB and geosmin production in summer-fall seasons (July through November). Figure 4 shows the profiles of MIB and geosmin along the canal in August 2000. Although relatively low levels occurred in most of the canal, MIB and geosmin increased more than three-fold in the downstream canal section above the Deer Valley WTP. The concentration gradients of MIB and geosmin along the canal suggested production of these odorous compounds within the Canal. During the summer months, planktonic microalgal biomass in the canal was typically below 10 mg chlorophyll *a* m^{-3}, composed mainly of diatoms along with small amounts of green algae and cyanobacteria. We were unable to isolate any MIB- and geosmin-producing algae from the planktonic samples. In contrast, over 120 mg chlorophyll *a* m^{-2} was associated with the periphytic (or benthic) algal community on the canal walls. Several filamentous cyanobacteria (*Oscillatoria splendida*, *Oscillatoria* sp., *Phormidium* sp. and *Pseudanabaena* sp.) were isolated from periphyton mats on the submerged canal walls and confirmed to be MIB- and geosmin-producers by GC/MS analysis.

Removal of periphyton from the submerged canal walls by brushing

We observed that periphyton were distributed from the top to the bottom of the submerged canal walls with the highest density appearing between 5 and 30 cm below the water level. We hypothesized that if periphyton on the canal walls that contained MIB- and geosmin-producers could be removed, production of these compounds would be reduced. In collaboration with Salt River Project, a custom-designed brushing device was employed. Figure 5A and B are photographs of the canal wall taken before and after brushing, illustrating that the majority of periphytic cyanobacteria and microalgal biomass were removed from the canal wall using this brushing device. Brushing removed over 80% of the periphyton biomass from the submerged walls, based on chlorophyll *a* analysis (Figure 5C).

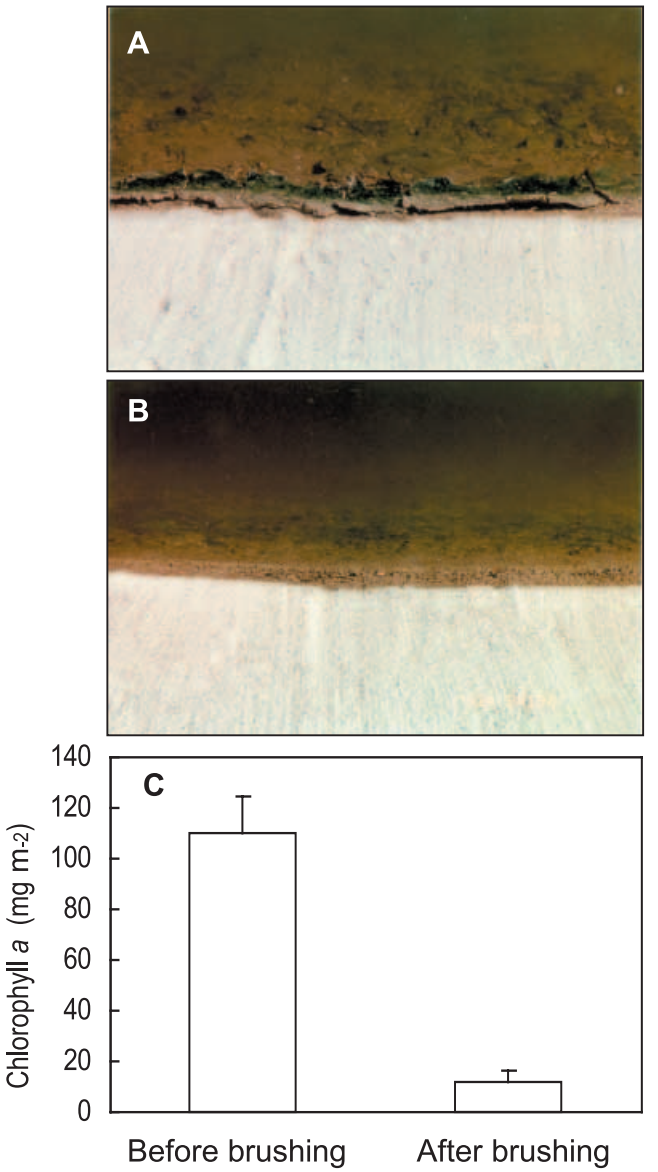

Figure 5 | Close-up photographs of the canal wall with attached algal mat before (A) and after brushing (B). Comparison of periphyton biomass, as indicated by chlorophyll *a* concentration, before and after brushing (C).

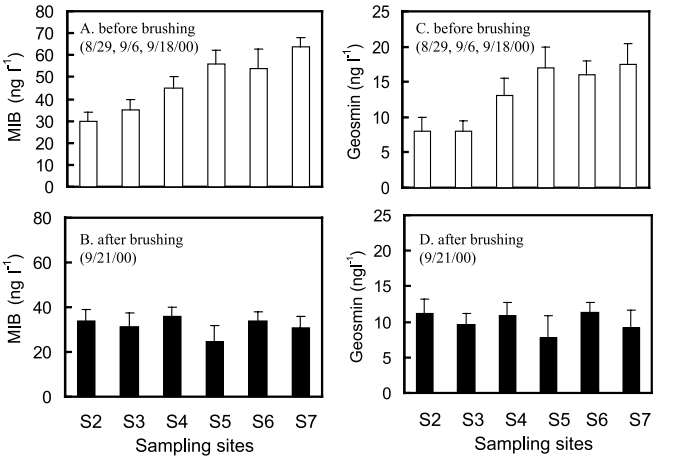

Figure 6 | Average concentration of MIB (A, B) and geosmin (C, D) in the canal section (*c.* 3 km) between Central Avenue and 19th Avenue before (open bar) (on 8/29/2000, 9/6/2000 and 9/18/2000), and after brushing treatment (closed bar) (9/21/2000). Brushing was conducted on 9/19-20/2000. Data are means of 3 replicates with bars denoting SD.

Reducing production of MIB and geosmin by brushing

Figures 6A and 6C show the concentrations of MIB and geosmin, respectively, along the 3-km stretch shortly before the brushing treatment. Before brushing, the MIB concentration doubled, and the geosmin concentration increased by over 140% between sites 2 and 7. The net increase in MIB and geosmin concentrations downstream was eliminated after brushing (Figures 6B and 6D). Three additional consecutive brushing treatments carried out in early-October through mid-November gave results consistent with these illustrated in Figures 6B and 6D. It was concluded that brushing was effective in removing algal biomass and reducing the production of MIB and geosmin in the treated section of the Arizona Canal.

Effectiveness of canal wall-brushing over time

How long does the effect of canal brushing persist? To answer this question, both periphyton biomass and concentrations of MIB and geosmin were monitored over time following brushing. Triplicate periphyton samples were collected using the custom-designed periphyton sampler at each site over a 2-week period. Figure 7 shows the changes in periphyton biomass (as indicated by chlorophyll *a* concentration) along the brushed section as a function of time after brushing. Periphyton biomass in the brushed section increased gradually over time and reached the level of the unbrushed section within 2 weeks. Along with the increase in periphyton biomass, periphyton composition underwent a noticeable change. Pigment

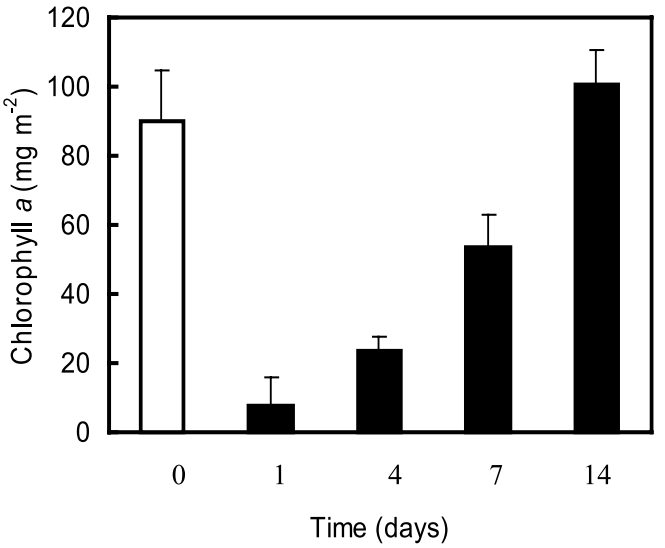

Figure 7 | Increase in periphyton biomass, as indicated by chlorophyll *a* concentration, on the canal walls before (open bar) and over time after brushing treatment (closed bar) (9/21/2000 through 10/4/2000). Data are means of 3 replicates with bars denoting SD.

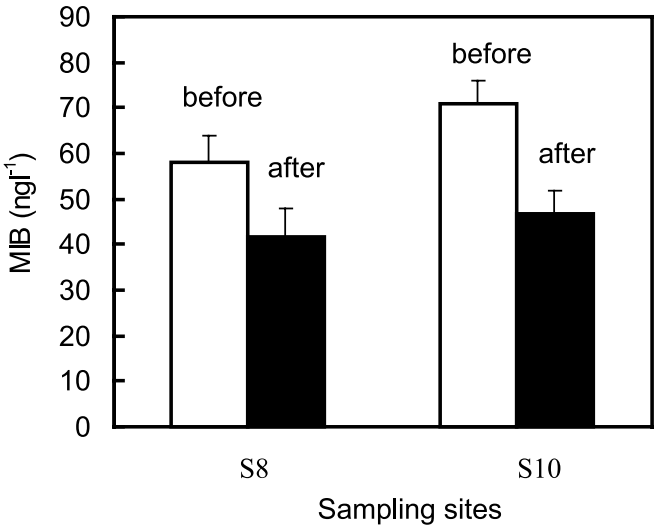

Figure 8 | Effect of upstream brushing treatment on downstream MIB concentration in the Arizona Canal over a 2-week period (9/21/2000-10/4/2000). Open bar, average MIB concentration before brushing treatment; closed bar, average MIB concentration over the 2 weeks after brushing treatment. S8, sampling site at 19th Avenue (end of the brushing treatment section); S10, sampling site near the Deer Valley WTP, 4 km downstream from 19th Avenue. Data are means of 3 replicates with bars denoting SD.

analysis indicated an increase in chlorophyll *c* concentration (associated mainly with diatoms) and chlorophyll *c* to *a* ratio following brushing. Light microscopic observation confirmed that periphytic diatom populations increased after brushing. Conversely, a decrease in the amount of MIB- and geosmin-producing cyanobacteria was evident. As a result, MIB and geosmin concentrations remained relatively low in the brushed section over the 2 weeks.

Brushing of the short canal stretch affected MIB and geosmin concentrations in the lower reach of the Arizona Canal

In order to evaluate the impact of brushing on downstream turbidity and concentrations of MIB and geosmin, a 4-km unbrushed canal section just below the brushed section was monitored for changes in turbidity and concentrations of MIB and geosmin. No significant increase in turbidity was detected at the Deer Valley WTP site, which was located at the end of the 4-km unbrushed section. However, shortly after brushing, a small short pulse of MIB (*c.* 10 ng l^{-1}) reached the Deer Valley WTP. The increase in MIB concentration between the 19th Avenue site and Deer Valley WTP prior to brushings was 20–25 ng l^{-1}. However, 1 day after brushing, the overall concentration of MIB at the downstream Deer Valley WTP was substantially lower than those detected before brushing (Figure 8). Unlike MIB, geosmin concentration did not increase at the Deer valley site after brushing. A short pulse of MIB that occurred downstream after brushing may have been due to release of odorous compounds from lysis of algal biomass and some release of soil-bound odorous compounds.

During the brushing period from mid-September through mid-November 2000, MIB and geosmin concentrations at the Deer Valley WTP site were lower than those observed prior to the brushing event in August and early September, and overall concentrations of these odorous compounds decreased from month to month (Figure 9). Our baseline monitoring data collected in 1999 and also in 2001 indicated that peak production of MIB and geosmin in this stretch of the Arizona Canal occurred in September to November (Figure 9).

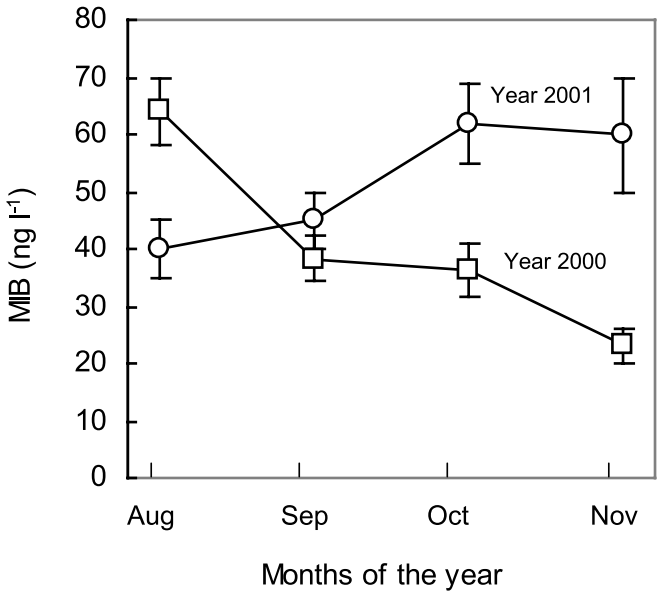

Figure 9 | Mean MIB concentrations at intake of Deer Valley WTP (S10) after brushing treatment (open squares) from late August through mid-November 2000 compared with August through November 2001 without brushing treatment (open circles). Data are means of ≥3 replicates with bars denoting SD.

DISCUSSION

MIB- and geosmin-associated musty/earthy tastes and odours in drinking waters are a matter of growing public concern. Various conventional and innovative control measures have been evaluated and adopted by water utilities to reduce the off-flavours (Mallevialle & Suffet, 1987; Lundgren *et al.*, 1988; Ando *et al.*, 1992; Egashira *et al.*, 1992; Wnorowski, 1992; Muramoto *et al.*, 1995; Suffet *et al.*, 1995). However, in-plant techniques and technologies are generally applied on either a small scale or are very expensive. Control of surface source waters has generally been considered to be a long-term management strategy (Means & McGuire, 1986; Suffet *et al.*, 1995, 1996). Where practical, source control might be a more efficient and cost-effective means of reducing taste and odour problems (McGuire & Gaston, 1988).

In this study, we have demonstrated that physical treatment, such as canal wall brushing, can be an effective source control measure for MIB- and geosmin-producing cyanobacteria. With brushing, over 80% of the periphyton biomass was removed from the submerged canal walls of the Arizona Canal, with a concomitant reduction in MIB and geosmin production. These results also confirmed that the major MIB and geosmin producers in the Arizona Canal were not commonly suspended in the water column, but were attached to the canal walls.

Brushing not only effectively removed nuisance periphyton from the canal walls, but also apparently selectively reduced the rate of recolonization of MIB- and geosmin-producers in this habitat. Although the periphyton biomass recovered within 2 weeks following brushing, MIB and geosmin concentrations remained low. Brushing appears to have altered the species composition of the periphyton community. A similar phenomenon of changing algal composition from filamentous cyanobacteria to diatoms was observed when the chemical diuron (0.01 mg l^{-1}) was applied to catfish ponds in an attempt to reduce the production of cyanobacteria-associated MIB (Zimba *et al.*, 2002).

In the Arizona Canal, MIB- or geosmin-producing periphytic cyanobacteria were not generally the dominant species, but rather appeared as discontinuous patches along the canal walls intermixed with other taxa. Such a phenomenon was also observed in other water bodies with taste and odour incidents (Izaguirre & Taylor, 1995; Sugiura *et al.*, 1998). On-going laboratory studies have revealed that several MIB- and geosmin-producing cyanobacteria isolated from the Arizona Canal showed specific growth rates (chlorophyll *a* increases over time) that were significantly lower than other non-odour producing strains from the same habitats. This might account for the slower recovery of these odour-producing species on the canal walls, and also explain the difficulty in isolating MIB- and/or geosmin-producing cyanobacteria from field samples.

The cost for the brushing operation was estimated, under our treatment conditions, to be *c.* $1,000 per kilometre of canal section, which was less than one tenth of the cost for powered activated carbon application in the WTPs along the Arizona Canal to reduce equivalent amounts of MIB and geosmin. Therefore, brushing appears to be not only an efficient, but also a cost-effective, technique for source water taste and odour control. It may also have an application for fish culture ponds

with concrete- or plastic-lined walls, if MIB/geosmin-producing periphyton were identified to contribute the off-flavour compounds to harvested fish.

CONCLUSIONS

Removal of localized MIB- and geosmin-producing cyanobacteria by mechanical brushing of submerged concrete canal walls was an efficient and cost-effective approach to reduce the production of MIB and geosmin in the Arizona Canal. The technique may be particularly applicable to the southwest region of the United States, such as California, Nevada, Utah, New Mexico and Arizona, where surface water supplies are stored in lakes and reservoirs and transported in open concrete canals/aqueducts to WTPs.

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