Control of MIB, Geosmin and TON by membrane systems

C. R. Reiss, C. Robert, C. Owen and J. S. Taylor

ABSTRACT

Control of taste and odour compounds in drinking water supplies represents a key treatment objective for many municipalities. Geosmin and 2-methylisoborneol (MIB) represent the primary compounds responsible for taste and odour present in surface waters throughout the world. This research evaluated the ability of membrane systems to control taste and odour when treating a highly organic surface water source and also when challenge tested with MIB and geosmin stock solutions.

Reduction of taste and odour compounds by conventional coagulation-sedimentation-filtration treatment, microfiltration (MF), or ultrafiltration (UF) was only significant when oxidation and coagulation were employed. Solely using porous filtration in the form of MF or UF membrane systems resulted in variable removal between 5 and 40%. None of the three treatment technologies could consistently meet the USEPA threshold odour number (TON) secondary standard of 3 units.

The cellulose acetate nanofilter consistently removed 35–50% of TON, MIB and geosmin; however, this would still not provide assurance of compliance with the TON standard of 3 units.

A polyamide nanofilter provided over 99% removal of MIB and geosmin, representing the most capable system evaluated. Application of the homogeneous solution diffusion equation indicated that size exclusion drives removal of taste and odour compounds.

Key words | geosmin, membranes, MIB, microfiltration, nanofiltration, taste

C. R. Reiss
C. Robert
Reiss Environmental, Inc.,
12001 Research Parkway, Ste 228,
Orlando FL 32826,
USA

C. Owen
Tampa Bay Water,
2535 Landmark Drive, Suite 211
Clearwater FL, 33761,
USA

J. S. Taylor (corresponding author)
University of Central Florida,
ENGR II, Rm 320, 4000 Central Florida Blvd.,
Box 25000, Orlando,
FL 32816-0450
USA
Phone: 407.823.2785
Fax: 407.366.1624
E-mail: taylor@mail.ucf.edu

NOMENCLATURE

CSF	coagulation sedimentation filtration
GAC	granular activated carbon
ILC	in-line coagulation
LHSD	linear homogeneous solution diffusion
MF	microfiltration
MGD	million gallons per day
MIB	2-methylisoborneol
MWCO	molecular weight cut-off
NF	nanofiltration
PAC	powdered activated carbon
RO	reverse osmosis
TDS	total dissolved solids
TOC	total organic carbon
TON	THRESHOLD ODOR NUMBER
UF	ultrafiltration
USEPA	United States Environmental Protection Agency
WTP	water treatment plant

INTRODUCTION

Control of taste and odour compounds in drinking water supplies represents a key treatment objective for many municipalities. Suffet *et al.* (1993) reported that 22% of the water providers surveyed in a United States study reported taste and odour problems in their source waters. The presence of objectionable taste and odour in drinking water represents an aesthetic issue resulting in customer complaints.

The most significant source of odour in water supplies is the growth and decay of microorganisms in surface water. Blue-green algae, green algae, diatoms and flagellates are four algae groups responsible for odour complaints. Geosmin (trans-1,10-dimethyl-trans-decalol) is an odour-causing metabolite produced by blue-green algae, which has an earthy, musty smell. Actinomycete bacteria are also present in surface water and produce 2-methylisoborneol (MIB),

another odour compound (Rashash 1994). Geosmin and MIB represent the primary compounds responsible for taste and odour present in surface waters throughout the world (Durrer *et al.* 1999; Graham *et al.* 2000).

There is no known health-related regulation associated with taste and odour. The United States Environmental Protection Agency (USEPA) has set a secondary standard of 3 units for threshold odor number (TON), an aggregate measure of the odour of water, for aesthetic purposes (USEPA 1991). The World Health Organization *Drinking Water Quality Guidelines* indicate that the taste and odour of drinking water should not be offensive to the consumer; however, no health-based guideline value is proposed (WHO 2004). The Ames test has been widely used since the 1970s as a preliminary screening tool for potential carcinogens. Neither geosmin nor MIB are mutagenic as determined by the Ames test (Dionigi *et al.* 1993; Nakajima *et al.* 1996), which has limited research.

However, the need for research into the presence of taste and odour compounds and associated control methods is important. Taste and odour compounds are detected at very low concentrations. The average person detects geosmin at 4 nanograms per litre (ng l^{-1}) and MIB at 9 ng l^{-1} (Ndiongue *et al.* 2004). Taste and odour problems have been traced to planktonic and benthic algae in water supplies, canals, surface impoundments and distribution networks (Izaguirre *et al.* 1982; Means and McGuire 1986; Izaguirre and Taylor 1995).

Control of taste and odour can be challenging. MIB and geosmin have stable ring formations that make bond-cleaving difficult (Figures 1 and 2). Therefore, MIB and geosmin are difficult to oxidize or to degrade microbiologically (Durrer *et al.* 1999; Saito *et al.* 1999; Jung *et al.* 2004).

Coagulation cannot remove MIB and geosmin effectively. Other control methods include oxidation by chlorine, chlorine dioxide and ozone, granular activated carbon (GAC) and

Figure 1 | Geosmin molecular structure.
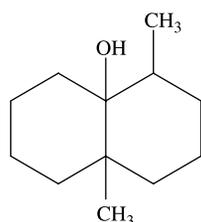
Molecular weight: 182.31 daltons
C 79.06%   H 12.16%   O 8.78%
Boiling point: 260°C

Figure 2 | 2-methylisoborneol molecular structure.
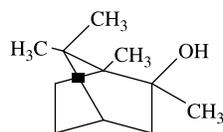
Molecular weight: 168.28 daltons
C 78.51%   H 11.98%   O 9.51%
Boiling point: 207°C

powdered activated carbon (PAC) adsorption, and gamma radiation (Duarte *et al.* 2002; Jung *et al.* 2004). Potassium permanganate is sometimes used for pretreatment of reservoirs and raw water streams for taste and odour control.

Membrane technologies represent an additional potential method of taste and odour control. Size-exclusion controlled processes such as microfiltration (MF) and ultrafiltration (UF) have been utilized as part of multi-unit process trains to control taste and odour. Ozone, GAC and PAC are used ahead of MF or UF to remove taste and odour compounds, and are required since MF or UF removes no dissolved compounds (Kelly *et al.* 2003; Garcia-Aleman *et al.* 2005).

The process train for the Region of Peel, Canada, 95.4 MGD water treatment plant on Lake Ontario is ozone–biologically active carbon–UF. Ozone and biologically active carbon were selected, in part, for their ability to control taste and odour that would otherwise pass through the UF membrane (Garcia-Aleman *et al.* 2005).

In summarizing UF pilot testing performed in France, Virginia and Texas, Kelly *et al.* (2003) acknowledged the need to add appropriate unit process(es) when taste and odour removal is required and described the benefit of using powdered activated carbon.

Diffusion-controlled membrane processes such as reverse osmosis (RO) or nanofiltration (NF) can remove low molecular weight dissolved molecules such as taste and odour compounds. However, little is known about the capability of RO or NF to remove taste and odour.

Alt *et al.* used bench-scale NF and RO systems to evaluate MIB and geosmin removal from the surface source for the Yuciapa Valley Regional Water Filtration Facility in Yuma, Arizona. Seven NF and RO membranes were tested, and geosmin and MIB removals from 50 to 99% were reported. No information on influent or finished water geosmin and MIB concentrations or challenge testing was reported (Alt *et al.* 2005).

In addition to a general lack of information on RO and NF taste and odour removal, the research to date has

focused on ambient concentrations of MIB and geosmin, which omits critically high events associated with seasonal changes in source water quality. Challenge testing with higher concentrations of MIB and geosmin provides an opportunity for conservative assessments of the limits of performance expected from membrane systems.

This project was conducted to comply with the USEPA ICR. The data from the project was utilized by USEPA in their ICR publication and by R. Reiss for his dissertation and can be assessed in those documents (USEPA 2000; Reiss 2005). The research presented herein evaluated the ability of membrane technologies to control taste and odour when treating a highly variable water quality surface supply in Tampa, Florida. This pilot testing documented the removal of taste and odour compounds at ambient conditions as well as removal capabilities when challenged with high concentrations of MIB and geosmin artificially introduced into the feed water.

METHODS AND MATERIALS

Source water

The source water for this research was the Hillsborough River in Tampa, Florida. The Tampa Water Department owns and operates the David L. Tippen Water Treatment Plant (DLT WTP), a 120 MGD (454 Ml day^{-1}) conventional ferric coagulation, sedimentation, filtration (CSF) water treatment plant (WTP) that was the site for this pilot study project. The Hillsborough River is a spring-fed river with supplemental supply coming from precipitation and watershed runoff. Water quality varies greatly between seasons with higher organic levels and lower total dissolved solids (TDS) during the wet (summer) season and higher TDS and lower organic levels during the dry (winter) season.

Water quality during the 15 months of pilot operation is presented in Table 1. As shown, taste and odour values varied over the course of the study. TON averaged 10.1 units, suggesting water with a high potential for taste and odour complaints unless adequate treatment is provided. Both geosmin and MIB were present, averaging 4.5 and 5.6 ng l^{-1}, respectively.

Pilot systems

Four different membrane pilot units were operated at the DLT WTP site in Tampa, Florida, treating raw water from the Hillsborough River. One MF system was used and consisted of a 10 gpm (37.85 L/min) pressurized, hollow fibre system manufactured by US Filter/Memcor. One UF system was used and consisted of a 10 gpm, immersed,

Table 1 | Hillsborough River raw water quality

Parameter	Units	Maximum	Minimum	Average	No. of observations
TON	Std units	50.0	1.0	10.1	32
MIB	ng l^{-1}	25.4	<1	5.6	18
Geosmin	ng l^{-1}	11.5	<1	4.5	18
TOC	mg l^{-1}	27.5	4.0	16.4	35
UV-254	cm^{-1}	1.9070	0.1508	0.7412	35
Colour	Cpu	297	34	153	33
Alkalinity	mg l^{-1} as CaCO$_3$	178	30	80	35
Total hardness	mg l^{-1} as CaCO$_3$	184	50	108	35
TDS	mg l^{-1}	270	63	169	32

hollow fibre system manufactured by Zenon. Both the MF and UF system are automatic backwash systems that are designed for removal of turbidity and pathogens from surface waters and were used to directly treat the raw water from the Hillsborough River. Specifications are provided in Table 2. The MF and UF systems were used with and without inline coagulation (ILC) of raw water, which reduced MF or UF system fouling and/or agglomerated dissolved constituents such as taste and odour compounds to allow filtration and removal. A dose of aluminium sulphate of no more than $20\,mg\,l^{-1}$ as alum was added when ILC was utilized. Configurations for the MF and UF systems are shown in Figures 3 and 4, respectively.

Two nanofiltration (NF) pilot units were utilized to treat filtrate from one of the three pretreatment systems: the MF pilot-scale system, the UF pilot-scale system, or conventional CSF filtrate from the full-scale WTP. MF and UF systems sieve particulates from water, and dissolved constituents pass through to the filtrate.

NF is particularly effective for removing total organic carbon (TOC), disinfection by-products precursors, and other dissolved constituents from surface and ground waters (Reiss and Taylor 1991; Taylor *et al.* 1992). However, NF systems are designed for low turbidity (0.5 NTU) feed waters and will plug if used directly on surface water supplies (Reiss and Taylor 1995). Therefore, use of NF systems for surface water applications requires pretreatment such as MF or UF.

The configuration of NF systems is standardized and accepted worldwide. Commercial configurations consist of either $4''$ (10.2 cm) diameter or $8''$ (20.4 cm) diameter membrane elements housed in pressure vessels (Figure 5). Each element is typically $40''$ (1.01 m) or $60''$ in (1.52 m) length with approximately $240''$ (6.10 m) to $280''$ (7.11 m) of membrane length per pressure vessel. Spiral wound NF elements are provided by several manufacturers. The two spiral wound NF elements tested in this project were the Hydranautics LFC1 and the Fluid Systems CALP. Specifications for each NF element are provided in Table 3. The configuration of the pilot-scale NF systems used to house the LFC1 and CALP membranes is shown in Figure 5.

Ambient performance evaluation

The four membrane pilot units and the filtrate from the conventional WTP were paired to form eight different process trains. These process train configurations were operated at the DLT WTP in Tampa, Florida, and assessed for control of taste and odour compounds. The UF, MF, LFC1, and CALP systems were continuously operated for approximately 1 year at 10, 15, 10, and 10 gpm, respectively. A side stream of filtrate from the CSF WTP was utilized as

Table 2 | Microfiltration and ultrafiltration specifications

Parameter	Memcor	Zenon
Model	CMF	ZW500
Nominal pore size (microns)	0.2	0.05
Fibre configuration	Hollow	Hollow
Module configuration	Pressurized	Immersed
Number of modules	3	3
Flow configuration	Outside-in	Outside-in
Material	Polypropylene	Polyvinylidene fluoride
Active membrane area, A	$355\,ft^2$ ($32.9\,m^2$)	$150\,ft^2$ ($13.9\,m^2$)
Number of fibres per module	NA	1,550
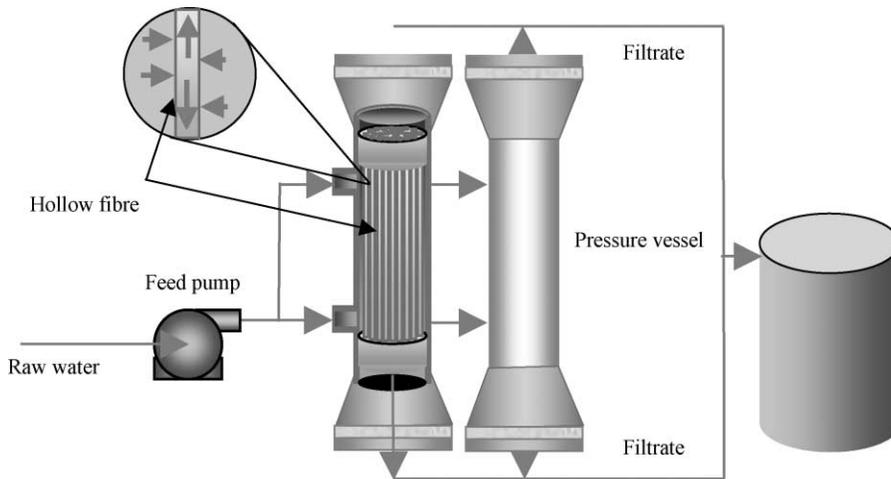
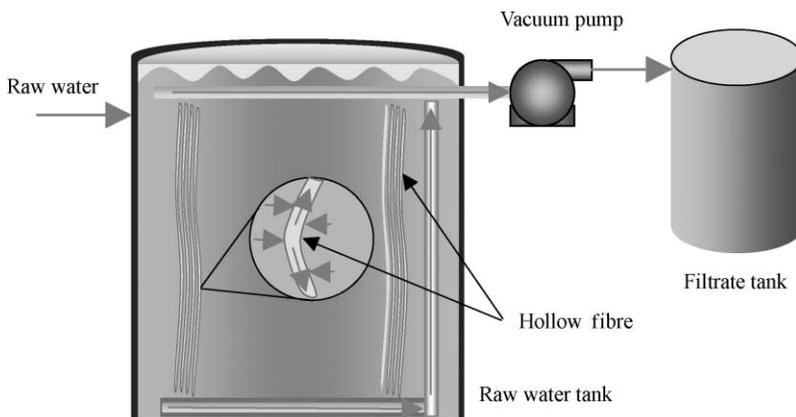**Figure 3** | Memcor MF pilot configuration.

feed for the CSF-NF experiments. The Hillsborough WTP consisted of potassium permanganate addition in the raw water line, ferric sulphate coagulation with a settling aid, PAC addition, sedimentation, chlorine followed by ammonia addition, filtration, boost chloramination, storage and distribution. The Hillsborough WTP has now upgraded capacity and facilities to include ozone and carbon and other capital modifications. The UF system was tested with and without in-line alum coagulation. The eight process trains were:

- UF → CALP NF   UF → LFC1 NF
- ILC-UF → CALP NF   ILC-UF → LFC1 NF
- MF → CALP NF   MF → LFC1 NF
- CSF → CALP NF   CSF → LFC1 NF

Ambient concentrations of MIB, geosmin and TON were measured biweekly. The purpose of this testing was to document the taste and odour control capabilities of each unit process as well as the combined process train, over a multi-season period. Documentation of removal capabilities of NF systems in particular is very limited, with this data providing a long-term assessment of performance.

Challenge testing evaluation

In addition to the ambient performance evaluation, challenge testing of the NF systems was performed. While it is known that removal of taste and odour compounds by CSF, MF or UF systems is probably limited, the capabilities of NF

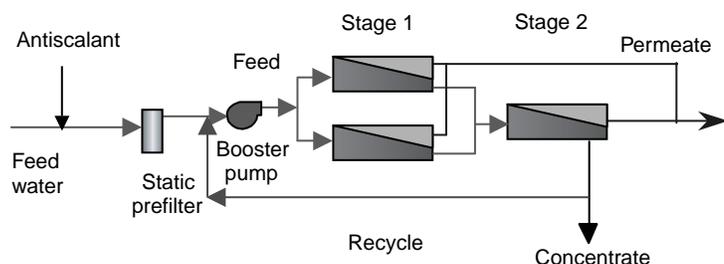**Figure 4** | Zenon UF pilot configuration.

Figure 5 | NF system configuration.

for removal of low molecular weight taste and odour compounds are potentially very high, but are poorly documented. Therefore, a series of tests were performed on each NF system at various flux and recovery settings. Reagent-grade MIB and geosmin solutions were prepared and injected into the feed stream of each NF system to provide a minimum of 100 ng l^{-1} of each compound in the feed water. This represents a conservative, challenging evaluation of the performance of the LFC1 and CALP nanofilters to reject these low molecular weight compounds. Samples were collected and analysed for the spiked

feed water, NF permeate from Stage 1, and NF permeate from Stage 2.

Two flux and two recovery settings were selected, to evaluate the variation in rejection capability of each compound and assess the degree to which diffusion was controlling rejection. Each NF system was tested at fluxes of 7 and 14 gfd (12 and 24 l m^{-2} h^{-1}) and recoveries of 65% and 85% for four experiments on each NF.

Based on the solution diffusion theory, models have been developed to predict permeate concentration. The linear model (Equation 1) incorporates solution diffusion

Table 3 | Nanofiltration specifications

Parameter	CALP	LFC1
Manufacturer	Fluid systems	Hydranautics
Element configuration	Spiral wound	Spiral wound
Membrane trade name	CALP	LFC1
Molecular weight cut-off (Daltons)	300	200
Membrane material (e.g. PVD, polyamide, etc.)	Cellulose acetate	Polyamide
Membrane construction (e.g. thin-film composite)	Asymmetric	Thin-film composite
Element size (e.g. 2.5″ × 40″, 4″ × 40″, (6.35 cm × 1.01 m) etc.)	4′ × 60″ (10.2 cm × 1.52 m)	4′ × 40″ (6.35 cm × 1.01 m)
Active membrane element area	125 ft^2 (11.6 m^2)	85 ft^2 (7.78 m^2)
Water mass transfer coefficient, MTCW	0.13 gfd/psi (6.15 cm/day-atm)	0.15 gfd/ps (7.10 cm/day-atm)
Maximum permissible SDI	5	4
Acceptable range of operating pressures	<240 psi (20.6 atm)	<600 psi (33.6 atm)
Acceptable range of operating pH values	3–7	3–10

theory and predicts that permeate concentration would increase with decreasing flux and increasing recovery (Taylor and Jacobs 1996). The linear model has been used to predict pesticide rejection (Duranceau & Taylor 1992; Chen *et al.* 2004) and operational effects (Reiss *et al.* 2001) on mass transfer in diffusion controlled membrane systems. This model was used to determine whether diffusion controlled the permeation of MIB and geosmin through the NF membranes.

$$C_p = \frac{C_f K_s}{J_s\left(\frac{2-2r}{2-r}\right) + K_s} \tag{1}$$

where: C_f = feed concentration, $mg\,l^{-1}$; r = water recovery (%/100).

The pilot units were in continuous operation at normal operational settings throughout the course of the challenge testing. Spiking of MIB and geosmin to each NF system was based on the volume of pretreated water fed to the train and the concentration of MIB and geosmin in the stock solution. The stock solution was injected into the feed stream at a rate as was theoretically required to obtain at least $100\,ng\,l^{-1}$ in the spiked feed water (Figure 6).

Tracer studies

The injection of the MIB and geosmin stock solution was continuous using a positive displacement chemical metering pump. Tracer studies were performed on the NF pilot units to ensure that the injected stock solution had adequate time to travel through the treatment unit and be captured in the subsequent permeate samples collected from each unit.
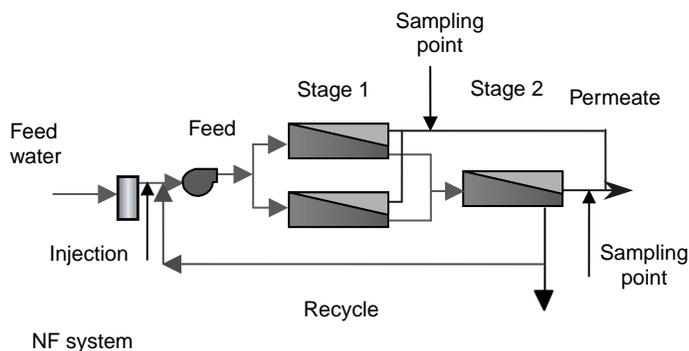
A pH tracer study of the NF systems was performed to determine the time of sampling the permeate stream following injection of MIB and geosmin. Note that the purpose here is to determine the time of sampling not the system time constants. Continuous injection of sulphuric acid was used as the tracer since the NF systems already had sulphuric acid systems operating as part of standard NF pretreatment processes. Acid injection was initiated at the influent to the NF system, with samples collected for influent, Stage 1 permeate, and Stage 2 permeate at 7 gsfd (28.49 cm/day) and 85% recovery in order to determine the maximum period for sample collection. The determination of sampling times is easily done using continuous feed as concentrations have to be monitored until steady state is attained as opposed to a spike injection which produces a non-steady state response and mathematical analyses are required for determination of system time constants. Results of this tracer study are presented in Figure 7. As shown, the influent pH dropped within 4 minutes of initiating the acid injection while the two permeate locations stabilized at the lower pH at approximately 9 minutes. Based on these results, the permeate was sampled 15 minutes after continuous injection of stock solution was initiated in the feed stream. Consequently, sample collection of the permeate stream 15 minutes after continuous injection of MIB and geosmin began was more than adequate to gather samples at steady state given that injection was continuous, which was the case.

RESULTS AND DISCUSSION

The ability of the treatment systems to control taste and odour compounds as measured by the rejection of TON,
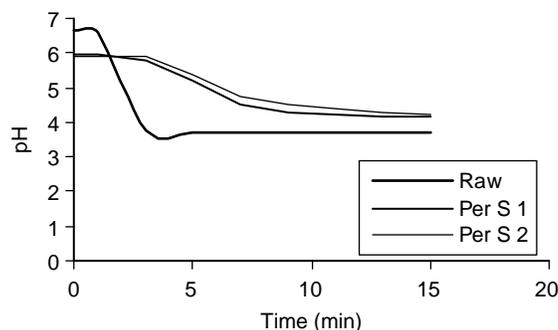

Figure 6 | MIB and geosmin addition and sampling points.

Figure 7 │ NF tracer study.

Figure 8 │ Removal of TON by the David L. Tippin Water Treatment Plant (CSF), UF, CUF and MF pilot plants.

MIB and geosmin was assessed at ambient conditions and through challenge testing of only NF units. Method No. 2150-B was followed for TON and Method No. 6040-B was followed for MIB and geosmin analyses as specified in the 19th edition of *Standard Methods* (1995). Results are presented separately for the conventional surface water treatment process (CSF), size exclusion processes (MF and UF) and for the NF systems. While hundreds of CSF, MF and UF systems have been constructed to treat surface waters, the need for advanced pretreatment of NF when treating surface waters has limited their application with only relatively few systems operating in the United States. Ambient results are presented for the CSF, UF, coagulation-UF (CUF) and MF units. Ambient and challenge testing results are presented for the NF systems. Note only samples with raw water concentrations above the detection limit are considered in these results as they allow assessment of removal capabilities of the treatment processes.

Conventional surface water treatment system results

The TON in the raw water and CSF, MF and UF filtrate is shown in Figure 8 for the ambient tests. Raw water ambient TON was highest (26 standard units) when CSF was evaluated, and approximately 7 (standard units) when UF, CUF and MF were evaluated. Removal of TON by one of the conventional surface water treatment processes and the size exclusion membrane processes (CSF, MF or UF) varied from 18 to 72%. CSF provided the highest removal of 72%. This was as expected, since the CSF WTP utilized potassium permanganate, high doses of ferric sulphate, and free chlorine as part of the treatment process. MF and UF
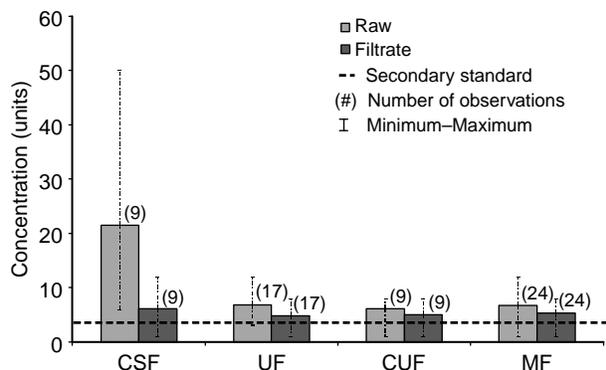
provided very limited removal (18 to 30%), as was expected for these processes, which do not significantly remove dissolved compounds. Coagulation preceded the UF system (CUF) for a portion of the time, but did not provide additional TON removal as shown in Figure 8.

Most important to note regarding these treatment processes is that none could consistently meet the USEPA TON secondary standard of 3 units for this source water, in which raw water TON was measured as high as 50 units and the average during testing of the CSF was 22 units.

MIB removal generally mirrored removal of TON, as presented in Figure 9. Note that the raw water MIB averaged less than the typical odour threshold of 9 ng l^{-1} for each of the processes presented. In addition, raw water MIB was less than the detection limit during UF operation; therefore no results are available.
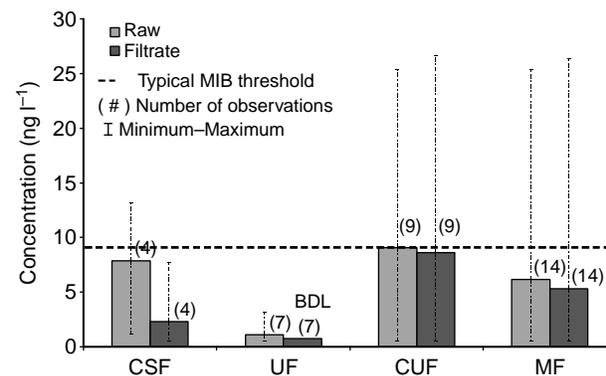

Figure 9 │ Removal of MIB by the David L. Tippin Water Treatment Plant (CSF), UF, CUF and MF pilot plants.

Nevertheless, this data shows that the chemical processes associated with CSF removed 71% of the MIB from the Hillsborough River. Conversely, the MF and UF systems, relying on physical removal or in the case of the UF system a low dose of coagulant, removed only 5 to 14% of the MIB. As presented previously in Table 1, MIB was measured in concentrations up to 25.4 ng l^{-1} in the raw water. During these periods, only the CSF process would be able to meet the 9 ng l^{-1} threshold standard.

Geosmin removal is presented in Figure 10 and exemplifies the limits of MF and UF to remove dissolved taste and odour compounds. Over the course of 15 months of pilot testing, geosmin samples were collected for each of the four unit processes. The number of samples varied from four when using CSF treatment to 14 when using MF treatment. With average raw water geosmin concentrations between 2.3 and 6.6 ng l^{-1}, CSF removed 78% of geosmin. MF and UF removed between 28 and 42% of geosmin. With a maximum raw water concentration of 11.5 ng l^{-1}, the typical geosmin threshold of 5 ng l^{-1} was only reliably met by the oxidation enhanced CSF plant process. The CSF plant process consisted of potassium permanganate addition in the raw water intake line and contact with free chlorine near the end of the sedimentation basin following ferric sulphate coagulation for a 3–5 minute period before the addition of ammonia for chloramine formation prior to filtration. Since the completion of this project, the plant has been upgraded to include ozone, which is a stronger oxidant than chlorine and does not form chlorinated by-products.
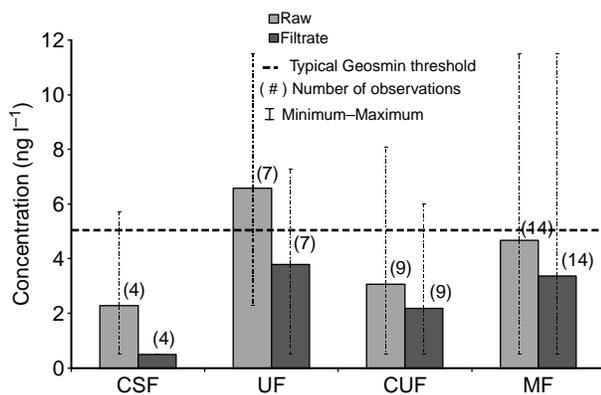
A summary of the removal percentages by pretreatment process is presented in Figure 11. As described, CSF provides a higher removal of TON, MIB and geosmin, over MF and UF processes. This can be attributed to the use of oxidants as well as coagulants in the CSF process. Addition of low doses of coagulant (less than 20 mg l^{-1} as alum) into the UF system did not provide significant additional removal. The removal of taste and odour compounds by MF and UF was higher than might be expected given that taste and odour is more commonly associated with dissolved compounds. It is likely that particulate and colloidal removal by MF and UF corresponded with the partial reduction in taste and odour concentrations.

While CSF showed substantial removal of taste and odour, taste and odour objectives were not always met during extreme events. This is consistent with experiences at the site facility and other conventional surface water treatment facilities throughout the United States that report taste and odour as a treatment issue (Suffet *et al.* 1993). Integration of RO or NF with other treatment processes can improve finished water quality.

Nanofiltration ambient water quality results

Removal of ambient taste and odour compounds by NF was evaluated over an extended period of time with samples collected at the influent to the NF systems as well as the combined permeate. Results are presented in Figure 12, 13 and 14 for TON, MIB and geosmin, respectively. The NF systems received various filtrates from the CSF, MF and UF
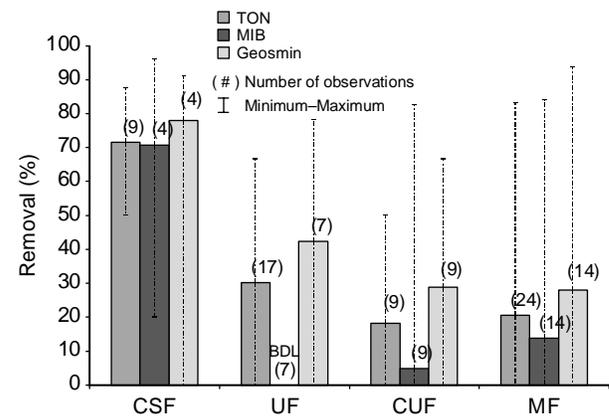

Figure 10 | Removal of geosmin by the David L. Tippin Water Treatment Plant (CSF), UF, CUF and MF pilot plants.

Figure 11 | Percentage removal of ambient taste and odour compounds by the David L. Tippin Water Treatment Plant (CSF), UF, CUF and MF pilot plants.
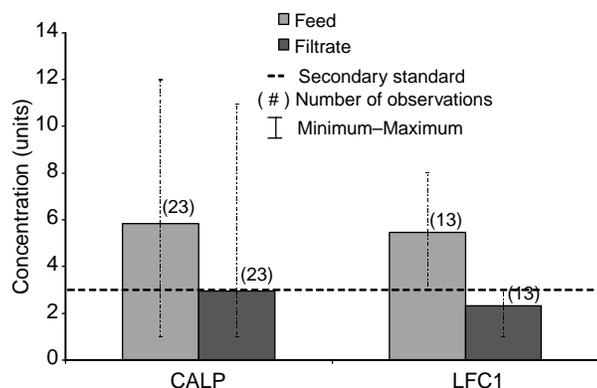
Figure 12 │ Removal of ambient TON by NF.

Figure 14 │ Removal of ambient geosmin by NF.

pretreatment systems. The average feed and permeate concentrations of TON, MIB and geosmin throughout the testing period are discussed in the following text.

As shown in Figure 12, reduction in TON levels by NF was significant and resulted in values lower than the secondary standard of 3 units for both the CALP and the LFC1 nanofilter. Note that average feed water concentrations were less than 6 units owing to the reductions achieved by upstream pretreatment processes. However, these results support the ability of NF to polish filtrate from conventional surface water treatment systems to meet taste and odour goals.

Removal of ambient MIB by NF is presented in Figure 13. As shown, the LFC1 nanofilter exhibited very high removal of MIB, with permeate values below the detection limit in all cases despite relatively high feed concentrations that averaged 15.4 ng l^{-1}. Conversely, the CALP nanofilter provided much lower removal, reducing MIB from an
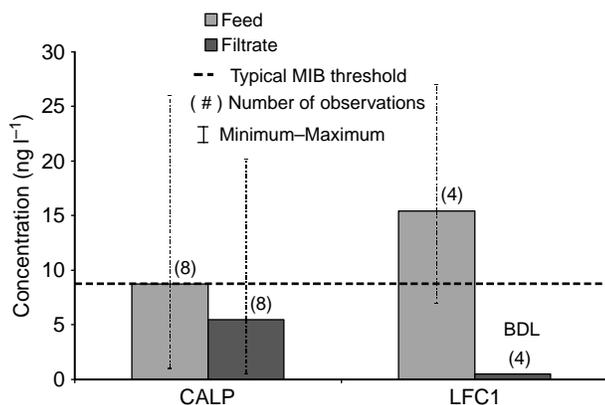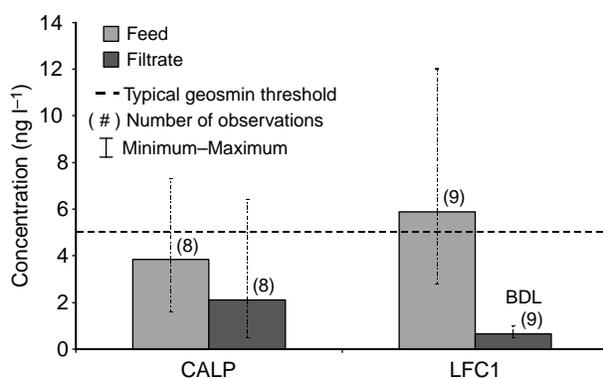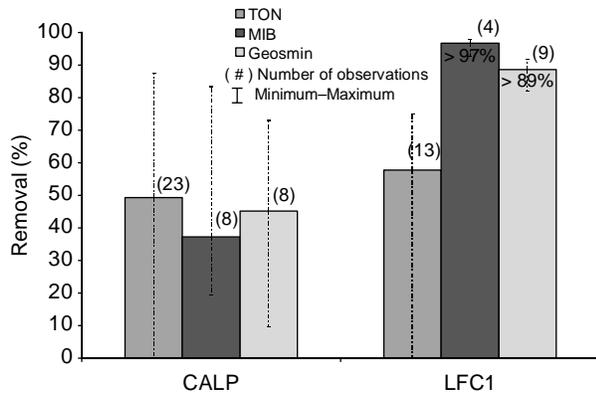

Figure 13 │ Removal of ambient MIB by NF.

average of 8.8 ng l^{-1} to 5.5 ng l^{-1}. Clearly, the removal efficacy of the LFC1 exceeded that of the CALP relative to MIB removal. Nevertheless, both NF systems could provide value in reducing surface water MIB concentrations.

Geosmin removal rates using NF were similar to those for MIB, with the LFC1 nanofilter providing complete removal of geosmin to below the detection limit (Figure 14). The CALP nanofilter provided credible but lower removal, with the average feed water geosmin concentration reduced to less than 2.1 ng l^{-1}.

The removal of ambient taste and odour compounds by NF is summarized in Figure 15. As shown, the CALP nanofilter provided 40 to 50% removal and the LFC1 removed 58 to 97% of the ambient TON, MIB and geosmin. Although high, MIB and geosmin removal was limited by the feed concentration. These results show the difference between nanofilters for removal of taste and odour. The CALP, a cellulose acetate based membrane, rejected less ambient TON, MIB and geosmin than did the polyamide composite based LFC1. Similar results have been observed for rejection of inorganic solutes, TOC and microorganisms (Lovins *et al.* 2003). This is important for communities with severe taste and odour concerns and the need for high levels of treatment or for surface water systems with limited upfront removal of taste and odour, such as those that use a stand-alone MF or UF system.
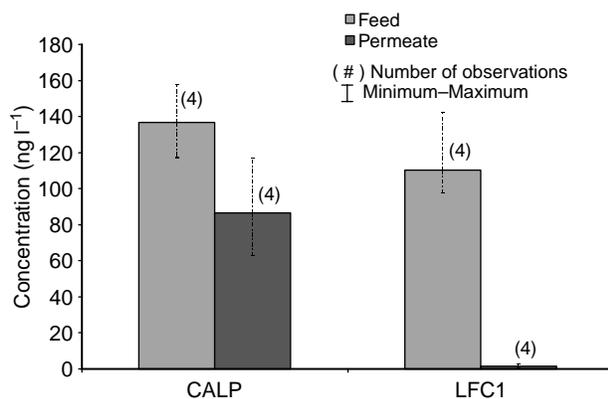
Nanofiltration challenge test results

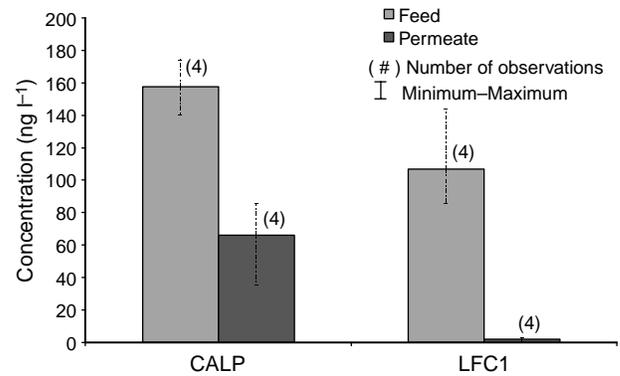To better understand the limits of removal using NF, challenge tests were performed with addition of MIB and

Figure 15 │ Percentage removal of ambient taste and odour compounds by nanofiltration.

Figure 17 │ Removal of challenge test geosmin by nanofiltration.

geosmin to the feed water. Concentrations of $100 \, ng \, l^{-1}$ for each compound were targeted. Results are presented in Figures 16 and 17 for average removal of MIB and geosmin, respectively.

The CALP feed MIB concentration averaged $137 \, ng \, l^{-1}$ with the combined permeate averaging $88 \, ng \, l^{-1}$. This consists of an average removal rate of 37%, which is consistent with the average of 37% removal obtained for the ambient water analysis. The removal capabilities of the CALP nanofilter did not vary with feed concentration. The LFC1 feed MIB concentration averaged $110 \, ng \, l^{-1}$ with the permeate concentration averaging $1 \, ng \, l^{-1}$. Note that measurable concentrations of MIB were detected in the LFC1 permeate, indicating that the removal limit of the LFC1 was reached at the $110 \, ng \, l^{-1}$ feed concentration. Nevertheless, these results indicate that the LFC1 could be

used for any natural surface water to provide near complete removal of MIB and would meet water quality goals.

The CALP feed geosmin concentration averaged $158 \, ng \, l^{-1}$ with the combined permeate averaging $66 \, ng \, l^{-1}$. This consists of an average removal rate of 58%, which is higher but in the range of the 45% removal obtained for the ambient water analysis. The removal capabilities of the CALP nanofilter increased slightly with feed concentration. The LFC1 feed geosmin concentration averaged $107 \, ng \, l^{-1}$ with the permeate concentration averaging $2 \, ng \, l^{-1}$. Note that measurable concentrations of geosmin were detected in the LFC1 permeate, indicating that the removal limit of the LFC1 was reached at the $107 \, ng \, l^{-1}$ feed concentration. As with the MIB results, these geosmin results indicate that the LFC1 could be used for any natural surface water to provide near complete removal of geosmin and would meet water quality goals.

While average results were presented above, a total of four experiments were performed for each nanofilter, representing two flux and two recovery settings. Detailed results by experiment are presented in Table 4. For assessment of the degree of influence due to diffusion and for mathematical prediction of the expected permeate concentration, the linear homogeneous solution diffusion (LHSD) model was solved for K_S, the solute mass transfer coefficient. Four data points were available for each analyte, by membrane. The resulting values are presented in Table 5. As shown, three of the four conditions did not converge. This indicates that diffusion plays a limited role, if any, in the reduction of MIB and geosmin using the two NF systems tested. The LHSD model would not be appropriate

Figure 16 │ Removal of challenge test MIB by nanofiltration.

Table 4 | MIB and geosmin concentrations by operating condition

		MIB (ng l⁻¹)		Geosmin (ng l⁻¹)	
	Flux/recovery (gfd/%*)	Feed	Permeate	Feed	Permeate
CALP	7/65	158	113	174	84
	7/85	118	75	162	66
	14/65	135	87	154	77
	14/85	137	68	140	37
LFC1	7/65	142	1	144	2
	7/85	102	3	103	1
	14/65	154	1	96	3
	14/85	140	1	86	2

*gsfd × 4.07 = cm/day

for determining the effect of operating condition on permeate water quality.

Rejection of MIB and geosmin molecules in the CALP and LFC1 nanofilters appears to be driven by size exclusion. Geosmin and MIB have molecular weights of approximately 182 and 168 daltons, respectively, which suggests greater removal would be achieved by the 200 molecular weight cutoff (MWCO) LFC1 nanofilter versus the 300 MWCO CALP nanofilter, as was realized. In addition, these molecular weights are an order of magnitude larger than solutes more commonly found to be diffusion controlled in NF and RO systems, such as sodium and chloride.

However, previous research has shown that organic parameters including TOC, colour and UV-254 are diffusion controlled for the LFC1 and CALP NF (Reiss *et al.* 1999). The inability to document diffusion-controlled rejection

Table 5 | Solute mass transfer coefficients

	CALP		LFC1	
	Kₛ (gsfd*)	Converged	Kₛ (gfd)	Converged
MIB	3.89E + 08	No	0.04	Yes
Geosmin	3.6	No	0.034	No

*gsfd × 4.07 = cm/day

could be explained for the LFC1 membrane by the low permeate concentrations, which approached the detection limit of 1 ng l⁻¹. However, the CALP permeate concentrations were sufficiently high yet diffusion effects were not observed. This further supports a size exclusion mechanism of removal. The absence of a significant charge associated with the MIB or geosmin molecule is likely a key factor.

CONCLUSIONS AND RECOMMENDATIONS

Reduction of taste and odour compounds by CSF, MF or UF was only significant when oxidation and coagulation were employed. Solely using porous filtration in the form of MF or UF membrane systems resulted in variable removal between 5 and 40%. These results held true for removal of TON, MIB and geosmin. None of the three treatment technologies could consistently meet the USEPA TON secondary standard of 3 units for this source water, in which raw water TON was measured as high as 50 units and the average during testing of the CSF was 22 units.

Advanced surface water treatment in the form of NF, a semi-permeable filtration technology, resulted in significant and consistent removal of TON, MIB and geosmin. This technology requires advanced pretreatment for application on surface waters; therefore it would be most applicable as a polishing step following conventional surface water treatment.

A cellulose acetate nanofilter consistently removed 35 to 50% of TON, MIB and geosmin; however, this would still not provide assurance of compliance with the TON standard of 3 units.

A polyamide nanofilter provided over 99% removal of MIB and geosmin, representing the most capable system evaluated. Use of polyamide NF to support compliance with taste and odour objectives offers significant benefits for continuous and high levels of removal.

Challenge tests using MIB and geosmin and operating at various nanofilter flux and recovery settings was performed. Application of the homogeneous solution diffusion equation was performed to determine whether rejection of taste and odour compounds by NF is diffusion controlled. Results indicate that size exclusion drives removal of taste and odour compounds, based on the data available.

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