An adaptive management framework was developed during the course of a three-year case study to reduce taste and odor (T&O) problems in the Phoenix, Ariz., metropolitan area. The collaborative project used an extensive monitoring program, rapid feedback, and extensive communication to allow flexible responses to changing circumstances. A multiple-barrier strategy was used with T&O control measures implemented in the reservoirs, canals, and water treatment plants. Research and implementation occurred concurrently, leading to substantial reductions in T&O problems over the course of the project.

Adaptive management using multiple barriers to control tastes and odors

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A recent national survey reported that 66% of adults in the United States were concerned about the aesthetic quality of water (WQA, 2001). More than half (52%) were concerned specifically about the "smell or taste of water." In the same survey, 41% of respondents used point-of-use or point-of-entry water treatment devices in their homes, and 39% used bottled water. Among the myriad tastes and odors that have been described for drinking water, "moldy" and "musty" are the most common.

Suffet et al (1996) reported that 22% of municipal water suppliers using surface water encounter musty and/or moldy taste and odor (T&O) problems. Two compounds, 2-methylisoborneol (MIB) and geosmin, generally cause musty, moldy, and earthy tastes and odors (Suffet et al, 1999; Young et al, 1996; Wnorowski, 1992). Specific blue-green algae (cyanobacteria) and actinomycetes produce both compounds. Human sensory thresholds for these compounds are in the low nanogram-per-litre range but vary among individuals (Young, 1996; Krasner et al, 1985). The relationship between perceived intensity of earthy flavor and the logarithm of MIB concentration follows a semilogarithmic relationship (Lin et al, 2002; Krasner, 1988).

BACKGROUND

Before 1999, the city of Phoenix, Ariz., experienced serious T&O problems, mostly during late summer and early fall. A particularly serious T&O problem occurred in 1997, when MIB levels in the Arizona Canal exceeded several hundred nanograms per litre for several weeks, triggering hundreds of complaints. The key aspects of this specific problem were:

- the primary T&O compound was MIB;
- MIB originated at several locations including water supply reservoirs, transmission canals, and treatment plants; and
- the problem was episodic but most serious in the late summer and early fall.

The goal of the three-year project (1999–2001) reported in this article was to develop and implement a T&O management strategy for the city of Phoenix. The project was a collaboration between the city of Phoenix, state regulators, water providers, and Arizona State University (ASU), and was guided by five principles.

Multiple-barrier approach. The management strategy would use a multiple-barrier approach, analogous to the approach now widely used for the control of pathogens. The goal of multiple barriers in water treatment is to improve reliability and cost-effectiveness. Multiple-barrier approaches divide the water supply system into components (watersheds, lakes, conveyance structures, wells, in-plant treatment, and distribution system). Management practices in the form of barriers against T&O events were used to control T&O levels in each of these components except the distribution system. In most circumstances, more than one barrier was used at a given time.

Measurable improvements. Measurable improvement in water quality (reduction of T&O problems) was the main goal of the project, and implementation success was evaluated using an objective metric.

Monitoring and communication. An extensive monitoring and rapid communication and feedback program was implemented to enable the water resources community to respond to changing circumstances in a framework of adaptive management.

Collaboration. Implementation of mitigation strategies occurred concurrently with research, requiring close collaboration among participating entities.

Open dialogue. The city of Phoenix implemented an "open data" policy, freely sharing data and inviting other municipalities to participate in dialogues. This resulted in informal participation by nearly all municipalities in the metropolitan area.

This article summarizes the results of that project, with a focus on implementation. The approach developed—the utilization of multiple barriers in an adaptive management framework—can readily be used by other utilities that seek to improve water quality.

ADAPTIVE-MANAGEMENT FRAMEWORK

Adaptive management is founded on the premise that environmental systems are complex and unpredictable. Management responses must therefore be flexible (adaptive; Gunderson & Holling, 2002). The main features of adaptive management include

- continuous monitoring and feedback and
- a management structure that can adapt to ever-changing conditions.

Adaptive management is now widely used in natural-resources management and has considerable potential for regional water quality management. It is particularly suitable for T&O management in complex water delivery systems because a T&O problem is episodic and varies spatially. The "early warning" approach developed by the Metropolitan Water District of Southern California emphasized the need to identify the temporal and spatial character of the T&O problem (Means & McGuire, 1986; McGuire, et al, 1981).

Recognizing these facts, monitoring for T&O compounds throughout the project was conducted weekly. During the peak of the T&O season this occurred at up to 20 locations within the source water supply system, including points in the major reservoirs, rivers, and canals, and at the inlet and outlet of each water treatment plant (WTP). These data, management recommendations, and research and operational notes were transmitted via an electronic newsletter delivered to approximately 80 water treatment operators, water resource managers, consultants, and others in the local water treatment community every week during the T&O season (March through October). This provided constant feedback and a flow of information and ideas. More extensive dialogue was achieved through biannual forums.

These mechanisms created continuous interaction between researchers and practitioners. Plant operators, chemists, and water resource managers quickly proposed implementation of new control measures in response to T&O episodes, sometimes taking advantage of unique situations to reduce T&O problems at little or no cost. As a result, the quality of water delivered to consumers improved over the course of the project.

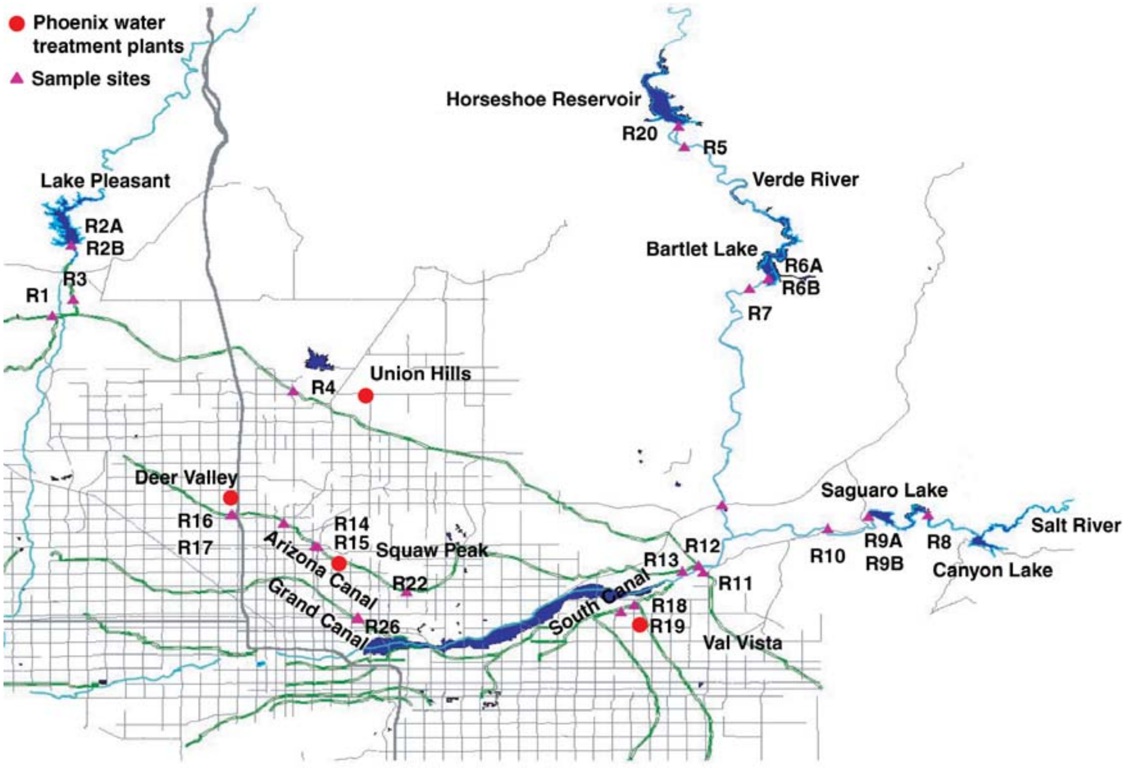
THE PHOENIX METROPOLITAN WATER SUPPLY SYSTEM

Surface water for municipalities in the Phoenix metropolitan area is supplied by the Salt River Project (SRP) and the Central Arizona Project (CAP), operated by the Central Arizona Water Conservation District (CAWCD). The SRP system includes water from the Salt River, which is impounded in a series of five reservoirs, and from the Verde River, which is impounded in two reservoirs, as shown in Figure 1.

The Verde River enters the Salt River upstream of the Granite Reef Reservoir. Granite Reef Reservoir is a small diversion reservoir that diverts the entire flow of the Salt River to the concrete-lined South and Arizona canals during normal (nonflooding) conditions. The South Canal delivers water to points south of the Salt River, and the Arizona Canal delivers water to points north of the Salt River. Together they deliver water to 12 WTPs. Under normal operation, most of the water delivered by SRP during the irrigation season (mid-May through mid-October) comes from the Salt River. SRP deliveries during the rest of the year come primarily from the Verde River.

The two lowest reservoirs on the Salt and Verde rivers were of particular interest in this study because some T&O problems originate in them. Saguaro Lake is a 69,765 acre-ft (85×10^6 m^3) pumped-storage reservoir used for hydroelectric power generation. It has a three-month hydraulic residence time (HRT). Water level is maintained at a near-constant depth. It receives water from a series of four upstream reservoirs with a combined total capacity of 2 mil acre-ft (2.5×10^9 m^3). Bartlett Lake, which receives water from Horseshoe Lake on the Verde River, is used primarily for flood control and water

FIGURE 1 Phoenix, Ariz., taste and odor project sampling areas



R—reservoir

supply, with no hydroelectric production. It has a maximum capacity of 178,186 acre-ft (219×10^6 m^3) and an HRT of 1.2 years. Water levels in Bartlett Lake can vary by up to 100 ft (32 m) during the year. Both reservoirs have a single outlet located near the bottom, and both exhibit summer thermal stratification and are isothermal during the winter. During the summer, the outlet withdraws water from the hypolimnion (bottom layer).

The CAP conveys water via concrete-lined, open-channel canals with pump stations from Lake Havasu along the Colorado River to the Phoenix area and points south. CAP water is stored in Lake Pleasant, an off-canal reservoir. In normal operation, Lake Pleasant is filled between mid-October through April, and water is released through a dual multilevel inlet/outlet tower during the irrigation season. Lake Pleasant is the largest of the study reservoirs, with a total capacity of 1,108,600 acre-ft ($1{,}364 \times 10^6$ m^3) and an HRT of 0.8 years. Water is released through two outlets: one at 1,506 ft (459 m) and one at 1,610 ft (491 m) above mean sea level. Like the SRP reservoirs, Lake Pleasant is monomictic (it stratifies in summer, but not in winter). The lower outlet is in the hypolimnion, and the upper outlet is in the epilimnion during summer stratification. CAP water is delivered to the Arizona Canal and the South Canal through the Granite Reef Interconnection Facility, where it mixes with SRP water. The proportion of CAP and SRP water delivered to the canals varies, depending on the water supply situation.

This project focused on five WTPs operated by the city of Phoenix. The Union Hills WTP is located on the CAP Canal approximately 20 mi (32 km) below Lake Pleasant. The Val Vista WTP is located on the South Canal approximately 1 mi (1.6 km) below its origin, and the Squaw Peak and Deer Valley WTPs are located on the Arizona Canal 9 mi (14.5 km) and 14 mi (22.5 km) from the head of the canal, respectively. The Verde WTP, located near the mouth of the Verde River, is operated occasionally but is not in regular operation. All five plants are conventional in design, with coagulation/flocculation, sedimentation, and filtration processes. None has special T&O unit operations such as granulated activated carbon or ozonation, but the WTPs can feed powdered activated carbon (PAC) at the head of the plant, which is subsequently removed by sedimentation and filtration.

Other municipalities in the metropolitan area operate approximately seven WTPs. Several WTPs use ozone with granular activated carbon (GAC) filtration/biofiltration or microfiltration with deep-bed GAC adsorption in part to manage T&O. The total capacity of all WTPs in the metropolitan area is 1,100 mgd (4.2×10^6 m^3/d).

TABLE 1 Evaluation of technical and economic/legal/institutional feasibility on T&O control measures evaluated during the first half of the project

Control Measure	Technical Feasibility	Economic/Legal/ Institutional Constraints	Overall Potential
Watershed nutrient control			
1. Alter Central Arizona Project canal pumping regime from Colorado River	May reduce nutrients but not necessarily T&O	Timing of pumping could be shifted	Low
2. Watershed nutrient control on Salt and Verde rivers	Nutrients near background levels	Not evaluated	Very low
Reservoir management			
3. Destratification	Uncertain measure for reducing T&O	Economically feasible	Further evaluation needed
4. Copper sulfate treatment	Possible short-term effectiveness	Expense ($140,000–$440,000 per treatment)	Low
5. Selective withdrawal (Lake Pleasant only)	Good potential; MIB lower in hypolimnion than epilimnion	Essentially no cost or institutional constraints	High*
6. Source selection (bypass pumping of Colorado River water; Lake Pleasant)	Can be used to avoid high MIB during turnover	Higher pumping cost	High*
7. Alum treatment of reservoirs	Would not necessarily reduce MIB	Up to $10 million per treatment	Low
8. Management of reservoir deliveries to avoid release of MIB	MIB would degrade in approximately one month	Deliveries cannot be altered	Very low
Canal management			
9. Blending of Salt River Project and Central Arizona Project surface waters	Theoretically reasonable	Institutional constraints limit blending	Moderate*
10. Copper sulfate treatment	Effective at reducing MIB production within canals for two to four weeks	Treatment cost is approximately $4,000 per site; 0.5-mg/L limit to avoid fish kills	High*
11. Lower nutrients in the canals	Could be done by reducing well pumping (high nitrate)	Cannot reduce pumping in irrigation season	Low
12. Chlorine treatment of canals	Would kill algae, but also fish	Fish kill unacceptable	Very low
13. Mechanical brushing of canal walls	Evaluated through field experiments and found to be acceptable	Reasonable cost if targeted (approximately $1,000/mi)	High*
Water treatment plants			
14. Source switching	WTPs receiving high-MIB water shut down; production is shifted to other WTPs	Other WTPs must have sufficient delivery and production capacity	High*
15. Pulsed prechlorination of forebays	Reduces algae growing within plants; may control in-plant MIB production	May not exceed MCLs for disinfection by-products	Moderate*
16. Addition of PAC	PAC could be used at all WTPs, with some limitations	PAC costs approximately $0.6–$1.5 million per year	Very high*
17. Retrofit existing filters with GAC without prechlorination	GAC removes MIB by adsorption/ biodegradation	High cost, but would achieve total organic carbon removal	Very high†
18. Incorporate ozone into treatment train	Ozone removes MIB, provides disinfection credit, but forms bromate	High cost and bromate MCL; lack of hydraulic head in most facilities	Low

GAC—granular activated carbon, MCL—maximum contaminant level, MIB—2-methylisoborneol, PAC—powdered activated carbon, T&O—taste and odor, WTP—water treatment plant

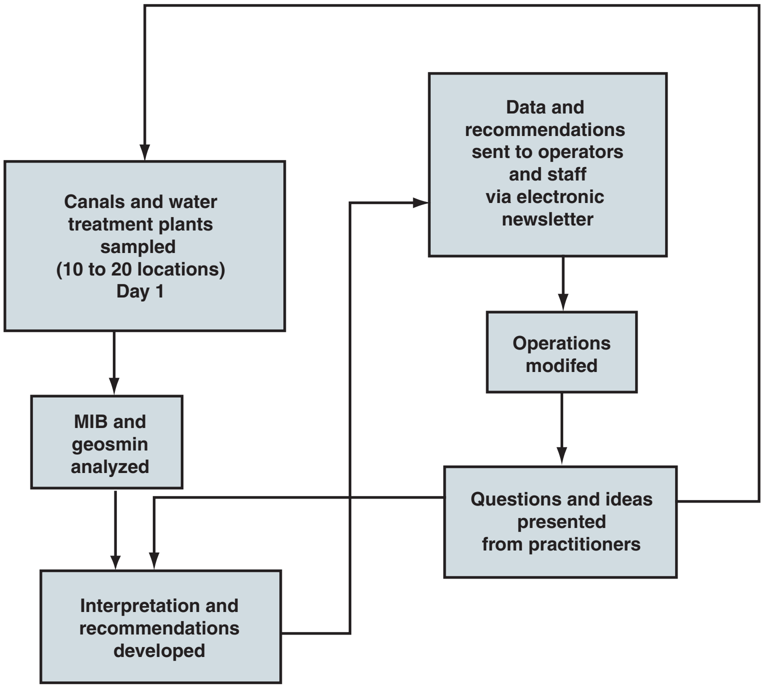
*Management practices that were implemented during this project.
†Practices that will be implemented in the near future.

PROJECT DESIGN

Multiple-barrier strategy. At the beginning of the project it was recognized that a multiple-barrier approach would be more reliable and cost-effective than relying on in-plant treatment alone (Baker et al, 2000; 1999). Potential barriers were evaluated for the watershed above the reservoirs, the major water storage reservoirs, the canal system, and the WTPs. Eighteen potential implementation measures were evaluated during the first half of the project on the basis of technical, economic, and political/legal feasibility, as shown in Table 1. (For a detailed evaluation, see Westerhoff et al, 2002.) To date, eight T&O management practices have been incorporated into the overall T&O management strategy (noted with asterisks in Table 1) and one (GAC filters) will be implemented within the next few years.

Monitoring network. An extensive monitoring program was developed both to develop a research database and to provide information to water resources managers and WTP personnel so that they could modify operations to accommodate changing conditions. Twenty-four sites were monitored at least monthly throughout the project (Figure 1). The canal and WTP sites, plus several additional canal sites, were monitored weekly during the T&O season, approximately June through November.

FIGURE 2 Communication and feedback loop schematic



MIB—2-methylisoborneol

Temperature, oxygen, and pH were measured in the field (including vertical profiles in the reservoirs), and Secchi disk transparency was measured in the reservoirs. Samples were collected for analysis of MIB and geosmin, total nitrogen, total dissolved nitrogen, total phosphorus, total dissolved phosphorus, chlorophyll a, and algal identification using *Standard Methods* (1995). T&O compounds were analyzed by solid-phase microextraction used with an autosampler and gas chromatography/mass spectrometry (GC/MS; Bruce et al, 2002; Watson et al, 2000; Lloyd et al, 1998). This technique allowed rapid turnaround for samples, usually within 48 h.

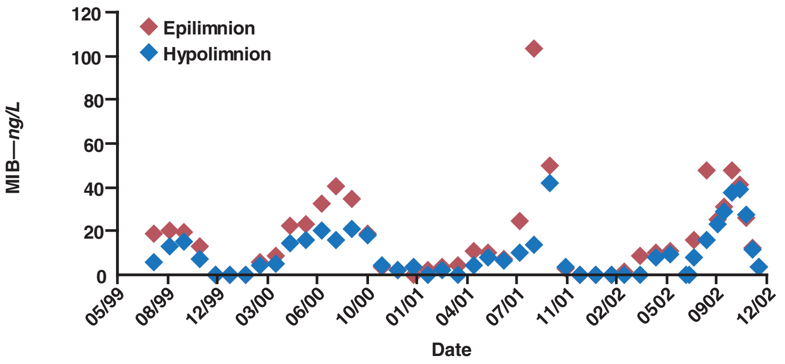
Laboratory and field experiments. Field monitoring was augmented by laboratory and field experiments. Algae were isolated and cultured to identify T&O–producing "culprit" organisms to determine the effect of environmental conditions on their production of T&O compounds and dissolved organic carbon. Other lab and field experiments were conducted to determine PAC adsorption isotherms and develop PAC selection and dosing criteria; evaluate the potential for oxidation of T&O compounds by ozone, chlorine, and chlorine dioxide; evaluate environmental conditions for the growth of isolated "culprit" algae; measure MIB degradation rates; examine the potential for MIB leaching from soils; and evaluate the effectiveness of canal treatments such as copper dosing and wall brushing (Hu et al, 2003; Bruce et al, 2002; Westerhoff et al, 2002).

Communication and feedback. A key element of the overall T&O management strategy was the development of a communication and feedback system between the city of Phoenix, SRP, CAWCD, and ASU. Formal communication occurred via two mechanisms. First, biannual forums were held throughout the project. These forums included ASU researchers and practitioners (WTP staff, water resource managers, and consultants) from municipalities throughout the metropolitan area. This gave practitioners continuous access to research progress and gave researchers greater insights into the practical, often changing realities of water treatment. Second, a newsletter was distributed at the beginning of the formal "implementation" phase (the middle of 2001). During the T&O season, the newsletter was disseminated weekly via e-mail to WTP operators, chemists, supervisors, and SRP and CAWCD staff. This enabled practitioners to respond quickly to changing conditions.

With rapid GC/MS analysis of MIB and geosmin, samples collected in the field could be analyzed within two days. Interpreting results and developing recommendations for treatment generally took another two days. Thus, the turnaround time from sample collection to receipt of data and recommendations was generally less than one week. The newsletter was sent (at no cost to recipients) to water treatment personnel and consultants in other regional municipalities who requested it, for a total "circulation" of approximately 80 people. The newsletter also created a dialogue for feedback from project participants and other "subscribers" to share observations and ideas, as shown in Figure 2. In addition to these formal mechanisms, extensive informal communication via e-mail and phone calls was stimulated by new findings that were reported in the newsletter.

Program evaluation. Because the goal of the program was to reduce the magnitude of the T&O problem, a metric was developed to incorporate three aspects of the problem as it affects municipal consumers: intensity, pop-

FIGURE 3 MIB concentrations in the epilimnion and hypolimnion of Saguaro Lake



MIB—2-methylisoborneol

ulation exposure, and duration. This metric was called the "consumer days below threshold" (CDBT). The intensity component was based on measured concentrations of T&O compounds. The reasons for focusing on MIB and geosmin were: (1) both compounds were found at levels that exceed sensory thresholds—commonly for MIB and less commonly for geosmin; (2) the musty/moldy odor of these compounds was commonly perceived; (3) MIB and geosmin were correlated with intensity of "musty/moldy" odors in flavor profile analysis (FPA) panels conducted by the city of Phoenix; and (4) analysis of other potential T&O–producing compounds (*cis*-3-hexen-1-ol, *cis*-3-hexenyl acetate, 2-isobutyl-3-methoxypyrazine, 2,4,6-tribromoanisole, and cyclocitral) showed that only one of them, cyclocitral, was present at concentrations (2–30 ng/L) that would be perceived, and the characteristic odor of this compound (hay/woody) was not noted.

For most samples, MIB concentrations were much greater than geosmin levels. Determining a threshold concentration was somewhat subjective, as sensory thresholds vary among individuals, among days for specific individuals, and as a function of other compounds in the water, especially chlorine (Lin et al, 2002; Young et al, 1996). For example, Young et al reported geometric mean MIB thresholds of 15 ng/L for taste and 18 ng/L for odor, but some individuals on their trained panels were able to detect concentrations as low as 2.5 ng/L (taste) and 6 ng/L (odor). However, it may not be necessary or practical to reduce MIB levels below the sensory thresholds of sensitive individuals. Concentrations of 5–10 ng/L often impart a "slight" earthy flavor, whereas a concentration greater than 30 ng/L typically induces a "moderate" earthy flavor. For the Phoenix FPA panelists, 72% of the time when odors were rated as "objectionable," MIB levels were >10 ng/L.

On the basis of these experiments, benchmark concentrations of 10 and 20 ng/L for evaluation were established. Because MIB concentrations often exceeded 50 ng/L in canals and reservoirs, keeping concentrations below 20 ng/L in the drinking water system would represent a significant improvement. Many individuals perceive 10 ng/L of MIB, but most would likely not experience an objectionable response. Because geosmin has roughly the same sensory threshold levels as MIB (Young et al, 1996), the 10- and 20-ng/L benchmarks were also used for geosmin.

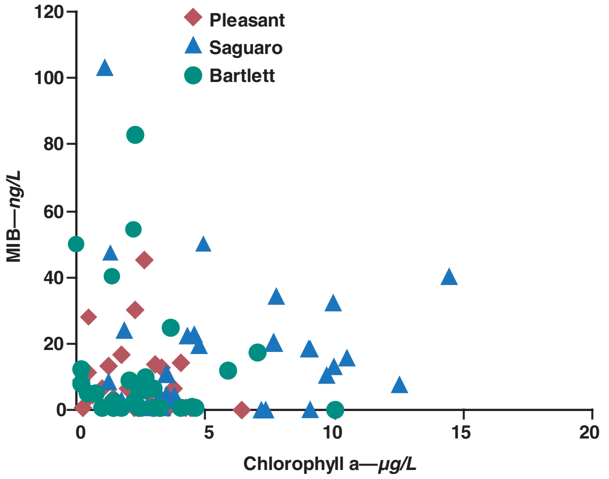
The population exposure and duration aspects of the CDBT metric were developed using measured concentrations of MIB and geosmin in the effluent of each WTP in conjunction with the total number of consumer days for each plant. For a given WTP, the number of consumer days (CDs) for a month is shown in Eq 1:

$$\text{CDs} = \frac{\text{Average daily water production}}{\text{Average per capita water used}} \qquad (1)$$

in which CDs are the total number of consumer days, average daily water production is gal/d × number of days in the month, and average per capita water used is measured in gal/d.

Average daily water production was determined for each treatment plant for each month of the year. Average

FIGURE 4 Chlorophyll a versus MIB in three study reservoirs



MIB—2-methylisoborneol

per capita water use for each month was computed from total water production for the city (sum of all five plants) and the service population. When MIB and geosmin concentrations were both below benchmark values, CDBTs accrued. Thus, for a given WTP and month, CDB-10 equals the number of consumer days with MIB <10 ng/L and geosmin <10 ng, or 0 otherwise, and CDB-20 equals the number of consumer days with MIB <20 and geosmin <20, or 0 otherwise.

CDB-10s and CDB-20s were then summed for all treatment plants for each month, each year, and the entire project period. This metric was used to evaluate the effectiveness of specific treatments, the contribution of various control measures on overall program effectiveness, and year-to-year trends in the magnitude of the T&O problem.

RESULTS AND DISCUSSION

Temporal and spatial dimensions of the problem. MIB concentrations in all three lakes rose to undesirable levels during the summer and early fall periods, then declined rapidly. This is illustrated for Saguaro Lake in Figure 3. During the lake stratification period, MIB levels in the epilimnion were generally higher than levels in the hypolimnion. The largest divergence occurred in Saguaro Lake during September 2001 when MIB concentrations were 105 ng/L in the epilimnion and 14 ng/L in the hypolimnion.

FIGURE 5 MIB concentrations in Salt River and Central Arizona Project source waters entering the Arizona Canal

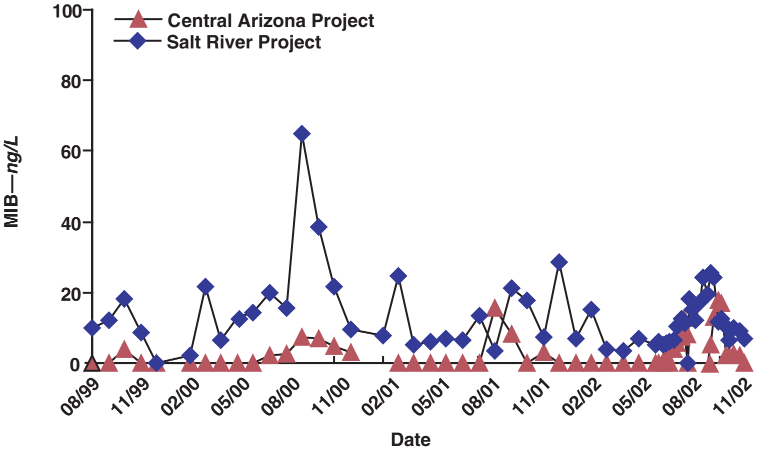
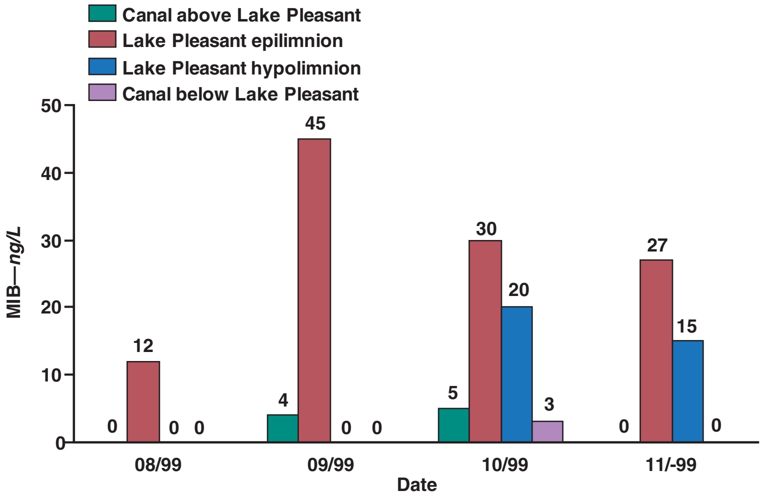


FIGURE 6 MIB in the Central Arizona Project Canal above and below Lake Pleasant and in the epilimnion and hypolimnion of Lake Pleasant in Fall 1999

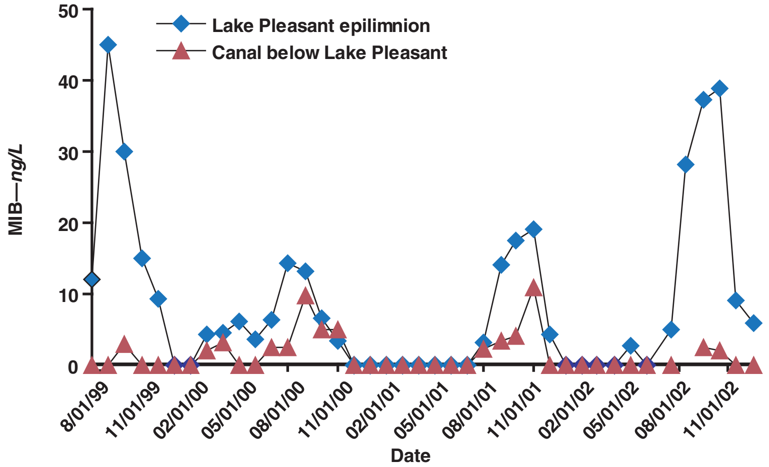


MIB—2-methylisoborneol

All three lakes experienced epilimnetic MIB concentrations >40 ng/L. During turnover, MIB levels increased in bottom waters, the result of mixing low-MIB hypolimnetic water with high-MIB epilimnetic water. This resulted in MIB episodes following turnover. MIB concentrations were not significantly correlated with chlorophyll a in any of the lakes (Figure 4) and were only weakly correlated with planktonic cyanobacterial abundance. This observation contrasts with several studies of smaller lakes and impoundments that show an association between chlorophyll a and tastes and odors (Smith et al, 2002; Walker, 1992; Arruda & Fromm, 1989). In these studies, T&O–producing algae were dominant organisms, whereas in this study, MIB–producing algae (confirmed by isolation experiments) were never dominant.

Water supplied by the SRP system had longer periods with elevated MIB levels than water supplied by the CAP system, as shown in Figure 5, in part because the operation of Lake Pleasant was modified early in the project to prevent release of high-MIB water (discussed later in this article). MIB was also produced by periphyton (attached algae) growing on the walls and bottom of the Arizona Canal. MIB concentrations at the Deer Valley WTP (20 mi [32 km] below the head of the canal) were up to 50

FIGURE 7 MIB in the epilimnion of Lake Pleasant and the Central Arizona Project Canal below Lake Pleasant (near the Union Hills WTP) from mid-1999 through 2002



MIB—2-methylisoborneol, WTP—water treatment plant

ng/L higher than MIB concentrations at the upper end of the canal.

An exhaustive effort to isolate specific cyanobacteria or algae responsible for producing MIB or geosmin from samples collected throughout the reservoir and canal system identified less than 10 producer taxa, including two *Pseudoanabaena* spp. and a *Phormidium* that produced MIB and two *Oscillatoria* spp. that produced geosmin (Westerhoff et al, 2002). The observation that very few species are responsible for T&O problems is consistent with observations in California reservoirs (Taylor et al, 1994; Izaguirre et al, 1982).

Effectiveness of individual management practices. Of the 18 management practices evaluated, eight were implemented at the operational scale. For discussion, the eight implemented practices are grouped into four categories: (1) modified reservoir operation (source selection and selective withdrawal in Lake Pleasant only); (2) PAC treatment; (3) source switching to avoid T&O episodes; and (4) canal treatments to remove culprit algae. Although the original plan had distinct research and implementation phases, once the project started, T&O control practices were implemented as soon as their effectiveness became apparent.

Modified operation of Lake Pleasant. Among the three lowest reservoirs in the source water system, Lake Pleasant was the most amenable to modified reservoir operation because it is an off-stream reservoir with dual-level outlet structures. Because it is an off-stream reservoir, water from the Colorado River can be delivered directly to the Phoenix area via the CAP Canal, a procedure termed "bypass pumping." Before 1999, normal operation was to fill the reservoir with Colorado River water in the winter, then release water from the upper outlet to Lake Pleasant throughout the irrigation season, with no bypass pumping. This operational plan released epilimnetic water with elevated MIB levels in late summer and fall. In mid-1999, the CAWCD responded to consumer complaints by switching to hypolimnetic release, as shown in Figure 6. This kept MIB levels <10 ng/L until lake turnover, even though MIB levels in the epilimnion increased to 45 ng/L in September.

When turnover started in October, the MIB concentration in the bottom water increased to 20 ng/L (Figure

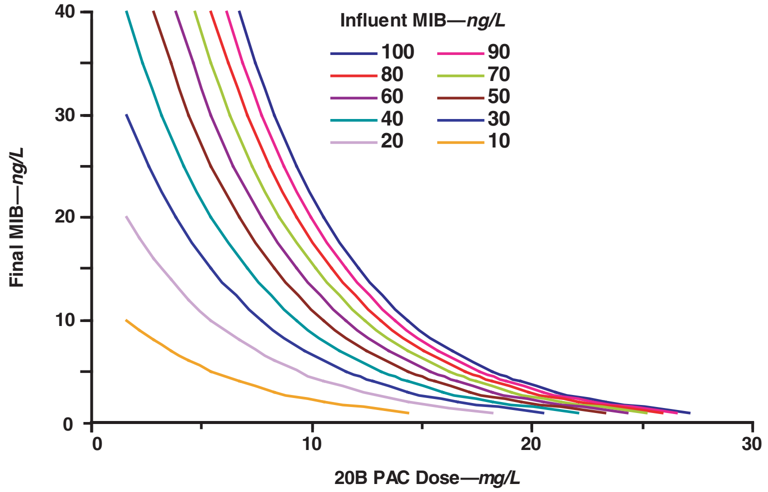
TABLE 2 Effect of altered operation of Lake Pleasant on CDs < 10 and 20 ng/L at the Union Hills water treatment plant

Parameter	CDs per years 2000	2001	2002
Total consumer days	163	174	160
Effect of Lake Pleasant operation on CDs <20 ng/L			
Observed (modified reservoir management)	163	174	160
Likely with prior management practice	163	174	127
Gain from management (% of total)	0 (0)	0(0)	33 (21)
Effect of Lake Pleasant operation on CDs <10 ng/L			
Observed (modified reservoir management)	163	162	160
Likely with prior management practice	137	132	127
Gain from management (% of total)	26 (16)	30 (17)	33 (21)

CDs—consumer days

6). At this time, deliveries from the reservoir were stopped and bypass pumping was used to deliver Colorado River water downstream, keeping MIB <5 ng/L throughout October and November. Modified operations, guided by monitoring data, were used throughout 2000, 2001, and 2002, keeping MIB in the CAP Canal below Lake Pleasant <10 ng/L on all but one occasion, as shown in Figure 7. By adopting this strategy, the Union Hills WTP has been able to provide customers water with little or no discernable tastes. The hypolimnetic water is anoxic and sometimes contains manganese, but this is readily removed with permanganate. As an additional precaution, copper sulfate is often added to the plant forebay to prevent algal growth within the plant.

FIGURE 8 MIB adsorption isotherm* for Norit 20B



MIB—2-methylisoborneol, PAC—powdered activated carbon

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The effect of this management practice was estimated by comparing CDB-10s and CDB-20s at the inlet to the Union Hills WTP with CDB-10s and CDB-20s that would have occurred if water had been released from the epilimnion of Lake Pleasant (Table 2). The difference between these two values is the gain in CDs attributable to modified reservoir operation. Because MIB in the epilimnion was <20 ng/L throughout 2001 and 2002, no gains in CDB-20s accrued by improved reservoir management. During 2002, MIB concentrations >20 ng/L in the epilimnion were observed (Figure 7), but hypolimnetic release prevented this MIB from entering the CAP Canal, resulting in a gain of 33 mil CDB-20s (21% of the CDs for 2002). MIB levels in the epilimnion of Lake Pleasant often were >10 ng/L, so improved reservoir operation added 26–33 mil CDB-10s, which was 16–21% of total CDs for those years.

The cost of switching releases from the upper to lower outlet was zero. Bypass pumping added cost because energy prices vary throughout the year. The same total amount of water is pumped with or without bypass pumping, but the cost of utilizing bypass pumping in late summer rather than in fall (the usual time for reservoir filling) is higher because energy costs are higher in the summer. It has been estimated that this differential was approximately \$21/acre-ft (\$17/1,000 m^3) based on 2000 energy costs (Kacerek, 2006). This was considered a modest cost for nearly eliminating T&O problems on the CAP Canal.

PAC treatment. All of Phoenix's WTPs have the capacity to add PAC during T&O episodes. PAC kinetics and dose–response experiments in raw and coagulated waters for MIB and geosmin removal were used to select an optimum PAC brand in 1999 (Bruce et al, 2002). PAC adsorption isotherms were conducted to determine MIB removal for various PAC brands. The selection of a PAC brand[1] (Figure 8) from more than 10 brands was based on MIB removal and cost specification rather than on the lowest bid alone. An index value was computed as shown in Eq 2:

$$\text{Index value} = [\%\ \text{MIB remaining}] \times [\text{price per pound}] \quad (2)$$

The index value was computed for the 5- and 15-mg/L PAC doses. The PAC brand with the lowest index value represents the most cost-effective supplier of PAC. PAC feed facilities at the WTPs were limited to 15 mg/L, so the selection of the PAC brand was critical in achieving improved MIB and geosmin removals. The selection of the best PAC must be determined empirically for each source water situation.

From mid-2001 through 2002, WTP operators were provided with MIB-monitoring results in source water and product water at least once a month (weekly during the T&O season), along with recommended PAC doses (based on Figure 8), via the T&O newsletter. In practice, widespread implementation of PAC dosing at recommended levels was slowed by limited PAC storage capacity, clogged feed lines, and slow delivery times for new PAC. The latter problem was exacerbated by the terrorist attacks on September 11, 2001.

The average actual operational efficiency of PAC treatment during periods when inlet MIB concentrations were >10 ng/L was 28% in 2001 and 30% in 2002. Significant cost savings were realized by monitoring, even after accounting for monitoring costs, because PAC was added

TABLE 3 Effect of PAC treatment on CDs* < 10 and 20 ng/L for Phoenix water treatment plants

	CDs per years		
	2000	**2001**	**2002**
Total CDs	441	447	458
Effect of PAC treatment on CDs <20 ng/L			
Observed (with PAC)	391 (88%)	417 (95%)	435 (95%)
Without PAC (estimated)	370 (84%)	376 (84%)	439 (96%)
Gain from PAC	21 (6%)	41 (9%)	–4 (–1%)
Effect of PAC treatment on CDs <10 ng/L			
Observed (with PAC)	310 (70%)	324 (72%)	346 (76%)
Without PAC (estimated)	251 (57%)	282 (63%)	331 (72%)
Gain from PAC	59 (19%)	42 (13%)	15 (4%)

CDs—consumer days, PAC—powdered activated carbon

*In millions

only when needed and only at concentrations needed to reduce MIB and geosmin to 10 ng/L.

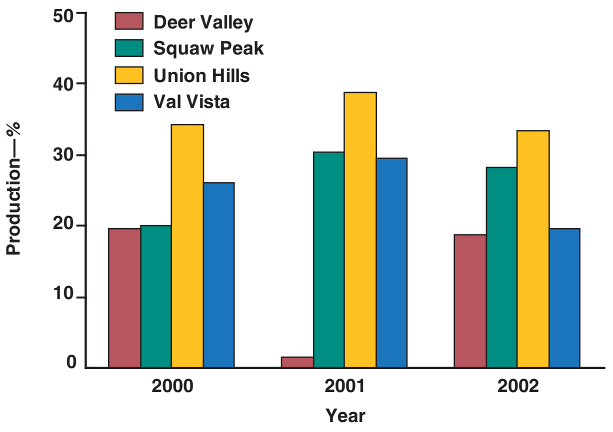
The effect of PAC treatment was calculated by comparing CDs when MIB and geosmin were < 10 and 20 ng/L in the inlet and outlet of each WTP (Table 3). This calculation assumes that in the absence of PAC treatment, CDB-10s and CDB-20s would be the same at the inlet and the outlet of each WTP. PAC treatment had a modest effect on T&O reduction, increasing CDB-20s by 6 and 9% in 2000 and 2001, respectively, and increasing CDB-10s by 19, 13, and 4% in 2000, 2001, and 2002, respectively.

In 2002, computed PAC treatment increased CDB-20s by 1%. The relatively small gains in CDBT values belies the effect of PAC treatment, because MIB levels were generally below benchmark values in the inlets to the WTPs (84–96% for CDB-20s and 57–76% for CDB-10s, as shown in Table 3). From this perspective, a gain in CDs from 5–10% is a big reduction in the T&O problem. The effect of PAC treatment would also have been higher in 2001 if the Deer Valley WTP had been operated throughout the T&O season. Instead, source switching reduced the need for PAC treatment. PAC treatment is important during years in which upstream reductions of T&O problems could not be accomplished. Finally, upgrades to the PAC storage capacities and feed pumps and installation of GAC filter caps would increase treatment efficiencies and contribute to increasing the number of CDB-10s and CDB-20s gained by PAC treatment.

Source switching. MIB concentrations usually increase as water moves along the Arizona Canal, because some species of blue-green algae attached to the walls and bottom of the canal produce MIB. Because of this, the Deer Valley WTP, located farthest downstream from Granite Reef Reservoir, receives the poorest quality water among Phoenix's WTPs. Deer Valley also had limited capacity to feed PAC. In 2001, the Deer Valley WTP received water with particularly high MIB concentrations. The plant was shut down for much of the year, and production was shifted to the other WTPs, all of which generally receive water with lower MIB and geosmin concentrations (Figure 9). The practice, termed "source switching," was successful at reducing T&O problems for consumers.

The effect of source switching was estimated by comparing the number of CDB-10s and CDB-20s that would have occurred if source switching had not been used. This calculation required two assumptions: (1) in the absence of source switching, monthly water production by each WTP in 2001 would have been the same as it was in 2000 and (2) if Deer Valley had been operating, it would have been using PAC with 30% treatment efficiency (the average plant-scale treatment efficiency for the Phoenix WTPs). On the basis of these assumptions, source switch-

FIGURE 9 Water production at Phoenix, Ariz., water treatment plants, 2000–2002



ing in 2001 had a major effect on the T&O problem, increasing CDB-20s by 54 million and CDB-10s by 50 million (Table 4).

TABLE 4 Effect of source switching on CDs* < 10 and 20 ng/L in 2001, using 2000 as a baseline

	CDs per years	
	2000	**2001**
Total CDs	441	447
Effect of source switching on CDs <20 ng/L		
With source switching	391	417
Without source switching	391	363
Gain by source switching in 2001	0	54
Effect of source switching on CDs <10 ng/L		
With source switching	310	324
Without source switching	310	274
Gain by source switching in 2001	0	50

CDs—consumer days

*In millions

Source switching also reduced water production costs by reducing PAC requirements and, because the Deer Valley WTP is lower in elevation than the other WTPs, by reducing pumping costs. For most years, source switching is limited because it requires full production capacity of the upstream WTPs, which is often not possible because of partial maintenance shutdowns and construction.

Canal treatments. MIB production often occurred within the Arizona Canal. Production was most often localized in "hot spots" that could be targeted by weekly monitoring. Treatments included physical cleaning of the walls by brushing and copper application (Hu et al, 2003). Brushing canal walls was done using a customized, hydraulic street sweeper brush attached by a long arm to a tractor. The tractor could clean both walls of the canal at a rate of approximately 1 mi (1.6 km) per day, but the brushing apparatus could not clean the bottom of the canal.

During 2001, SRP used a proprietary chelated copper product[2] at copper dosages of 0.2–0.5 mg/L over a reach of the concrete-lined canal (2–4 mi [3–6 km]). Use of this product was discontinued in 2001, after lab experiments and field observations revealed that it exerted chlorine demand with concurrent production of chloramines. This would be undesirable in the WTPs because formation of chloramines would decrease disinfection efficiency. From that point on, copper sulfate[3] was used. In both cases, copper solution was added from a mixing tank to achieve a total copper concentration of 0.5 mg/L in the canal for a period of 8 h. The effect of copper on periphyton was visible, causing bleaching of the periphyton. The manufacturer of the chelated copper product has recently modified its formulation and states that free-chlorine consumption no longer occurs.

The effect of canal treatments can be seen in a plot of MIB gain in the Arizona Canal (Figure 10). MIB gain was the difference between MIB concentrations at the Deer Valley WTP and at the head of the Arizona Canal just below the point where CAP and SRP waters were mixed. Data for 2002 suggest that canal treatments were effective. The first copper treatment (8 h, added at 0.5 mg/L) occurred August 30. The MIB gain dropped from 19 ng/L just before treatment (August 26) to 3 ng/L September 3, but then started to climb again. Copper was added again near the head of the canal September 14, followed by brushing of a 2-mi "hot spot" located approximately 3 mi above the Deer Valley WTP September 19. The MIB gain dropped from 21 ng/L September 16 to 15 ng/L September 23, and the trend continued downward through October 7 (8 ng/L).

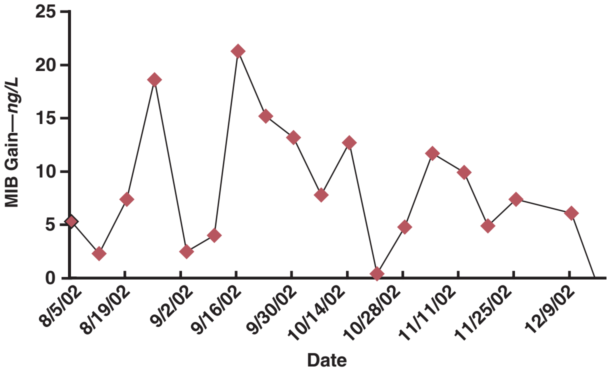
These data suggest the copper treatments were successful in reducing MIB. However, there was no side-by-side control, so the downward trend following canal treatments cannot be definitively attributed to copper treatment. It appears that canal treatments at least halted the increase in MIB gains and prevented extreme MIB episodes like those observed in 2000 and 2001, when MIB gains often exceeded 40 ng/L.

Canal treatments would probably never eliminate MIB gains in the Arizona Canal, but it is a cost-effective, ancillary tool that could reduce the cost of PAC treatment. For example, if a copper treatment reduced MIB concentrations from 40 to 20 ng/L at the inlet to the Deer Valley WTP, the cost of PAC needed to reduce MIB to 10 ng/L at the WTP would be reduced by approximately $1,000 per day. Because each copper treatment costs approximately $5,000–$10,000 (depending on point of application), the break-even point would occur if the treatment was effective for only 5–10 days. Observations from 2001 and 2002 (not shown) suggest that copper treatments are effective for two to three weeks.

Overall program evaluation. The CDBT metric was used to evaluate the overall success of the program and the effect of several individual T&O control measures for 2000, 2001, and 2002 (Table 5). The control measures include modified Lake Pleasant operation, source switching, and PAC treatment. One other measure—the blending of SRP and CAP water at the head of the Arizona Canal—was used only once as a deliberate T&O control measure for approximately two weeks.

The effectiveness of individual control measures varied considerably for several reasons. First, hydrologic and climatic conditions differed among years. In gen-

FIGURE 10 Water production at Phoenix, Ariz., water treatment plants, 2000–2002



MIB—2-methylisoborneol

eral, 2002 was a "good" year—there probably would have been 419 mil CDB-20s (91% of all CDs) in the absence of a T&O management program. T&O management added another 15 mil CDB-20s, bringing the total to 95% of all CDs. In contrast, T&O problems were more serious in 2001. Without management, there would have been only 322 CDB-20s, approximately 72% of total CDs.

Second, opportunities for specific management options varied among years. In 2001, Phoenix had excess capacity at some treatment plants because of minimal maintenance shutdowns, giving it the opportunity to shift production from the Deer Valley WTP to other WTPs. Source switching added 54 mil CDB-20s. Because MIB levels at several WTP influents were often high, use of PAC added another 41 mil CDB-20s.

The effectiveness of control measures also depended on the benchmark value (10 or 20 ng/L). Modified Lake Pleasant operation didn't add any CDB-20s, because there weren't many days in which the MIB concentration of water released from Lake Pleasant would have been >20 ng/L, even without management. However, modified Lake Pleasant operation was consistently important in keeping MIB levels <10 ng/L, adding 26–33 mil CDB-10s annually (Table 5).

Overall, the T&O management program added an average of 43 mil CDB-20s per year, increasing the percentage of CDB-20s from 83% of total CDs without management to 92% with management. For the 10-ng/L benchmark, the T&O management program added an average of 93 mil CDs per year, increasing the percentage of CDB-10s from 52% without management to 73% with management. These calculations do not include benefits to other cities that share the water supply system, which were considerable. For the period of August–October, the height of the T&O problem, CDB-20s increased steadily from 60% of total CDs in 1999 to 96% in 2002. Planned upgrades in PAC delivery systems for several WTPs should increase the percentage of CDs below T&O benchmark values even further.

Adaptive management framework. A unique aspect of this project was a high degree of interaction between researchers and practitioners, developed through biannual forums and a newsletter. Originally envisioned as a method to simply disseminate sampling results and PAC feed recommendations quickly to WTP operators and others, the newsletter rapidly evolved into a continuous, widespread dialogue among researchers and practitioners.

Once provided with information, WTP operators and chemists and water resource managers quickly proposed implementation of control measures. For example, source switching, not envisioned at the beginning of the project, was suggested by Phoenix's water resource manager at one of the forums in response to observations of rising MIB levels in the canal. The measure was immediately used in mid-2001 with considerable success. By 2002, at least a dozen suggestions regarding modifications of control treatments had developed through these dialogues.

An important aspect of the T&O management program was that constant feedback allowed participants to adapt to changing conditions—the essence of adaptive management. Modified operation of Lake Pleasant worked well throughout the project, guided by weekly feedback from the monitoring network. On the other hand, source switching worked well in 2001, because unique circumstances allowed it, but it was not an important management practice in 2000 or 2002. There was no opportunity to use blending of CAP and SRP water to a great extent during the three-year project period, but under certain circumstances, blending could be quite effective.

Although the project initially envisioned using a command-and-control strategy, the project evolved into a case study of adaptive management. In the process, a considerable democratization process was observed, in which WTP staff at all levels felt empowered by information to develop new ideas. In a few cases, the lag between observation of a T&O episode and a new management concept was as short as a few days. Very often, the emergence of a T&O episode would generate a flurry of e-mail among ad hoc subgroups to examine solutions, with implementation of management practices occurring within days to weeks.

Adaptive management has considerable potential for regional water quality management. Because it has a strong democratic element, it is well-suited to informal collaboration among multiple entities (e.g., cities) that share common goals but are not part of an overarching bureaucracy. Although the T&O problem could have been addressed by brute force (e.g., continuous PAC treatment at high dosages), the use of multiple barriers, continuous monitoring, and feedback—with PAC as one of several treatment options—was far less expensive, even when monitoring costs were included.

TABLE 5 Effectiveness of overall T&O management strategy on CDs* < 10 and 20 ng/L

	CDs per years		
	2000	2001	2002
Total CDs	441	447	458
Effect of overall management strategy on CDs <20 ng/L			
CDB-20s (measured)	391	417	435
Likely CDB-20s without management	370	322	419
Implemented management options:			
Lake Pleasant operation	0	0	0
In-plant treatment	21	41	-4
Source switching	0	54	20
Sum of control measures	21	95	15
Effect of overall management strategy on CDs <10 ng/L			
CDB-10s (measured)	310	324	346
Likely CDB-10s without management	225	198	279
Implemented management options:			
Lake Pleasant operation	26	30	33
In-plant treatment	59	42	15
Source switching	0	54	20
Sum of control measures	85	126	68

CDs—consumer days, CDB-10—the number of consumer days when MIB <10 ng/L and geosmin <10 ng/L, or 0 otherwise, CDB-20—the number of consumer days if MIB <20 ng/L and geosmin <20 ng/L, or 0 otherwise, MIB—2-methylisoborneol

*In millions

Adaptive management is also well-suited to addressing multiple water quality problems. In the Phoenix region, these include disinfection by-products, arsenic, emerging contaminants, salinity, and others—all interrelated problems that are part of the complex urban water environment. Rapid advances in ground-based and airborne remote-sensing technology and the requisite cyberinfrastucture to communicate, store, and manage data have greatly enhanced the potential for applying adaptive management concepts to water quality management in the twenty-first century.

CONCLUSIONS

The T&O management strategy developed in this project had several features that contributed to its success. First, it utilized a multiple-barrier approach, taking advantage of the configuration of the system to use appropriate barriers in the supply reservoirs, the canals, and the treatment plants. At least three barriers (source switching, modified reservoir operation of Lake Pleasant, and PAC treatment) contributed quantifiable gains in CDB-10s and/or CDB-20s. Canal treatments probably helped lower PAC costs, and blending—though not widely used—would be useful under circumstances not encountered in the three-year project. The implemented T&O management program taken as a whole substantially increased the percentage of CDs below each of the benchmark values. Second, the project involved continuous monitoring throughout the water supply system. This was essential for cost-effectiveness of PAC treatment. Third, the project developed an adaptive management framework, characterized by monitoring, feedback, and flexible management. The adaptive aspect was important, enabling Phoenix's WTP staff to take opportunities that could not necessarily be envisioned in an inflexible command-and-control management strategy.

Although this project focused on tastes and odors, general aspects of the management strategy—the use of multiple barriers, continuous monitoring for efficient operational control, and the flexibility provided by adaptive management—are broadly applicable to regional water management strategies to address multiple water quality issues. With growing demand for urban water supply and a finite supply of high-quality freshwater, cities throughout the world will find it increasingly necessary to adopt regional adaptive management strategies to be able to provide their citizens safe and aesthetically acceptable water.

ACKNOWLEDGMENT

The authors thank Edna Bienz, Alice Brawley-Chesworth, Nicole Bugila, Keith Greenburg, Yu-Chu Hsu, Maureen Hymel, Dick Musil, and Kevin Williams from the city of Phoenix; Gregg Elliott, Brian Moorehead, and Dallas Reigel from SRP; and Tim Kacerek from CAWCD. The authors also thank their ASU collaborators: Darlene Bruce, Thomas Dempster, Mario Esparza, Kirsten Hintze, David Lowry, Marisa Masles, My-Linh Nguyen, and Qiang Hu. Early conceptualization of this project was developed with Mike Gritzuk, Matt Palenica, Bob Hollander, Randy Gottler, Jennifer Calles, and Walid Alsmadi from the city of Phoenix. The insights provided by Bill Taylor from the Metropolitan Water District of Southern California, who served as an external advisor, were greatly appreciated.

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FOOTNOTES

[1] Norit 20B, Norit Americas, Inc., Marshall, Texas

[2] Cutrine-Plus, Applied Biochemists, Inc.

[3] Earthtec, Earth Science Laboratories, Rogers, Ark.

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REFERENCES

Arruda, J.A. & Fromm, D., 1989. The Relationship Between Taste and Odor Problems and Lake Enrichment From Kansas Lakes in Agricultural Watersheds. *Lake & Reservoir Mgmt.,* 5:45.

Baker, L.A. et al, 2000. Multiple Barrier Approach for Controlling Taste and Odor in Phoenix's Water Supply System. Proc. Water Quality Technology Conf., Salt Lake City.

Baker, L.A.; Westerhoff, P.; & Sommerfeld, M., 1999. Multibarrier Concept for Taste and Odor Control. Proc. North American Lake Management Society Conf., Reno, Nev.

Bruce, D.; Westerhoff, P.; & Brawley-Chesworth, A., 2002. Removal of 2-methylisoborneol and Geosmin in Surface Water Treatment Plants in Arizona. *Jour. Water Supply Res. & Technol.—Aqua,* 51:4:183.

Gunderson, L.H. & Holling, C.S., 2002. *Panarchy: Understanding Transformations in Human and Natural Systems.* Island Press, Washington.

Hu, Q. et al, 2003. Canal Wall Brushing: A Control Measure for Taste and Odor Problems in Drinking Water Supplies in Arid Environments. *Jour. Water Supply Res. & Technol.—Aqua,* 52:8:545.

Izaguirre, G. et al, 1982. Geosmin and 2-methylisoborneol From Cyanobacteria in Three Water Supply Systems. *Appl. & Envir. Microbiol.* 43:708.

Kacerek, T., 2006. Personal communication.

Krasner, S.W., 1988. Analytical Methods for the Identification and Quantification of Earthy/Musty Flavors in Drinking Water: A Review. *Water Quality Bulletin,* 13:78.

Krasner, S.W.; McGuire, M.J.; & Ferguson, V.B., 1985. Tastes and Odors: The Flavor Profile Method. *Jour. AWWA,* 77:3:34.

Lin, T.F.; Wong, J.Y.; & Kao, H.P., 2002. Correlation of Musty Odor and 2-MIB in Two Drinking Water Treatment Plants in South Taiwan. *Sci. Total Envir.,* 289:225.

Lloyd, S.W. et al, 1998. Rapid Analysis of Geosmin and 2-methylisoborneol in Water Using Solid-phase Micro Extraction Procedures. *Water Res.,* 32:7:2140.

McGuire, M. J. et al, 1981. Closed-loop Stripping Analysis as a Tool for Solving Taste and Odor Problems. *Jour. AWWA,* 73:10:530.

Means, E.G. & McGuire, M.J., 1986. An Early Warning System for Taste and Odor Control. *Jour. AWWA,* 78:3:77.

Smith, V.H. et al, 2002. Managing Tastes and Odor Problems in a Eutrophic Drinking Water Reservoir. *Lake & Reservoir Mgmt.,* 18:4:319.

Standard Methods for the Examination of Water and Wastewater, 1995 (19th ed.). APHA, AWWA, & WEF, Washington.

Suffet, I.H.; Anselme, C.; & Mallevialle, J., 1996. AWWA Taste and Odor Survey. *Jour. AWWA,* 88:4:169

Suffet, I.H.; Khiari, D.; & Brucher, A., 1999. The Drinking Water Taste and Odor Wheel for the Millennium: Beyond Geosmin and 2-methylisoborneol. *Water Sci. & Technol.,* 40:6:1.

Taylor, W.D. et al, 1994. Application of Limnological Principles for Management of Taste and Odor in Drinking Waters: A Case Study. Proc. AWWA WQTC, San Francisco.

Walker, W.W., 1992. *Analysis of 1990–1992 Monitoring Data From the Vadnais Lakes Diagnostics Study.* The Board of Water Commissioners, St. Paul, Minn.

Watson, S.B. et al, 2000. Quantitative Analysis of Trace Levels of Geosmin and MIB in Source and Drinking Water Using Headspace SPME. *Water Res.,* 34:10:2818.

Westerhoff, P.; Sommerfeld, M.; & Baker, L., 2002. Reducing Taste and Odor and Other Algae-related Problems for Surface Water Supplies in Arid Environments. http://ceaspub.eas.asu.edu/pwest/myweb/Taste%20and%20Odor%20Stuff/Final%20Report-August2002.pdf (accessed April 2006).

Wnorowski, A.U., 1992. Tastes and Odors in the Environment: A Review. *Water SA,*18:3:203.

WQA (Water Quality Association), 2001. *National Consumer Water Quality Survey.* WQA, Lisle, Ill.

Young, W.F. et al, 1996. Taste and Odor Threshold Concentrations of Potential Potable Water Contaminants. *Water Res.,* 30:2:331.