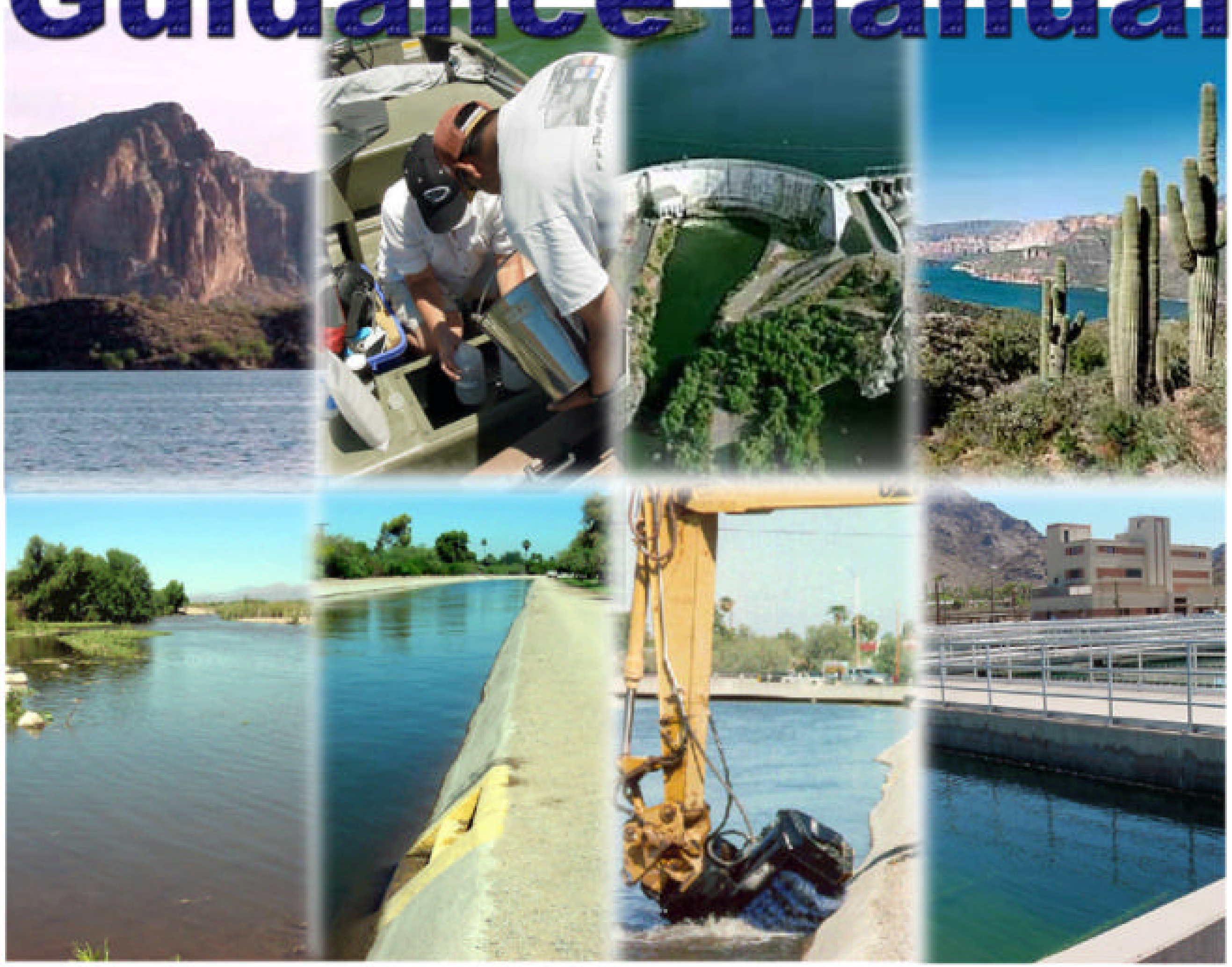
Guidance Manual



Reducing 2-Methylisoborneol (MIB) and Geosmin in the Metropolitan-Phoenix Area Water Supply

A Cooperative Research and Implementation Program by
Arizona State University
City of Phoenix
Salt River Project
Central Arizona Project

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Guidance Manual

for

Reducing 2-Methylisoborneol (MIB) and Geosmin in the Metropolitan-Phoenix Area Water Supply

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ACRONYMS

ADEQ – Arizona Department of Environmental Quality
AF/Day – acre-feet per day
CAP – Central Arizona Project
CAWCD – Central Arizona Water Conservation District
CFS – Cubic feet per second
COP – City of Phoenix
DOC – dissolved organic carbon
DBP – disinfection by-product
FPA – flavor profile analysis
GAC – granulated activated carbon
GC/MS – gas chromatography/mass spectroscopy
HAA – haloacetic acid
HPC – high plate counts
HRT – hydraulic retention time
M&I – municipal and industrial
MCL – maximum contaminant limit
MGD – million gallons per day
MWD – Metropolitan Water District of Southern California
MIB – 2-methylisoborneol
NAWQA - National Water Quality Assessment program (USGS)
PAC – powdered activated carbon
SPME – Solid Phase Micro-Extraction
SRP – Salt River Project
T&O – taste and odor
THM – trihalomethane
TOC – total organic carbon
USEPA – United States Environmental Protection Agency
USGS – United States Geological Survey
UV – ultraviolet
WSD – Water Services Division (Phoenix)
WTPs – Water Treatment Plants

GLOSSARY

Activated carbon – carbonaceous material developed by heating various organic substrates to very high temperatures in the absence of oxygen. The result is a material with exceptionally high surface area and high adsorption capacity. In water treatment, both granulated activated carbon (GAC) and powdered activated carbon (PAC) are used to adsorb soluble organic compounds from water.

Algaecide – a chemical used to kill algae.

Blue-green algae – primitive algae with a simpler cell structure than more evolutionarily advanced algae, characterized by special pigments that sometimes (but not always) impart a bluish-green color to the algae. Some grow attached to substrates (periphyton) and others grow suspended in the water column (phytoplankton).

Chelation – weak bonding between an organic molecule and metal ions.

Chlorophyll – the pigment in plants that imparts the green color and gives the plant an ability to carry out photosynthesis.

Chloramines – compounds formed by reaction of chlorine with ammonia. Chloramines are sometimes used for disinfection in water treatment.

Destratify – to eliminate layering or stratification, as in the thermal barrier in a stratified lake. Lakes in Arizona normally stratify during the late spring or summer and destratify around October or November.

Disinfection by-product – compounds formed by reaction of chlorine with dissolved organic carbon such as trihalomethanes, haloacetic acids, etc.

DOC – dissolved organic carbon, an aggregate measure of all organic carbon compounds dissolved in water.

Epilimnion – the upper layer of a stratified lake. During summer stratification, the epilimnion water temperature is warmer than the hypolimnion.

Geosmin - volatile organic compound produced by blue-green algae and certain other microbes. Geosmin is not known to be harmful to humans, but imparts an unpleasant earthy odor and taste to the water at concentrations > 5-10 ng/L.

Haloacetic acids – a group of compounds characterized by substitution of a halogen to replace a hydrogen on the carboxyl group of an acetic acid molecule.

Headspace – space above liquid sample that contains volatile gases.

Hypolimnion – the lower layer of a stratified lake. During summer stratification, the hypolimnion has lower water temperatures than the epilimnion.

Metalimnion – the middle layer in a lake, between the hypolimnion and epilimnion, where the temperature changes with depth.

MIB – 2-methylisoborneol, a volatile organic compound produced by blue-green algae and certain other microbes. MIB is not known to be harmful to humans, but imparts an unpleasant moldy/musty taste to the water at concentrations > 5-10 ng/L.

ng/L – nanogram per liter or one part in a trillion.

Oscillatoria – a filamentous genus of blue-green algae or cyanobacteria. There are many species of *Oscillatoria*, some are phytoplanktonic (suspended) and others periphytic (attached). Some species produce MIB and/or geosmin.

Prechlorination – chlorination that occurs before water reaches the coagulation-flocculation basin.

Presedimentation – sedimentation that occurs in a basin in front of the coagulation-flocculation basin.

Thermocline – the depth at which the maximum temperature gradient occurs in a stratified lake; the metalimnion.

Trihalomethanes – a group of organic compounds with halide groups (Cl, Br, F) replacing hydrogen groups on a methane core, (e.g, $CHCl_3$, CH_2Cl_2, CH_3Cl).

TOC – total organic carbon; an aggregate measure of all organic matter, including dissolved and particulate occurring in the water.

ACKNOWLEDGEMENTS

This project has been a large team effort involving many individuals within the City of Phoenix, the CAWCD, and SRP. Much of the early conceptualization of the project was developed in collaboration with Mike Gritzuk, Matt Palenica, Bob Hollander, Randy Gottler, and Jennifer Calles. We would also like to thank Dr. Bill Taylor and his colleagues at the Metropolitan Water District of Southern California for their advice on developing a rapid response system. Within the Water Services Division, Walid Alsmadi (Project Manager), Edna Bienz, Natasha Bernard, Alice Brawley-Chesworth, Paul Burchfield, Aimee Conroy, Tom Doyle, Ron Jennings, Francisco Gonzales, Keith Greenburg, Yu Chu Hsu, Maureen Hymel, Ron Jennings, Mike Lauer, Tom Martin, Shan Miller, Dick Musil, Paul Mally, Chris Rounseville, Mel Schlink, Raymond Schultz, Bonnie Smith, Jeff Van Hoy, Mike Welch, Kevin Williams, and Vic Vanderslice contributed to the project. Many of the T&O management concepts outlined in this manual originated from these individuals. Gregg Elliott, Bob Gooch, Brian Moorehead, Rick Prigg, Dallas Reigel from SRP; and Doug Cosby, Brian Henning, and Tim Kacerek from CAWCD contributed ideas, encouragement, and sometimes, sweat, to the project. Finally, we thank our ASU postdoctorial associates, graduate students, and technicians: Darlene Bruce, Qiang Hu, Mario Esparza-Soto, My-Linh Nguyen, Tom Dempster, Michelle Cummings, Kirsten Hintze, Mari Rodriguez, Samanth Dawson, Marisa Masles, and Dave Lowry for their ideas, analyses, and labor.

SUMMARY

The goal of this *Guidance Manual* is to provide the water treatment community in the Phoenix area practical guidance on controlling tastes and odors in water supplies. It was developed at the end of a three-year project, "Reducing Tastes and Odors and Other Algae-Related Problems for Surface Water Supplies in Arid Environments," conducted by the City of Phoenix and Arizona State University. The goal of the project was not only to investigate the T&O problem, but to implement control measures to reduce the T&O problem. This goal was, in large measure, achieved. Phoenix's municipal water customers now receive better-tasting water than they did before the project began. But more importantly, the project developed a scientific and management framework to guide future activities that will result in improved drinking water quality.

This *Guidance Manual* serves as a tool for T&O management programs in the Phoenix metropolitan area. Individual cities and regional groups of cities and agencies (Salt River Project, Central Arizona Water Conservation District, Arizona Department of Environmental Quality) and others can use this document to develop integrated strategies for minimizing taste and odor episodes in raw drinking water supplies. Individual water treatment plants can use this document to treat/remove MIB and geosmin from raw water entering the plant. Chemists and biologists can use this document to aid in detection of taste and odor compounds and identification of culprit organisms responsible for such compounds.

This document is organized into six sections; the key ***principles and objectives*** of the T&O management program are presented in Chapter 1. Chapter 2 examines the ***spatial and temporal dimensions*** of the T&O problem. Chapter 3 presents the ***multiple barrier concept*** – the idea that a T&O management program should include "barriers" that extend from the watershed down through the water treatment plants and the distribution system. This concept has long been used as the foundation for pathogen control in the water treatment field. Chapter 3 also outlines the concept of a ***rapid response system*** that can provide water treatment personnel with the ability to respond quickly to T&O episodes. Again, this is a borrowed concept, developed in consultation with the Metropolitan Water District of Southern California. Chapter 4 outlines a ***prescribed monitoring program*** and some general predictions on the dynamics of the T&O situation in the Phoenix area. Chapter 5 provides guidance on ***specific management practices*** that can be used to control and manage T&O episodes. This chapter includes sections on water supply operations, management of canals, source switching, and controls within water treatment plants. Chapter 6 outlines the rationale for ***program assessment*** and an approach for conducting continuing and annual program evaluations. Finally, Chapter 7 presents three ***case studies*.** Each addresses a specific T&O episode that was encountered over the past three years. Each case study includes sections on monitoring results, diagnosis of the problem, treatment selection, treatment application and follow-up monitoring.

The ***Guidance Manual*** is supported by other products from this project. The **Final Project Report** is a detailed compilation of research conducted throughout the project and an assessment of the implemented T&O mitigation program. A CD-based **Interactive Taxonomic Guide** is a tool developed to assist in the identification of T&O "culprit" algae. Finally, the project has generated numerous scientific presentations and publications that add to the understanding of T&O problems.

This document is a living document and should change over time to include new information and improved practices. It should, however, continue to serve as a practical guide to detect and respond to taste and odor problems in municipal and other water supply and distribution systems.

SECTION 1

INTRODUCTION

1.1 PREFACE

Metropolitan Phoenix regional drinking water utilities have a long history of providing water that meets all health standards. Unfortunately, water delivered to customers often has unpleasant tastes and odors which have no primary regulatory limits. For the most part, these tastes and odors are caused by several soluble compounds released into the water by blue-green algae (cyanobacteria) growing in the canals and reservoirs of the water supply system. The two compounds responsible for the bulk of the problem are 2-methylisoborneol (MIB) and geosmin. These compounds are not harmful, but they depart to the water earthy, musty or moldy tastes at very low concentrations. For most people, the sensory threshold for these compounds is about 10 ng/L (10 parts per trillion). Usually these tastes and odors are mildly unpleasant, but on occasion the water can become undrinkable by a segment of the population. During these "T&O episodes," MIB levels can frequently exceed 50 ng/L.

1.2 HISTORICAL PERSPECTIVE

In the mid-1980s analytical techniques emerged (e.g., closed-loop stripping with gas chromatography-mass spectroscopy) that enabled detection and identification of specific compounds in water that are responsible for earthy, musty, and moldy odors (Suffet et al., 1999). The Metropolitan Water District of Southern California (MWD; see www.mwdH2O.com) was one of the first utilities to address the T&O problem. During the 1980s, MWD developed an integrated strategy to control tastes and odors (Means and McGuire, 1986; Taylor, et al., 1994). Their strategy utilized both source water control and water treatment. As a result, water utilities and customers in Southern California are provided with water containing less than 10 ng/L of MIB or geosmin throughout the year. Like the Phoenix Metropolitan Area, MWD imports its water from the Colorado River, stores water in terminal reservoirs, and has multiple local water suppliers.

Throughout the 1980s and 1990s cities in the metropolitan Phoenix region were coping with rapid population growth, and associated increasing water demand, and a series of USEPA regulations regarding disinfection and disinfection by-products. During this period, water departments also noted seasonal customer complaints of unpleasant and earthy, musty, or moldy tastes and odors. Some cities established trained panels (flavor profile analysis panels) of customers and city personnel to identify and track the odors, and guide changes to water treatment plant operations. Other cities applied the standard water treatment process of powdered activated carbon (PAC) addition to treat seasonal taste and odor events. At that time, it was unclear where taste and odor compounds were produced. Possible sources included watershed reservoirs, rivers, concrete-lined and unlined canals, water treatment plant holding basins, or pressurized finished water distribution systems. Some local water utilities and contract laboratories had the analytical capability to detect MIB and geosmin, but turnaround times were slow (2 to 6 weeks), making the data of limited use. Analytical costs were also high.

From 1996 through 1998 separate studies by the University of Arizona and Arizona State University, funded by metropolitan Phoenix water providers and users, documented trends in MIB and geosmin occurrence throughout the upstream water supply reservoirs, canals, and water treatment plants. The conclusion was that some of the water treatment plants in the region received water with MIB and geosmin concentrations ranging from 20 to more than 70 ng/L during the late summer and early fall of each year. The concentrations in finished water were not well-documented. In source waters, concentrations over 100 ng/L were occasionally reported. While MIB concentrations were higher than geosmin concentrations in upstream reservoirs and at the head of the SRP canal, geosmin concentrations occasionally exceeded MIB concentrations at some locations in the SRP canal system (e.g., Consolidated Canal near wells pumping ground water containing elevated nitrate concentrations). Frequent customer complaints and the high cost of PAC treatment prompted cities to develop a watershed approach to taste and odor control, rather than simply relying upon PAC treatment within water treatment plants. Managing taste and odors in the water supply before it enters a specific WTP, offered the opportunity to control MIB and geosmin concentrations to a large number of downstream raw water WTP intakes.

Since the mid-1990s a number of new water treatment plants have been designed to treat T&O problems, even though the USEPA has no regulated limit for these compounds. Treating the compounds improves the aesthetic quality of the finished drinking water. For example, ozonation and/or biofiltration have been designed into treatment plants in Chandler, Gilbert, and Peoria, Arizona. These systems are optimized for taste and odor control and minimization of regulated by-products (e.g., bromate, trihalomethanes, haloacetic acids).

1.3 HISTORY OF THE ASU/CITY OF PHOENIX TASTE AND ODOR PROJECT (1999-2002)

Taste and odor episodes in 1997 resulted in hundreds of complaints from customers and spurred the development of a three-year collaborative project between the City of Phoenix and Arizona State University. The Salt River Project (SRP) and Central Arizona Water Conservation District (CAWCD) were active participants in the project. The project's primary goal was: to reduce the prevalence of T&O problems in the City's water supply. Achievement of the project's goal was underpinned by the following principles:

1. The T&O management program would be based on the *multiple barrier concept* that has long been used by the water treatment industry as a model for controlling pathogens (Baker, et al., 1999); (Baker, et al., 2000). The barriers (treatment measures) would be implemented in the watershed, the reservoirs, the canal

system, and the water treatment plants. Initially more than 20 potential management alternatives were evaluated. At the midpoint of the project, about half these were discarded on the basis of either technical evaluation, political feasibility, or cost. The others were implemented and are discussed in this manual.

2. *Continuous monitoring* would be needed to manage tastes and odors. The monitoring system that evolved now has 20 baseline monitoring sites located throughout the water supply system that are sampled once a month (Figure 1.1) and another dozen "intensive monitoring" sites that are sampled as frequently as once a week during T&O episodes.

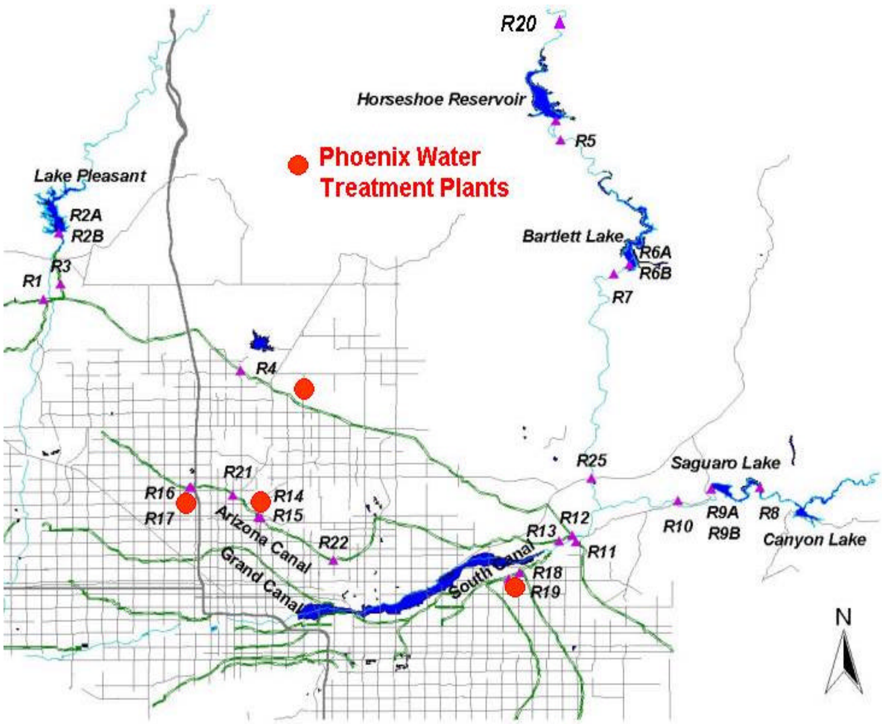


Figure 1-1. Schematic of watershed and locations of baseline monitoring sites (R#) and location of Phoenix's water treatment plants (R10 – Val Vista WTP; R4 – Union Hills WTP; R15 – Squaw Peak WTP; R16 – Deer Valley WTP).

3. A *rapid response* system was needed to provide data to COP staff quickly. Tastes and odor problems are episodic, often arising quickly at various locations. To manage the problem effectively, COP Water Services Division (WSD) and water quality managers at SRP and the CAWCD need to be able to implement control measures quickly, often in the time span of one or two weeks. An electronic "Taste and Odor *Newsletter*" evolved that is now distributed during the T&O season, from approximately June through November. The *Newsletter* reports system-wide monitoring data and recommends treatment strategies.

4. The effort would require *broad collaboration*. Everyone involved with water treatment and delivery would have to participate for the program to be successful.

Biannual T&O project meetings facilitated broader involvement, as did the *Newsletter*. In the end, at least 50 individuals from WSD staff, SRP, CAWCD, and ASU contributed specific ideas or otherwise facilitated implementation of the program.

5. The program was to be *sustainable* beyond the life of the project. This *Guidance Manual* and the accompanying research report represent part of that effort.

6. Because algae are a source of dissolved organic carbon (DOC), which reacts with disinfectants to form regulated disinfection by-products, the study would also include an effort to identify sources of DOC within the watershed and to elucidate characteristics of this DOC. The watershed design approach for studying sources of tastes and odor compounds was ideally suited for studying sources of DOC with little incremental cost. This document focuses exclusively on T&O management. The DOC-DBP work is reported elsewhere (Nguyen, 2002; Nyguen, et al., 2002).

1.4 LONG-TERM IMPLEMENTATION GOALS FOR T&O CONTROL PROGRAM

Most metropolitan water utilities agree that a target concentration of < 10 ng/L for MIB or geosmin is appropriate for finished drinking water. Achieving this goal requires a combination of upstream watershed management strategies followed by an economically-optimized series of controls within the distribution canals that transport water to water treatment plants. The key to controlling episodes of high MIB or geosmin lies within careful and frequent monitoring, implementation of controls that effectively limit production and in-plant treatment. Long-term strategies for minimizing tastes and odors may include:

- System monitoring using in-situ probes within the reservoirs, remote sensors at key locations in the canals, flavor profile analysis panels (FPAs) and/or rapid and sensitive genetic methods for detecting the presence of culprit algae known to produce MIB and geosmin.
- Managing surface and ground water resources to minimize MIB or geosmin concentrations in raw water by using source water with the lowest MIB or geosmin concentration. Care should be taken to limit input of nitrogen or phosphorous nutrients into the water supply.
- Optimizing practices to remove attached algae (brushing and chemical addition) while reducing risks of turbidity plumes or potentially harmful chemicals. Minimizing algae attached to concrete-lined canal walls through the use of state-of-the-art biocide coatings that are applied to concrete walls.
- Optimizing water production at different WTPs within a city to minimize production at the facility with the highest historical MIB or geosmin levels. Use historical MIB or geosmin levels to determine which in-plant WTP controls are most important at each facility, and upgrade the facilities appropriately.
- Optimizing existing processes for MIB and geosmin removal, and design upgrades in treatment processes to meet multiple water quality objectives.

SECTION 2

BACKGROUND ON TASTE AND ODOR EPISODES IN THE METRO-PHOENIX AREA WATER SUPPLY SYSTEM

2.1 SOURCES OF TASTE AND ODOR PROBLEMS

Dozens of chemicals may cause T&O problems in surface waters, but in most systems, only a few are important. This is true for the Phoenix metropolitan area water supply. By far, the most prevalent T&O compounds are MIB and geosmin. These two volatile compounds are usually present, but not necessarily at levels above human sensory thresholds throughout much of the year and at most locations in the water supply system.

MIB and geosmin are produced by blue-green algae (cyanobacteria) found in the reservoirs and the canals (Bruce, et al., 2000). Although there are numerous species of blue-green algae in the water supply system, laboratory culture studies have revealed only ten (10) isolates that are confirmed MIB or geosmin producers out of approximately 1300 algal strains that have been isolated from the water system.

These "*T&O culprits*" were collected and isolated from six baseline sampling sites and four intensive sampling sites in the system. The 10 isolates belong to six distinct taxa. Nine of the isolates were *periphytic* (attached algae living on rocks or attached to larger plants) and one was *planktonic* (algae suspended in the water column). The types and locations of the T&O culprits were:

- periphyton growing on the cement-lined walls of the Arizona Canal,
- periphyton in the Verde River below Bartlett Lake,
- periphyton in the Verde River between Horseshoe Lake and Bartlett Lake, and
- periphyton and plankton in Saguaro Lake.

2.2 FREQUENCY AND DISTRIBUTION OF T&O EPISODES

2.2.1 Seasonal Pattern of the T&O Problem

Concentrations of MIB at Phoenix's water treatment plants vary depending on the individual plant and the time of year. MIB concentrations at the Union Hills WTP have generally remained < 10 ng/L since the CAWCD modified its operation of Lake Pleasant in 1999. MIB concentrations at the Val Vista WTP generally remain < 20 ng/L except during late summer/early fall (Figure 2-1).

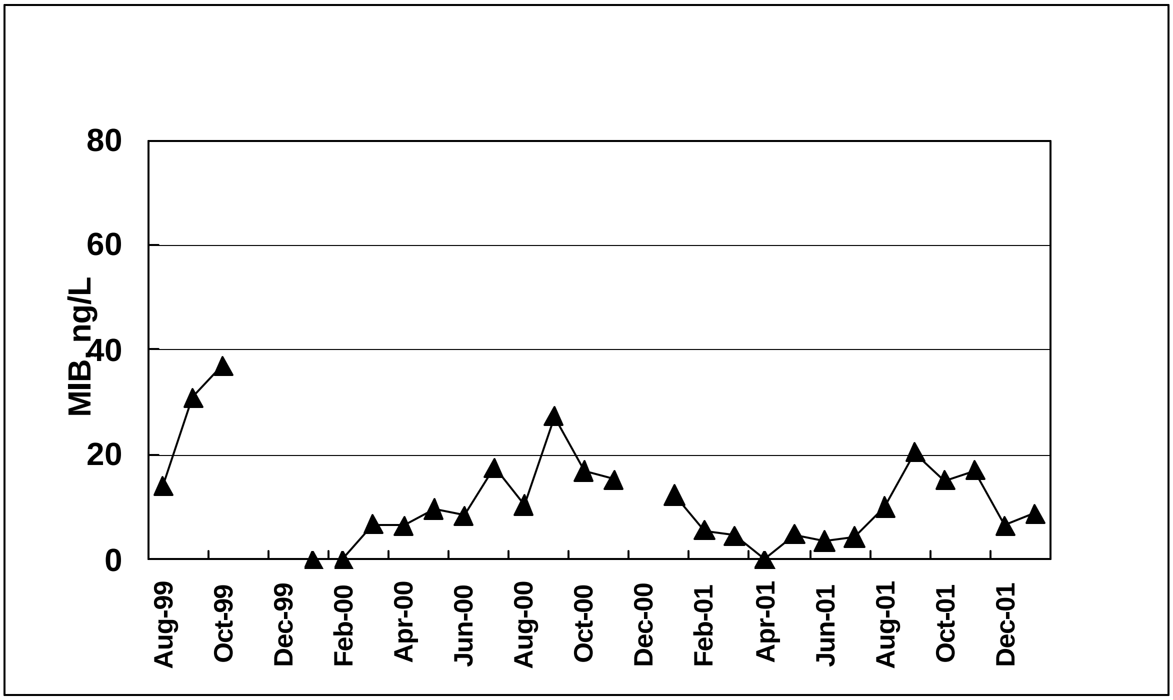


Figure 2-1. MIB at the inlet to the Val Vista WTP.

MIB concentrations at the Squaw Peak WTP (Figure 2-2) were slightly higher than at Val Vista. As with Val Vista, MIB values > 20 ng/L occur primarily in late summer and rarely exceeded 30 ng/L.

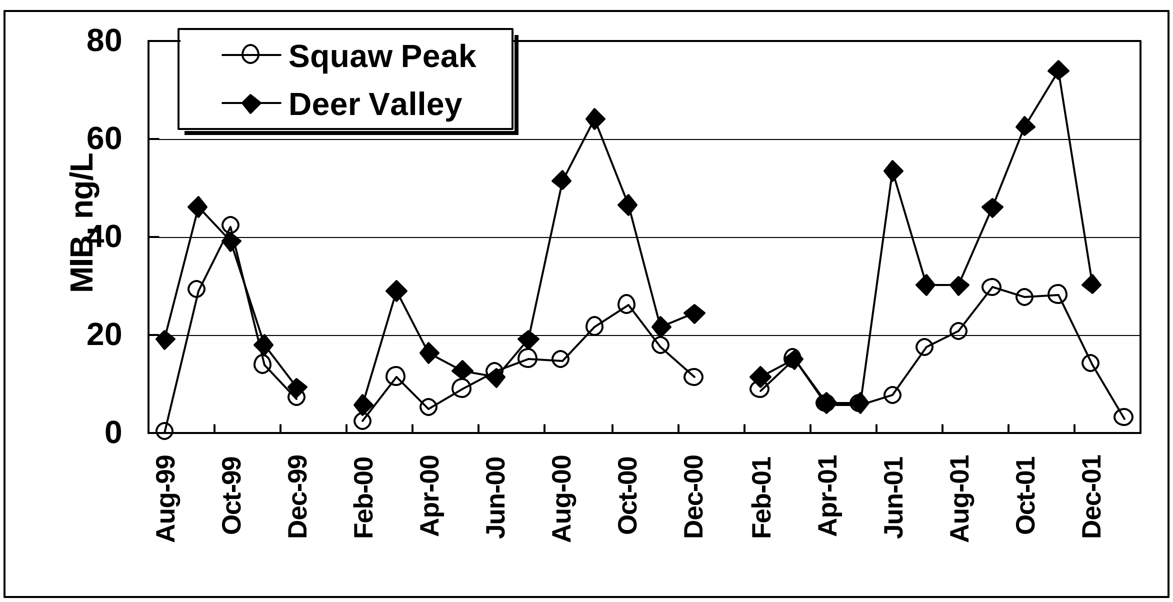


Figure 2-2. MIB at the inlets of the Squaw Peak and Deer Valley WTPs.

The stretch of the Arizona Canal from the Squaw Peak WTP to the Deer Valley WTP was a major source of MIB. The Deer Valley WTP therefore had much higher concentrations of MIB than Squaw Peak. MIB concentrations at the inlet to the Deer Valley WTP generally remain above 20 ng/L from August through November, with sporadic episodes occurring before August.

The frequency of MIB values > 10 ng/L and > 20 ng/L during the three-year T&O study can be used as a rough guide for planning the annual T&O management program. Figures 2-3 through 2-5 show the percentage of samples with MIB > 10 ng/L and 20 ng/L during each month of the three-year T&O study. At the Val Vista WTP, MIB concentrations > 10 ng/L can be expected more than 50% of the time from July through November. MIB concentrations > 20 ng/L was common in September.

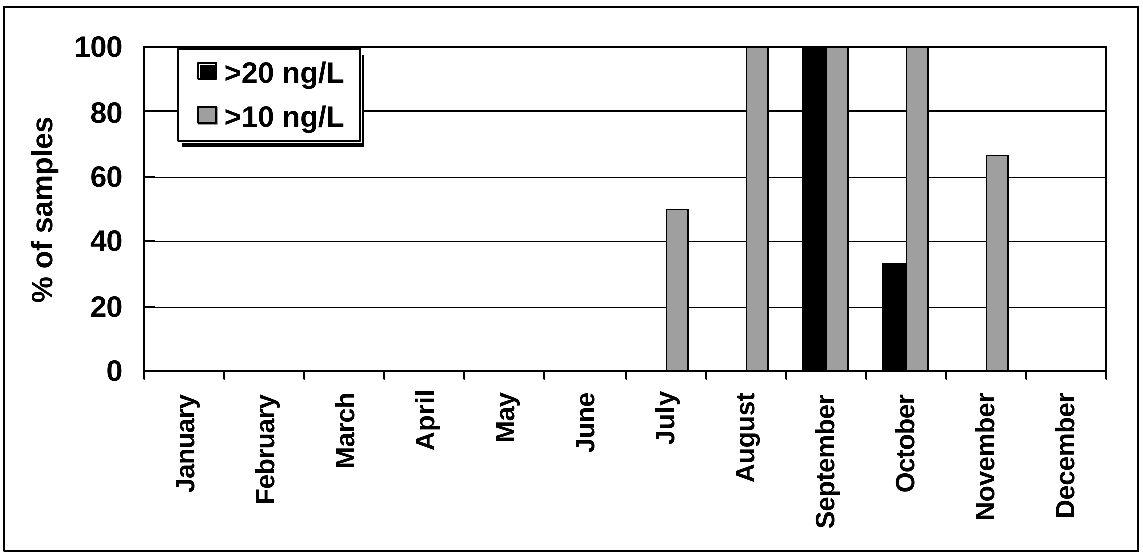


Figure 2-3. Percentage of samples with MIB > 10 ng/L and > 20 ng/L at the Val Vista WTP.

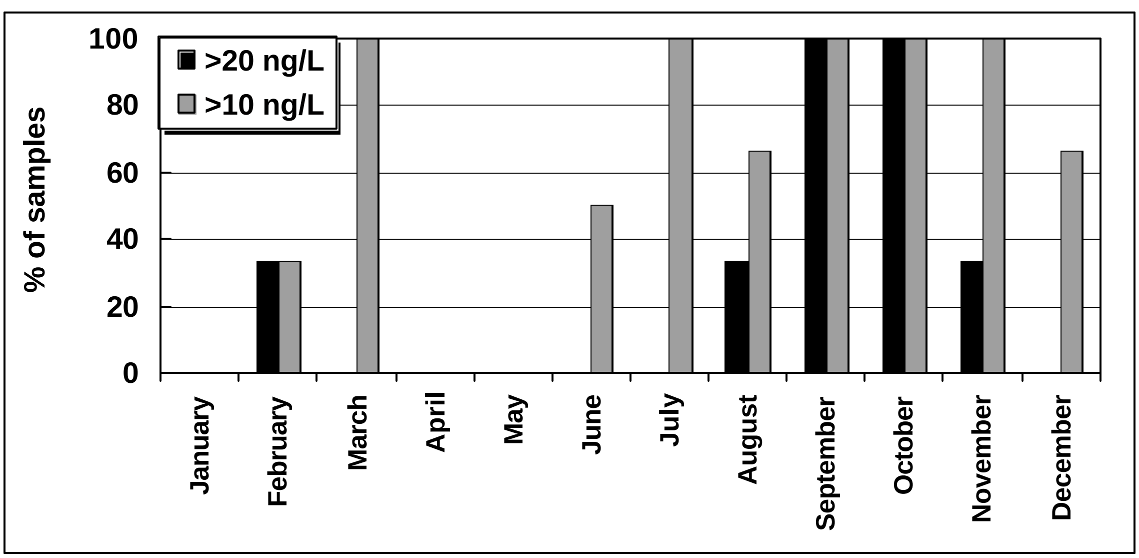


Figure 2-4. Percentage of samples with MIB > 10 ng/L and > 20 ng/L at the Squaw Peak WTP.

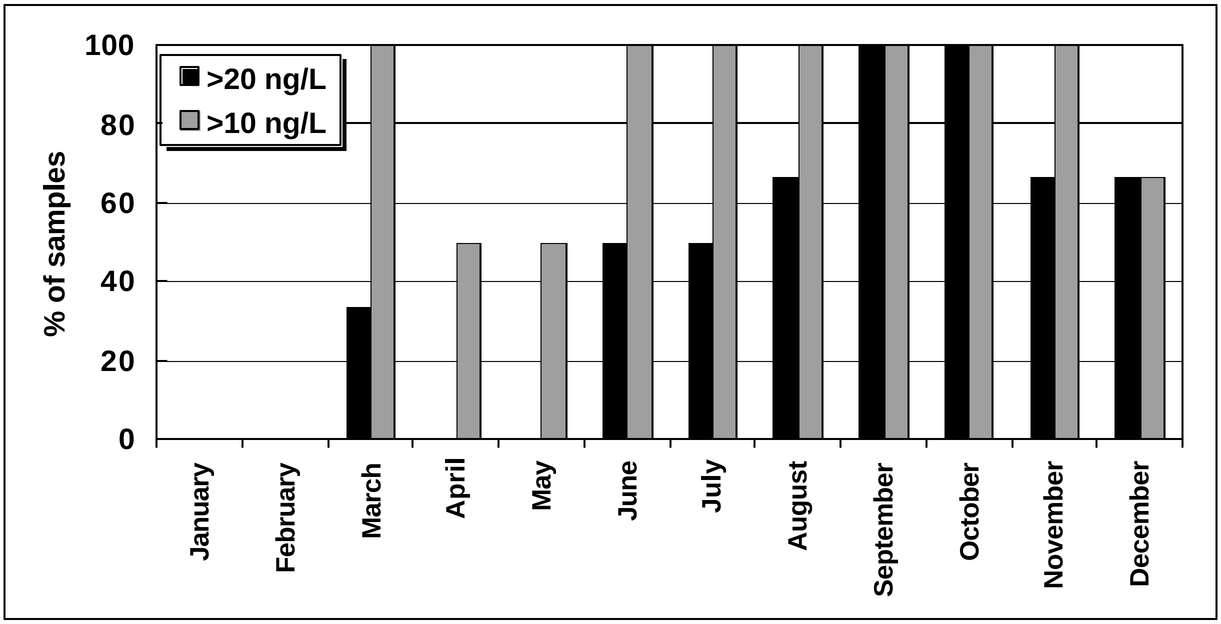


Figure 2-5. Percentage of samples with MIB > 10 ng/L and > 20 ng/L at the Deer Valley WTP.

At the Squaw Peak WTP, MIB levels exceeded 20 ng/L more than 50% of the time in September and October. MIB levels were > 10 ng/L more than half the time from June through December, and in the month of March.

The situation is typically much worse at the Deer Valley WTP. For all months with observations, MIB levels routinely exceeded 10 ng/L, and MIB levels generally exceeded 20 ng/L from June through December.

In summary, the likelihood of encountering elevated MIB levels at Phoenix's WTPs follows the order:

(highest) Deer Valley >> Squaw Peak >> Val Vista >> Union Hills (lowest)

The occurrence of elevated MIB levels at each of the water treatment plants is summarized in Table 2-1.

Table 2-1. Number of months per year with MIB concentrations above threshold levels at Phoenix's water treatment plants

Water Treatment Plant	MIB > 10	MIB > 20
Union Hills	0	0
Val Vista	5	2
Squaw Peak	8	2
Deer Valley	10	7

2.3 ORIGIN OF THE TASTE AND ODOR PROBLEM

2.3.1 Reservoirs

The reservoirs were major sources of MIB produced by planktonic or shallow periphytic blue-green algae. MIB concentrations in the epilimnion were generally greater than in the hypolimnion when the reservoirs were stratified (usually May through October) (Figures 2-6 through 2-8). In some instances, peaks in numbers of blue-green algae were associated with MIB peaks, whereas in other cases there did not appear to be a relationship. The algae blooms associated with peak MIB levels were mainly composed of filamentous forms in the family Oscillatoriaceae (see Figure 4-1).

The culprit organisms tended to favor elevated temperatures typical of the summer and early fall. They produce MIB or geosmin that accumulates in the cells. Although these compounds may leak from the living cells, the cells retain much higher concentrations than the surrounding aqueous environment. When cells die and lyse, larger quantities of MIB or geosmin are released into the water. Some of these organisms also appear to be capable of turning MIB/geosmin production/release on and off. Furthermore, production can be influenced by environmental conditions.

MIB production in the reservoirs is not always a problem for downstream water users. During summer stratification, MIB is produced in the epilimnion and water is released from the hypolimnion. If the stratification is strong enough to prevent vertical mixing, water being released from the bottom may have low MIB concentrations, even when MIB concentrations in the epilimnion are very high. When stratification breaks down and the reservoir mixes, MIB concentrations in the outlet water often increase. Predicting where and when MIB releases from reservoirs occur is discussed in Section 4.

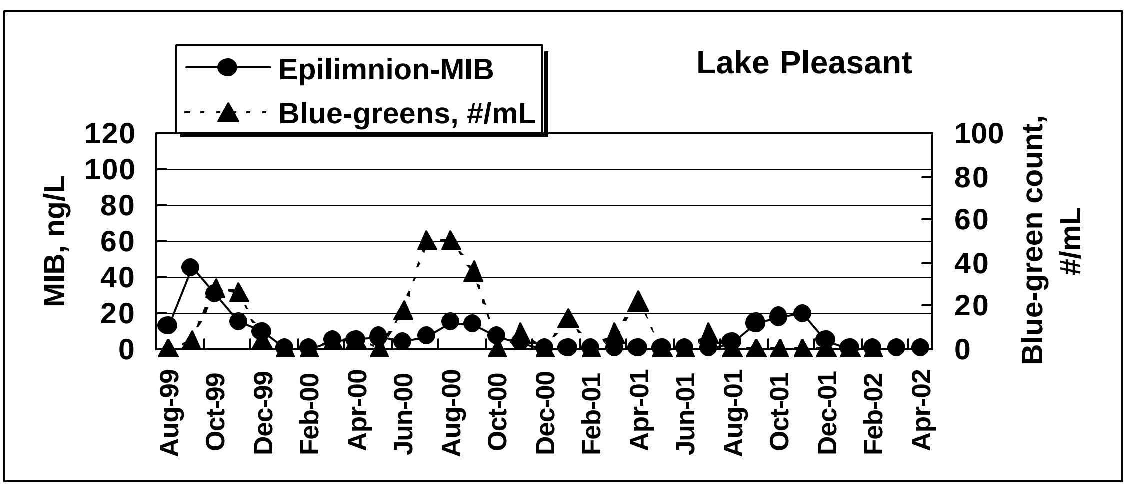


Figure 2-6. MIB and blue-green algae numbers for Lake Pleasant.

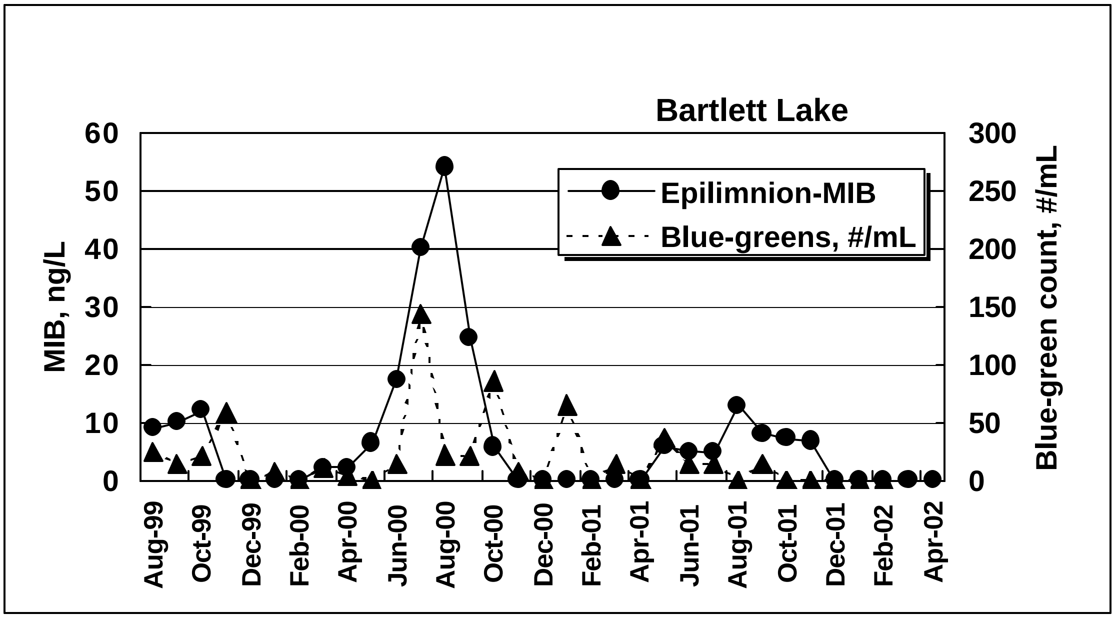


Figure 2-7. MIB and blue-green algae numbers for Bartlett Lake.

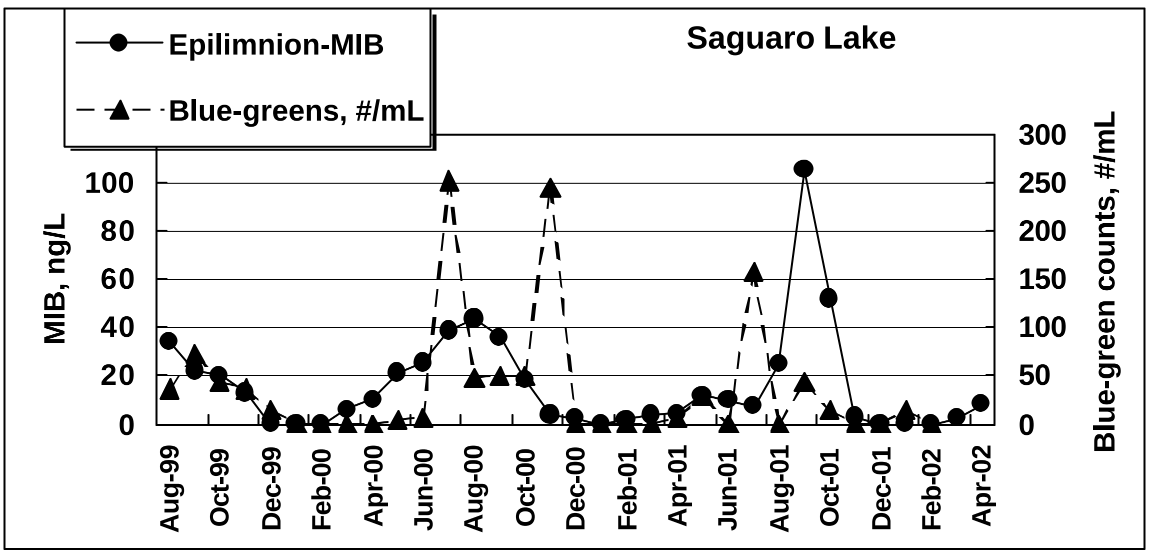


Figure 2-8. MIB and blue-green algae numbers for Saguaro Lake.

2.3.2 Arizona Canal

MIB is also produced within the Arizona Canal. On many occasions, the Arizona Canal was the predominate source of MIB. MIB production in Figures 2-9 and 2-10 was calculated by subtracting the MIB concentration at the head of the Arizona Canal below the CAP inlet (site R13) from the MIB concentration at WTPs. "MIB production," therefore, refers to MIB produced by culprit algae growing in the Arizona Canal above each of the water treatment plants.

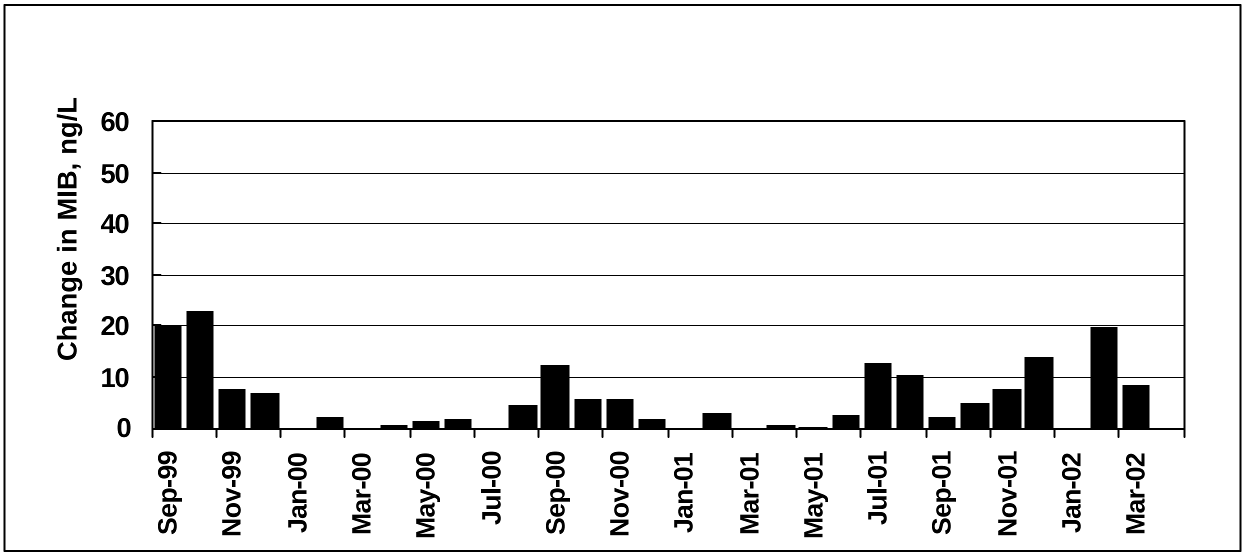


Figure 2-9. MIB production within the Arizona Canal above the Squaw Peak WTP, ng/L.

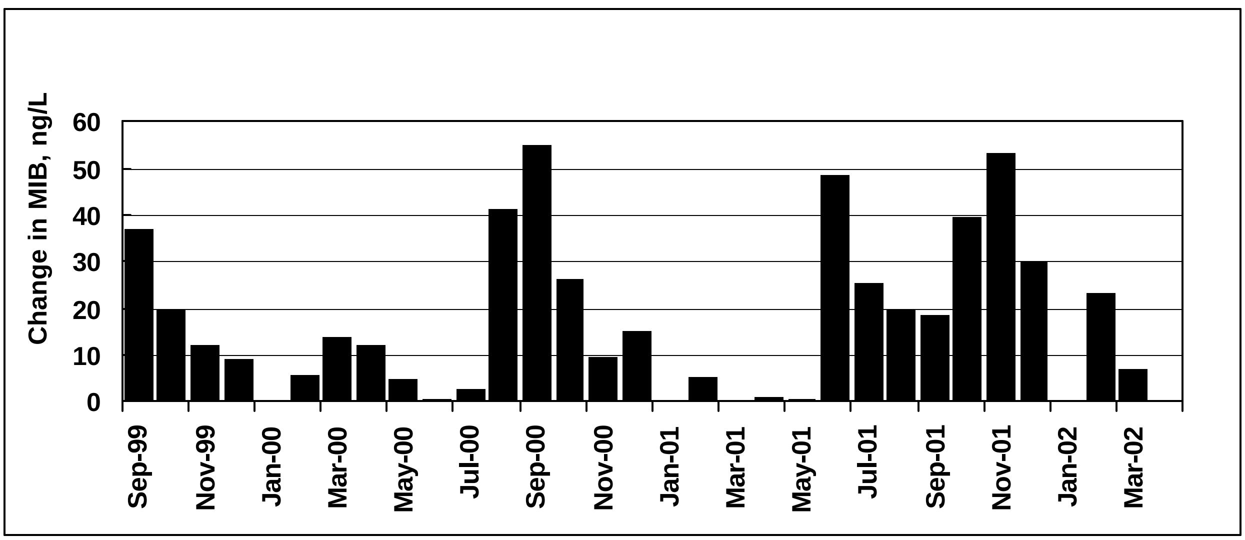


Figure 2-10. MIB production within the Arizona Canal above the Deer Valley WTP, ng/L

During the winter and early spring, there was little MIB production in the Arizona Canal above the Squaw Peak WTP (Figure 2-9), and occasionally even a net loss. Peak MIB production in the Arizona Canal above the Squaw Peak WTP (10-20 ng/L) generally occurred in September and October.

MIB was produced in the Arizona Canal above the Deer Valley WTP almost every month of the year (Figure 2-10). Average MIB production often exceeded 20 ng/L from August through November. During some years, MIB production in the Arizona Canal above the Deer Valley WTP exceeded 50 ng/L.

The difference in MIB production between the Arizona Canal at Deer Valley and MIB production at Squaw Peak represents MIB production between Deer Valley and Squaw Peak. During the late summer and fall, MIB production in the canal stretch between the two water treatment plants can exceed 20 ng/L. The very high MIB production in this stretch of the canal is probably exacerbated by well pumping into the canal, which increases the nitrate concentration in the canal. This increase is not large relative to drinking water standards, but it is sufficient to promote algae growth.

2.3.3 Water Treatment Plants

Algae grow in the WTPs and should be controlled (see Section 4). Analysis of temporal and spatial patterns in several water treatment plants has shown some in-plant MIB/geosmin production. Antidotal evidence suggests that periodic prechlorination may prevent colonization of T&O "culprit" algae.

SECTION 3

MULTIPLE BARRIER T&O CONTROL

3.1 MULTIPLE BARRIER STRATEGY

The central theme of the proposed T&O management strategy is the concept of multiple barriers. The multiple barrier concept in water treatment is widely used for pathogen control. "Barriers" in pathogen control include watershed management (for example, eliminating animal and human waste inputs into streams), sedimentation and filtration within water treatment plants to remove pathogens, initial chlorination to kill pathogens, and maintenance of chlorine residual to kill any pathogens that might enter the distribution system by regrowth, plumbing malfunctions, etc.

The concept is similar for T&O control. During the T&O study, more than 20 specific control measures were evaluated. Several measures emerged as the key elements of an overall T&O management strategy. These are discussed briefly below and in more detail in Section 5:

- <u>Reservoir management</u>. Blending of waters from the Colorado River and the two outlet structures (upper and lower) in Lake Pleasant was an effective reservoir management practice. Through managing waters from these three sources, CAWCD has been able to keep MIB and geosmin in the CAP Canal below Lake Pleasant < 10 ng/L.
- <u>Canal treatments</u>. Canal treatments were effective in removing T&O-producing algae growing on the sides of the Arizona Canal, thereby reducing the production of MIB. Because algae growing on the canal walls can be a major source of MIB, sometimes contributing > 50 ng/L MIB to water flowing through the canal, canal treatments to remove algae are an important part of the overall T&O management program.
- <u>SRP-CAP Blending</u>. During the late summer and fall, CAP water generally has lower concentrations of MIB than SRP water. This provides an opportunity for blending the two source waters to reduce MIB concentrations in water delivered to the treatment plants. For most years, using more SRP water early in the season, and more CAP water later in the season, would improve the quality of water delivered to Phoenix's municipal customers. The opportunity for blending, however, depends upon the hydrologic status of the system. Revisions in the legislation controlling the SRP-CAP Water Exchange Agreement in 2002 enhance the opportunity for blending as an effective T&O control measure.
- <u>Source switching</u>. The concept behind source switching is that poor quality water can sometimes be avoided by switching production from a plant that is receiving poor-quality water to one or more plants that are receiving better tasting water. For example, taking the Deer Valley WTP off-line during 2001 and shifting production to the Union Hills and Squaw Peak WTPs avoided the problem of high MIB in the lower end of the Arizona Canal and resulted in

better quality water delivered to consumers. Phoenix now has five water treatment plants and will have a sixth within about five years.

- In-plant treatment. PAC treatment in the WTPs, thereby enhancing this capability, has been an effective method of removing MIB from source waters. Although PAC treatment could theoretically keep MIB levels below 10 ng/L throughout the year with no upstream management, practical limitations constrain the effectiveness of PAC treatment. These limitations include limited PAC storage capacity, problems with pumping systems, and hydraulic short-circuiting. Furthermore, even if these limitations could be overcome, a multi-barrier strategy would be more cost-effective than reliance on PAC treatment alone.

3.2 RAPID RESPONSE SYSTEM

A key concept of the T&O Management Strategy is the use of a rapid response system that allows COP and other water supply agencies to respond quickly to emerging T&O problems. This idea was adapted from the MWD, which established the general concept in the mid-1980s. The concept was revised and implemented to meet the specific needs of Phoenix's water supply system (Figure 3-1).

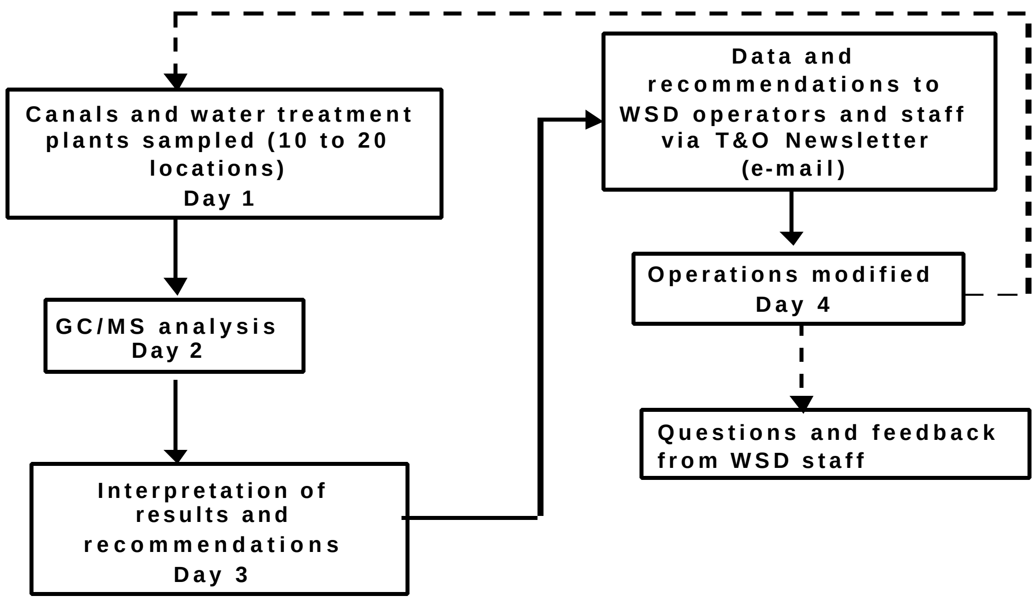


Figure 3-1. Flow chart of the rapid response system. Dashed lines indicate feedback and validation of correction actions.

Central to the rapid response system are **intensive monitoring** and a **communication strategy**. The monitoring program is described in Section 4. The core of the communication system is an e-mail-based *Taste and Odor Newsletter* that has four functions:

1. Relay the most recent monitoring data to everyone within the WSD who needs this information,
2. Provide recommendations on management practices that need to be used,
3. Provide a forum for relaying technical commentary, and
4. Provide a mechanism for generating feedback from water treatment personnel (lab chemists, plant operators, etc.).

During the summer and early fall when MIB/geosmin concentrations begin to increase, the *Newsletter* should be written and distributed every week, because T&O conditions change rapidly. Furthermore, the management strategy must continuously evolve as COP gains experience, builds new infrastructure, and employs new technologies. A common sequence during a typical week would be: samples collected (day 1); samples analyzed (day 2); data and interpretation (day 3), the *Newsletter* is written and delivered by e-mail (day 4) (Figure 3-1).

Another important component is regular *T&O workshops* which should be held once or twice a year. The goal of these workshops is to present results of the continuing program evaluation, discuss problems, share ideas for improved solutions, and discuss future plans. For example, a spring workshop could be used to prepare for the upcoming T&O season. By this time, the annual hydrologic and water supply situation is known, an evaluation of the program successes and failures for the previous season should be ready, and the budgetary situation should be well-understood. A fall-winter workshop would provide an opportunity to evaluate the success of the T&O management program during the previous season.

These workshops should include treatment plant operators and chemists, the monitoring group, the water resources manager, and managers from the SRP and CAWCD.

SECTION 4

MONITORING AND PREDICTION

4.1 MONITORING PROGRAM

4.1.1 Location of Sampling Sites

The location and timing of T&O problems changes constantly. It is therefore necessary to maintain an extensive monitoring program to allow effective responses to be implemented throughout the season, as the situation demands. A monitoring program also provides data to evaluate the T&O program.

A regional monitoring program should include the terminal water supply reservoirs, the CAP and SRP water delivery canals, the inlet and outlet of each water treatment plant, and the water distribution system.

This section identifies specific locations within the watershed and canal systems that would provide significant benefit to the metropolitan Phoenix region, and specific WTPs. General criteria for monitoring within pressurized water distribution systems of a particular city are also provided. Proposed sampling sites, based on the three-year T&O study, are indicated on Table 4.1.

Table 4-1. Location and rationale for proposed monitoring sites.

Monitoring Site	Rationale
Terminal Lakes Lake Havasu (CAP samples) Lake Pleasant (SRP samples) Lake Bartlett (SRP samples) Lake Saguaro (SRP samples)	Algae growth in the lakes is a primary source of T&O entering WTPs; monitoring reservoirs also predicts of the duration of T&O occurrence, allowing utilities to order PAC supplies, etc. Both the epiliminion and hypolimnion should be sampled during summer stratification.
Rivers Verde River at Beeline Hwy Salt River at Bluepoint Bridge	These sites are downstream of terminal lakes and represent influent water to the SRP canal system; storm runoff affects T&O in rivers.
CAP Canal Above Aqua Fria Siphon Wadell Canal Above SRP cross-connect	CAP canal provides water to Union Hills WTP and to the head of the SRP canals. Historically T&O levels are lower in CAP water than SRP water and offer opportunities to blend sources to control T&O.
Arizona Canal Above/below CAP cross-connect At Beeline Highway Pima Road 56th Street Central Avenue	For the past 3 years, three different “hot spots” for T&O production have been identified. Frequent monitoring has identified “hot spots” and allowed for copper treatment or canal brushing by SRP to reduce in-canal T&O production.
South Canal Below CAP cross-connect End of South Canal	Quantifies potential production in the South canal and provides baseline for Cities of Chandler (Consolidated Canal) and Tempe (Tempe Canal)
Water Treatment Plants (Influent and effluent samples) Union Hills (CAP canal) Squaw Peak (AZ canal@ 24th St) Deer Valley (AZ canal@ 24th Ave) Val Vista (South Canal) Additional City WTPs	Influent T&O concentrations allow optimization of treatment conditions (e.g., PAC type and doses); finished water is quality perceived by customers. PAC treatment efficiency can be computed from influent and effluent samples. Determine whether in-plant production of MIB/geosmin occurs.

Canals should be intensively monitored every week from early June to late November, when water temperature is higher than 70^{o} F (21^{o} C). Intensive monitoring ensures the detection of rapid increases in MIB and geosmin concentrations in the water, which can change within a period of days. At other times of the year, monthly samplings are recommended because MIB and geosmin concentrations are more stable. Sampling sites should be no more than 3-4 miles apart to ensure accurate detection of the canal section that is producing MIB/geosmin. At known MIB/geosmin-producing canal sections upstream of WTPs, such as the Arizona Canal stretch between 24th Street and 29th Avenue, sampling sites should be more closely spaced (1-1.5 miles).

4.2 MEASUREMENT PARAMETERS

Based upon three years of monthly and intensive monitoring an array of water quality parameters were selected that should be monitored in the future to provide immediate guidance on MIB or geosmin control options and data for predicting likely MIB or geosmin trends two to six weeks in advance. Physical observations yield important clues regarding interpretation of the data and for management. The presence of stagnant water, the presence of algae mats, the "sniff test," and other observations in the field are needed for these purposes. A field sampling sheet is attached as Appendix A. Specific field and laboratory parameters and the recommended sampling frequency are presented in Table 4-2 and briefly discussed.

Table 4-2. Sampling frequency and water quality parameters to be measured (June-December)

Monitoring Site	Sampling Frequency	Water Quality Parameters
Terminal Lakes	1x-2x per month	Field: Depth profiles of temp, DO; Secchi disk depth Lab (Epi- and hypolimnion samples): MIB, geosmin, chlorophyll *a*, conductance (two 500 mL glass bottles), algae identification
Rivers	Approximately weekly	Field: temperature Lab: MIB, geosmin, nitrate, chlorophyll *a*, specific conductance (two 500 mL glass bottles), algae identification
CAP Canal		
Arizona Canal (up to 10 locations during the T&O season)		
South Canal		
Water Treatment Plants		

Temperature: Temperature is a good predictor of potential T&O episodes. Temperature profiles in the reservoirs are also needed to determine whether the reservoirs are stratified.

Dissolved oxygen: Dissolved oxygen is another useful indicator of stratification in the reservoirs. During summer stratification, DO levels drop, often to near zero in the hypolimnion. Increasing DO levels in the hypolimnion are a good indication (sometimes better than temperature) that the reservoir is beginning to destratify. DO levels are measured using a DO meter with a long submersible cord. It is not necessary to measure DO in the canals or the water treatment plants.

Specific conductance: Specific conductance is useful in determining the source of water within the canals. A large change in specific conductance over a short period (a week or two) generally indicates a change in source water. Specific conductance is related to total dissolved solids (TDS). The TDS of the Verde River system (300-500 mg/L), Salt River system (1000-1400 mg/L), and CAP system (600-900 mg/L) are quite different but can vary from year to year depending upon dilution from watershed snowpack or monsoon rainfall.

Nitrate: Algae growth is often limited by nitrogen, so this nutrient can be useful in predicting when algae are likely to grow. Nitrate is a very good indicator of well water inputs. Background nitrate nitrogen concentrations in surface water are usually < 0.1 mg/L; but may increase to > 0.5 mg/L when well water is being pumped into the canals.

Algae: Producers of MIB/geosmin are primarily blue-green algae belonging to the taxonomic family Oscillatoriaceae, a group of microscopic filamentous organisms that are common to fresh waters (Figure 4-1). Algae in the reservoirs are collected using a submersible Kemmerer sampler that is triggered to collect samples at specific depths. Periphyton samples can be collected using a periphyton sampler developed for this project (Appendix B) or by grab samples from canal walls or shoreline.

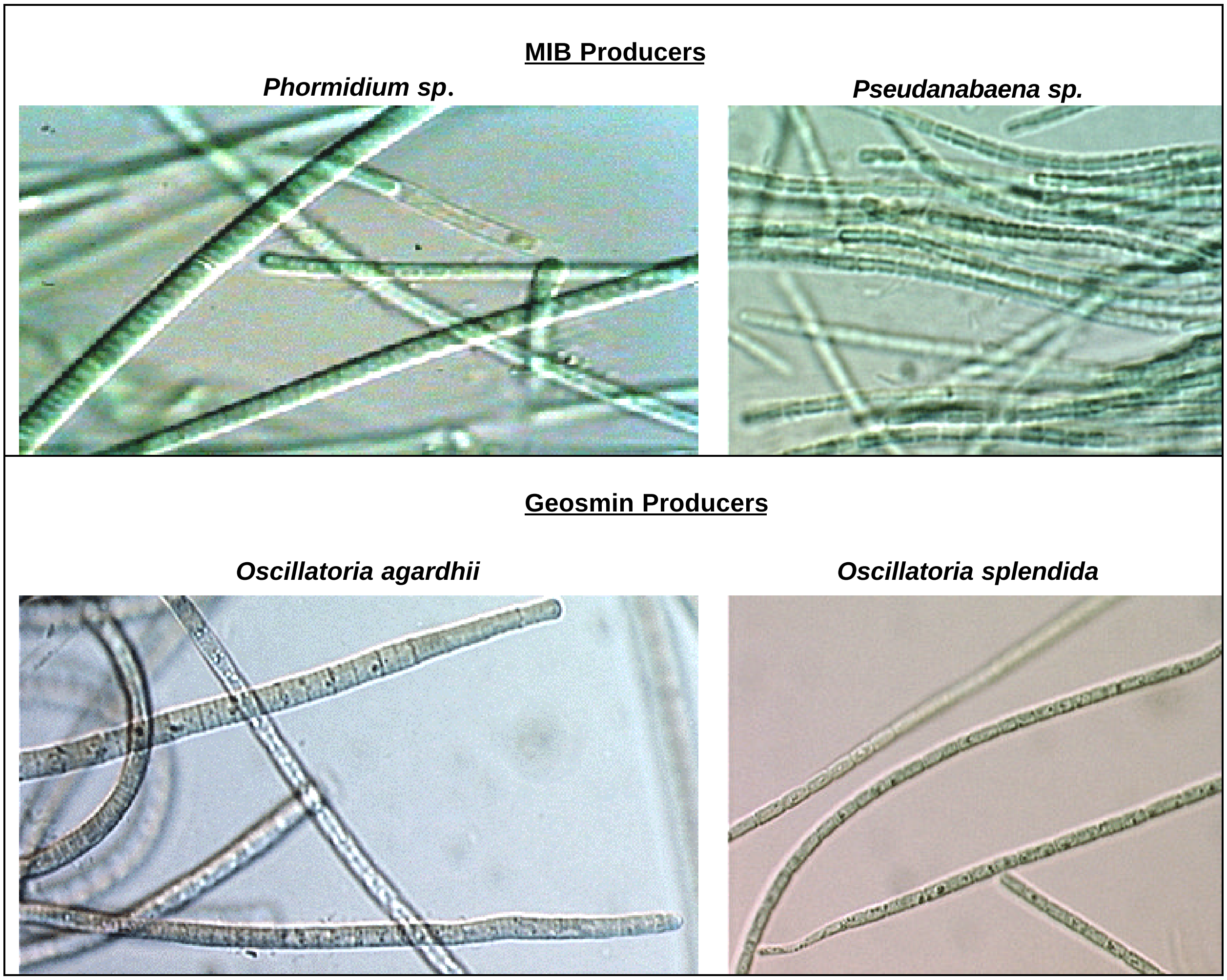


Figure 4-1. Blue-green algae producers of MIB and geosmin belonging to the taxonomic family Oscillatoriaceae.

An estimate of periphyton biomass on canal walls and lake plankton can be determined by extracting an aliquot of periphyton sample in 100% acetone at 4^0 C in the dark for 48 hours and then measuring for chlorophyll *a* absorbance at 664 nm with a spectrophotometer (American Public Health Association et al., 1999).

The Interactive Taxonomic Guide (CD-ROM) developed for this project enables one to identify a potential producer, but confirmation of production requires validation by GC/MS analysis of the isolated organism. Generally, production of MIB/geosmin increases with increase in producer biomass. However, since periphytic producers usually represent only a small fraction of the total algal biomass, biomass estimates (chlorophyll *a*) are of limited value in predicting MIB/geosmin production, especially in the reservoirs. In the Arizona Canal, MIB concentrations typically became elevated when chlorophyll *a* values exceed 10 mg/m^2.

Although many species of blue-green algae are present in the reservoirs and canals, not all species within a given genus, or even strains within a species produce MIB and geosmin. The presence of certain culprit algae may not necessarily mean that MIB and/or geosmin is being produced. Several of the MIB producers appear to be able to turn on/off production in the laboratory. Production of T&O compounds should be verified by GC/MS analysis.

MIB and geosmin. Analyze by FPA, or preferably by GC/MS. Rapid turnaround is paramount for making decisions on water supply management, canal treatment, or in-plant process options. Analytical results reported within 72 hours of sampling is a reasonable goal.

Flavor Profile Analysis (FPA) panels should be trained by experts and chlorine should be quenched with hydrogen peroxide in order to specifically detect MIB or geosmin.

MIB and geosmin can be measured using Solid-Phase Microextraction/Gas Chromatography/Mass Spectroscopy (SPME-GC/MS) (Watson et al., 2000; Lloyd et al., 1998). Details of the method used in the recent study are given in Appendix C.

4.3 MONITORING IN PRESSURIZED WATER DISTRIBUTION SYSTEMS

Algae do not pass through sand filtration systems at the WTPs nor grow in the absence of light, and therefore typically are not present in pressurized pipe water distribution systems carrying finished drinking water from the WTPs. However, fungi, bacteria (e.g., actinomycetes) and other organisms can grow in water distribution systems and also impart earthy, musty, moldy odors to water. Therefore, customer complaints about tap water may be caused from either: (1) T&O compounds in finished water leaving the WTP or (2) T&O compounds produced within the pressurized water distribution system. If a water utility suspects the latter due to numerous complaints from a localized region of the water distribution system, then samples from the distribution system should be collected. Preferred sampling would include a responsive program where samples from the service tap and customer faucet are collected and analyzed for chlorine residual (field) and MIB/geosmin (lab). Many complaints are actually from chlorine residual. If a routine monitoring program is desired, then points within the water distribution system should represent points of historic microbial concern (e.g., high plate counts, low chlorine residuals).

4.4 PREDICTION OF T&O PROBLEMS

4.4.1 Rationale for Prediction

The ability to predict the occurrence of T&O episodes is important for water resources planning and for water treatment plant staff for three reasons:

1. Some T&O episodes may be prevented. For example, canal treatments can be used to prevent the growth of T&O culprit algae. To utilize canal treatments effectively, it is desirable to know where and when T&O episodes are likely to

occur, because it is too expensive to treat the entire canal throughout the T&O season.

2. Some T&O episodes may be avoided. In many cases, it may not be possible to prevent the production of T&O compounds upstream, but water resources managers could manage the water supply system to prevent poor-tasting water from reaching consumers. This can be done through reservoir management, blending of source waters, or source switching (reducing production at a WTP receiving poor-tasting water while simultaneously increasing production at a WTP receiving better quality water). These management procedures will be discussed later.

3. Water treatment plants can remove T&O compounds, but need advance warning to do this effectively. T&O compounds can generally be reduced below threshold levels using powdered activated carbon (PAC) within the WTPs. However, treatment plant operators need to know when T&O episodes will occur so that they can order PAC and prepare their WTPs for an episode.

4.4.2 Reservoirs

MIB was produced in all three of the water storage reservoirs above the canal distribution system (Section 2). Prediction of when MIB is likely to be released from each reservoir, and its impact on Phoenix's water supply, is now possible.

As noted above, MIB is produced by certain blue-green algae, which grow primarily either in shallow near shore areas or suspended in the epilimnion. MIB concentrations in the epilimnia of all three reservoirs commonly exceed 20 ng/L during the summer stratification period. Concentrations of MIB in the outlets from the reservoirs during summer stratification are nearly always much lower than found in the epilimnion, because water is released from the hypolimnion. Figures 4-2 through 4-4 show MIB concentrations in the reservoirs and their outlets.

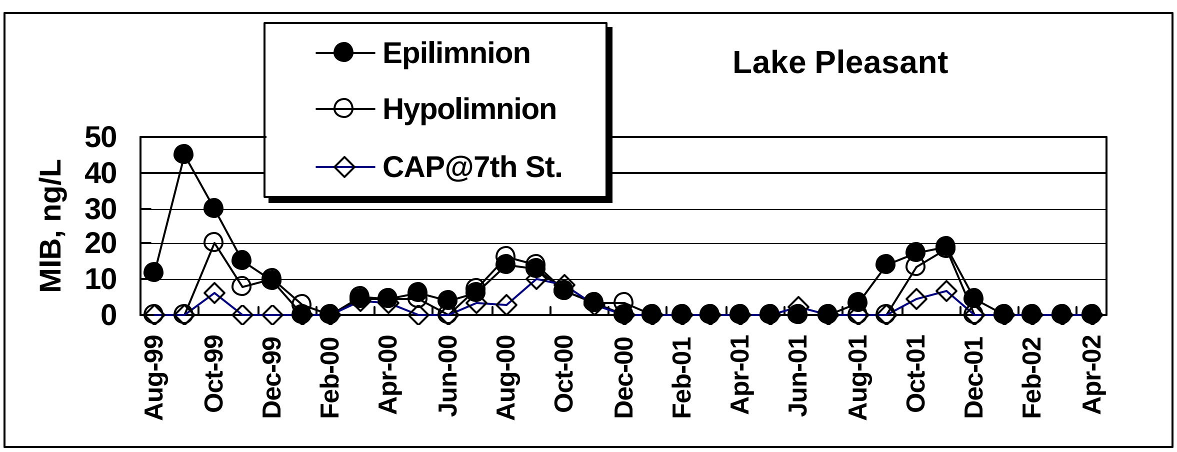


Figure 4-2. MIB in the epilminion, hypolimnion, and outflow from Lake Pleasant.

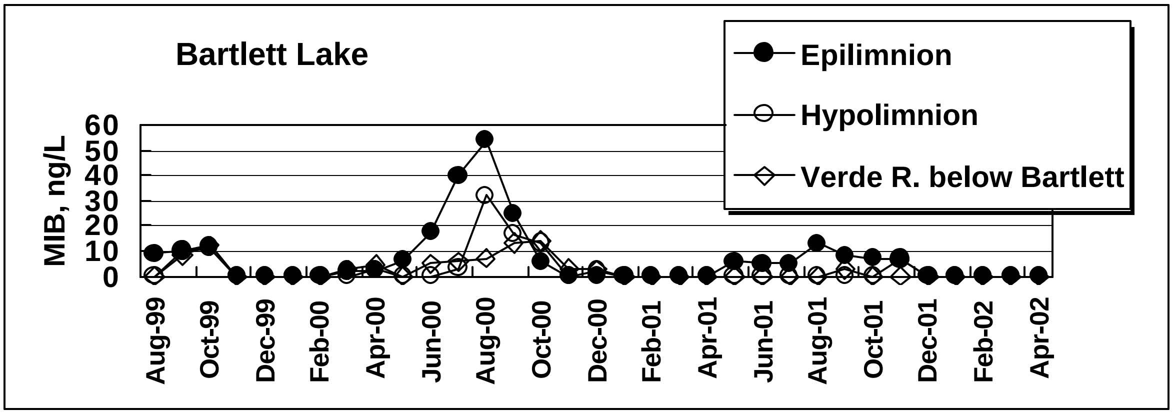


Figure 4-3. MIB in the epilimnion, hypolimion, and outflow from Bartlett Lake.

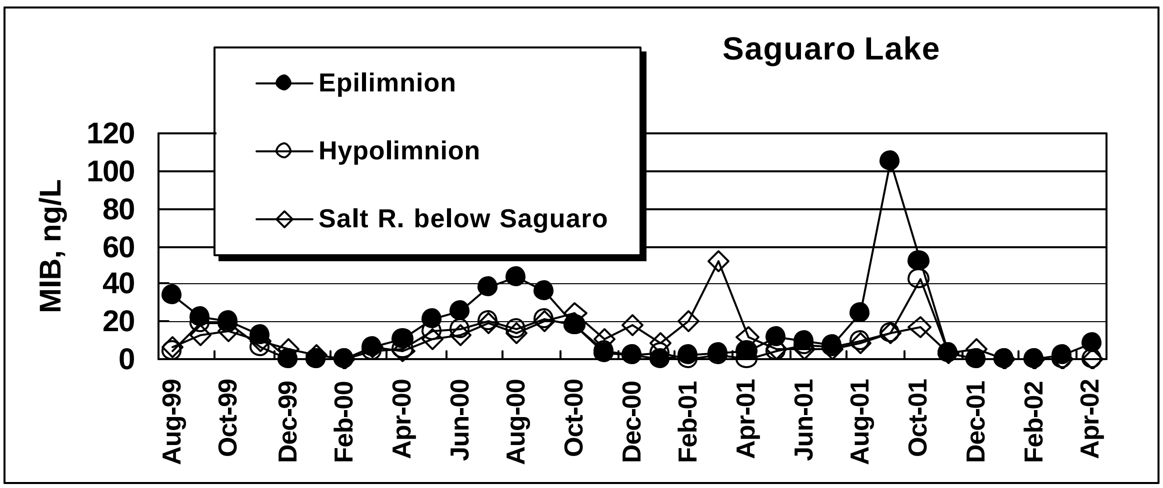


Figure 4-4. MIB in the epilimnion, hypolimion, and outflow from Saguaro Lake.

For Lakes Pleasant and Bartlett, MIB in water released from the hypolimnion during the stratification period rarely or never exceeds 10 ng/L (Figures 4-2 and 4-3). Water released from Saguaro is most often in the range of 10-20 ng/L during the summer stratification period. The higher concentrations for Saguaro occur for two reasons. First, MIB concentrations in the epilimion of Saguaro Lake are higher than in the other two reservoirs (Figure 4-4). Second, Saguaro is not as strongly stratified, as the other two reservoirs, which results in more mixing between the epilimnion and hypolimion.

Mixing of the water column occurs in Saguaro and Bartlett Lakes around mid-October, and in Lake Pleasant in November. At lake turnover, MIB levels become uniform throughout the lake, increasing the concentration of MIB released downstream. For both Bartlett and Saguaro, peak MIB concentrations in the released water occurred during October, following turnover (Table 4-3).

Table 4-3. Average monthly MIB concentrations over the three-year T&O study for the CAP Canal at 7th Street (release from Lake Pleasant and/or Colorado River water), the Verde River below Bartlett Lake, and the Salt River below Saguaro Lake. The time of thermal destratification turnover is indicated by boldfaced values.

	CAP at 7th Street	Verde R. below Bartlett Lake	Salt River below Saguaro Lake
January	0	0	4
February	0	0	7
March	1	1	19
April	1	2	5
May	0	0	8
June	1	2	9
July	1	3	12
August	2	2	10
September	4	8	16
October	4	**13**	**19**
November	**5**	2	8
December	0	1	10

MIB in the reservoirs degrades slowly after turnover, reducing the concentrations throughout the winter. Lab experiments and mass balance studies show that a typical MIB degradation rate is about 1 ng/L-day (Figure 4-5).

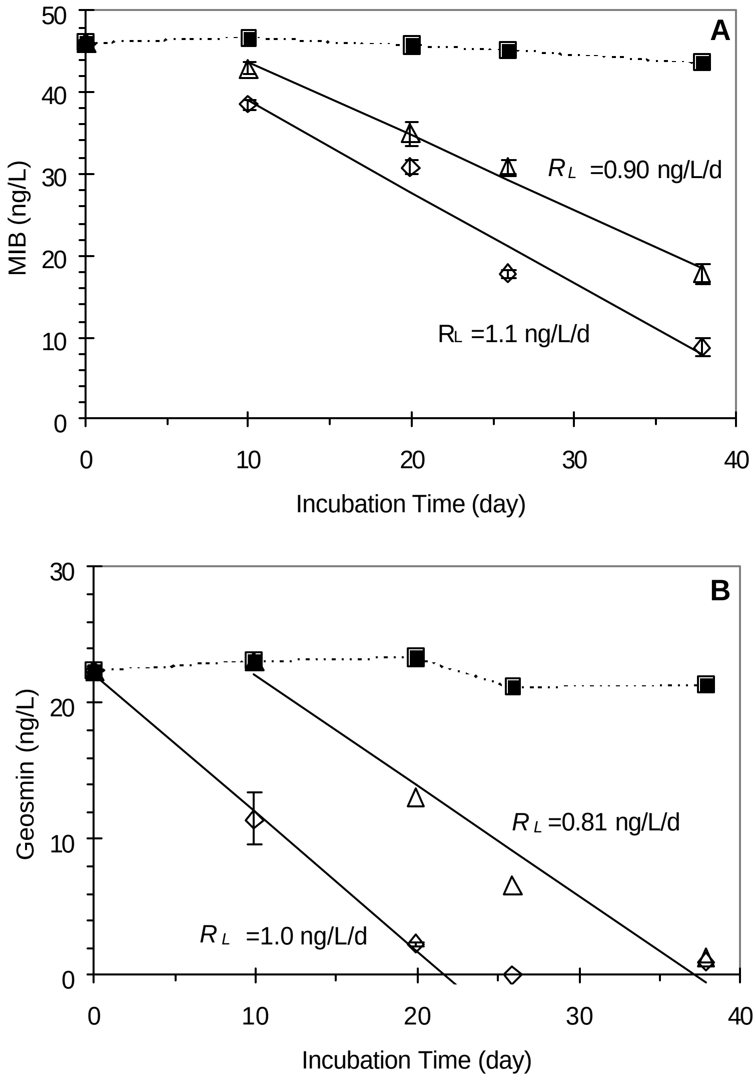


Figure 4-5. Kinetic degradation of MIB (A) and geosmin (B) in water collected at a depth of 5 m from Saguaro Lake (September 2000). Abiotic (filtered) control sample (■); sample without added bioseed (△); sample with the added bioseed (◇). Error bars are one standard deviation. Lines represent fitted laboratory pseudo zero-order rates (R_L).

Finally, the amount of MIB in SRP water depends upon which side of the system is delivering water. The timing of the Salt-to-Verde shift is important. This shift normally occurs in October (Table 4-4). Because MIB levels are normally higher in the Salt River than in the Verde River, the switch generally decreases MIB in water delivered to the Arizona and South Canals.

Table 4-4. Timing of the Salt-to-Verde shift over the past five years.

Year	Timing of the Salt-to-Verde shift
1996	October 25
1997	October 25
1998	October 23
1999	October 2
2000	October 3
2001	October 17

In summary, management implications of these patterns are:

Lake Pleasant. MIB is produced in the epilimnion, reaching concentrations of 15-45 ng/L during late summer. However, CAWCD has altered its operations so that the high-MIB epilimnetic water never reaches the CAP canal. *CAP water is therefore a reliable source of low MIB water throughout the year.* The operational modifications used by the CAWCD to maintain low MIB water and the implications for blending are discussed in (Section 5).

Bartlett Lake. MIB is produced in the epilimnion during the summer when the reservoir is well-stratified. Concentrations in the hypolimnion are lower. Because water is released the hypolimnion, water released to the Verde River during summer stratification has MIB < 10 ng/L. MIB concentrations in the outlet of Bartlett Reservoir increase to 10-15 ng/L after fall turnover. However, Phoenix's WTPs receive very little Verde River water until the Salt-to-Verde switch occurs in early to mid-October. By this time, much of the MIB in Bartlett Lake has been degraded. By November, MIB concentrations in the Verde River normally decline to < 10 ng/L. *In summary, the only time the Verde River contributes significantly to T&O problems is during the brief period in October just after the Salt to Verde switch.*

Saguaro Lake. Among the three reservoirs, Saguaro Lake generally has the highest MIB levels. The mid-summer MIB peak exceeded 100 ng/L in 2001 (Figure 4-4). As with the other reservoirs, MIB levels are lower in the hypolimnion. From August through October, when most of the water entering the Arizona and South Canals is coming from the Salt River, MIB levels in the Salt River below Saguaro Reservoir averaged ca. 15 ng/L, with little year-to-year variation (standard deviation = 6 ng/L). *In summary, among the three reservoirs, Saguaro is the most significant source of MIB.*

The very high levels in the Salt River below Saguaro River during the winter are misleading. During this period, there is very little flow in the river. MIB is probably produced by algae living on the bottom of the river and builds up with the low flow because there is no dilution. This midwinter buildup of MIB is not a problem because very little water from the Salt River is delivered to Phoenix during this period.

4.4.3 MIB production in the Arizona Canal

There is considerable MIB production within the Arizona Canal, particularly during late summer (Section 2). The source of MIB-producing algae growing in the canals can be greatly reduced by treating the canals with copper or brushing (Section 5). It would be prohibitively expensive to treat the entire Arizona Canal throughout the whole year. To be cost-efficient, it is necessary to *target* the treatments. Targeting is based on two general observations:

1. At any given time, most of the MIB produced in the Arizona Canal is produced within fairly short sections of the canal.

2. Although small amounts of MIB are produced in the Arizona Canal throughout the year, peak production occurs at specific times of the year.

It is impossible to predict *exactly* where and when MIB pulses will occur, but some patterns can be seen. First, temperature seems to be a critical factor. The linear relationship between temperature and MIB production is weak, but there is a temperature threshold for high within-canal MIB production. This relationship is shown in Figures 4-6 and 4-7.The temperature threshold appears to be around 22 ^{o} C. When the temperature in the spring is below 22 ^{o} C there is very little MIB production in the Arizona Canal. MIB production starts when the temperature rises above 22 ^{o} C; MIB episodes are often observed before the temperature reaches 25 ^{o} C. MIB production above the Squaw Peak WTP is almost always less than 10 ng/L when the temperature is less than 22^{o} C. MIB production above the Deer Valley WTP remains less than 20 ng/L until the temperature reaches 22 ^{o} C. This does not mean that there is always MIB production when the temperature is greater than 22^{o} C, but that MIB production will almost *always* be relatively low until the temperature reaches 22^{o} C. This point generally occurs in early June. MIB production within the Arizona Canal typically remains significant through the end of the year (until canal shutdown).

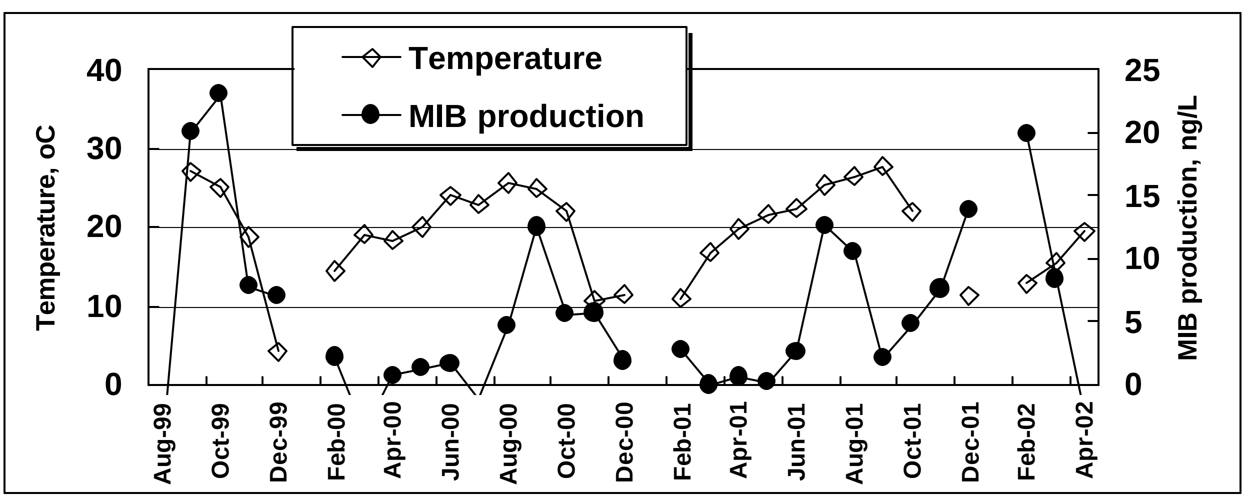


Figure 4-6. Trend of within-canal MIB production and temperature at the Squaw Peak WTP.

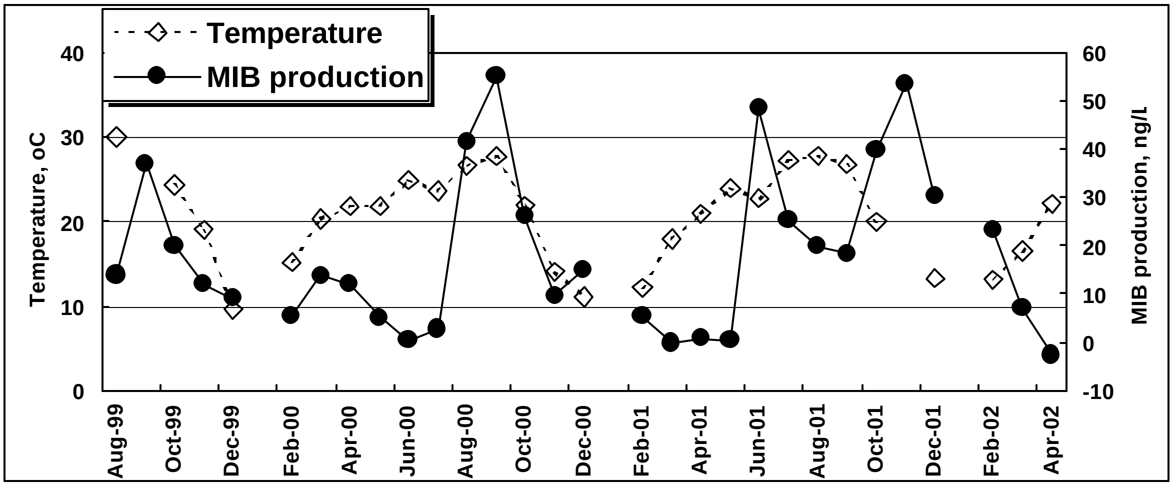


Figure 4-7. Trend of within-canal MIB production and temperature at the Deer Valley WTP.

Most of the MIB production in the Arizona Canal occurs in "hot spots." These include: the upper Arizona Canal between Highway 87 and Mesa Drive and the Arizona Canal between the Squaw Peak and Deer Valley WTPs (Figure 4-8). The latter is the single most significant hot spot for MIB production on the Arizona Canal.

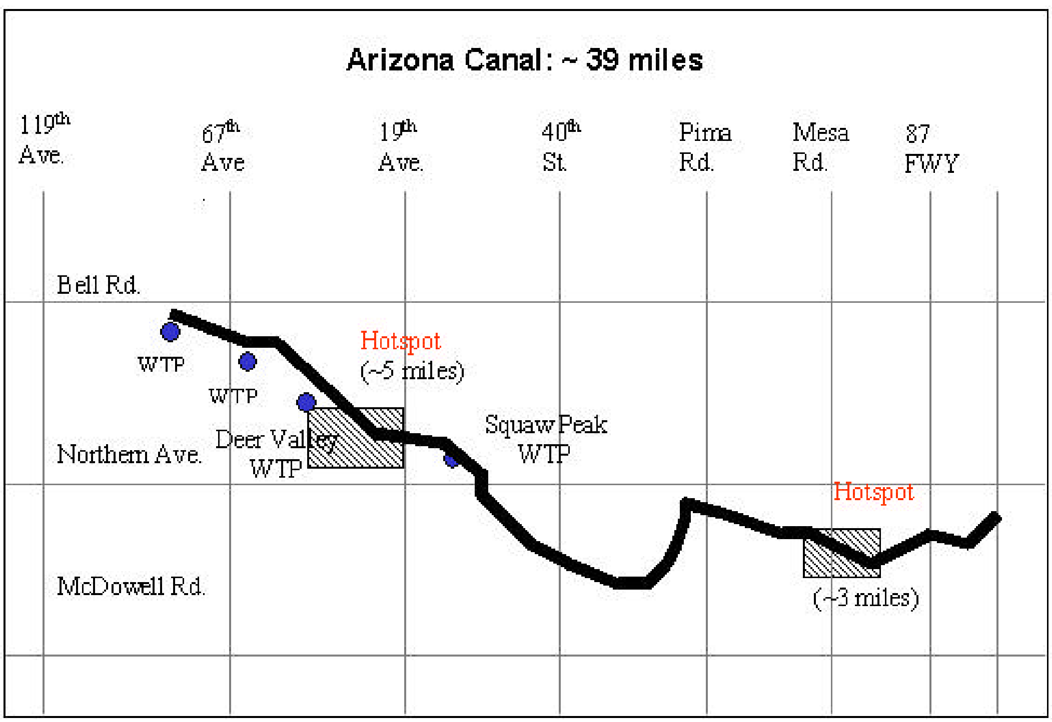


Figure 4-8 Two "hot spots" of MIB production in the Arizona Canal observed in 2001.

An intensive monitoring program, beginning around June, should be initiated each year to detect MIB production within the Arizona Canal. This monitoring program should collect samples once every one to two weeks at about 10 sites along the length of the Canal.

SECTION 5
SPECIFIC MANAGEMENT PRACTICES

5.1 BACKGROUND

Decisions to alter management of water supplies, treatment of canals, or changes in water treatment plant operations require high-quality and up-to-date monitoring data (i.e., process control monitoring – Section 4). Without such information decision-making is usually too slow to have a significant benefit, and could actually be detrimental. This section identifies details of specific management barriers. Section 6 addresses methods for effective communication of data to allow rapid decision-making.

5.2 WATER SUPPLY OPERATIONS

5.2.1 Rationale

Management of water supply operations can be used to minimize MIB inflows to the Arizona Canal. Managing source waters to keep MIB as low as possible is important for three reasons:

1. It significantly lowers the cost of in-plant PAC treatment.

2. The Deer Valley and Squaw Peak WTPs currently cannot treat water with very high MIB (> 20 ng/L) levels because the current PAC-feed facilities are inadequate.

3. It benefits many cities.

Two major modifications that have been used with some success are (1) modified operation of Lake Pleasant, and (2) blending of SRP and CAP waters.

5.2.2 Modification of Lake Pleasant Operation

Lake Pleasant has two outlets located at 1506’ and 1610’ above mean sea level, and is a pumped storage reservoir. The flexibility of Lake Pleasant’s plumbing system allows considerable flexibility in water operations. The CAWCD has used this flexibility to alter the operation of Lake Pleasant and improve the quality of water delivered to the CAP Canal.

Prior to 1999, normal operation was to pump water from the Colorado River from November through May. Starting in May, water was released from Lake Pleasant to the CAP Canal downstream throughout the summer. Water was released from the upper penstock. During the summer, this meant that water was being released from the epilimnion. Because MIB was produced in the epilimnion, water released had high levels of MIB, creating a T&O problem downstream.

In the fall of 1999, CAWCD responded to consumer complaints by switching to hypolimnetic release (Figure 5-1). This kept MIB levels < 10 ng/L until turnover. After turnover, the average concentration of MIB increased to 20 ng/L (Figure 5-1, October). At that time, CAWCD stopped releasing water from the reservoir and routed water from the Colorado River directly to the Phoenix metropolitan area (by-pass pumping). This operational strategy succeeded in keeping MIB concentrations in water delivered to the Phoenix area < 10 ng/L throughout the season. If CAWCD had not modified its operation, MIB levels in water delivered to customers would have approached 50 ng/L.

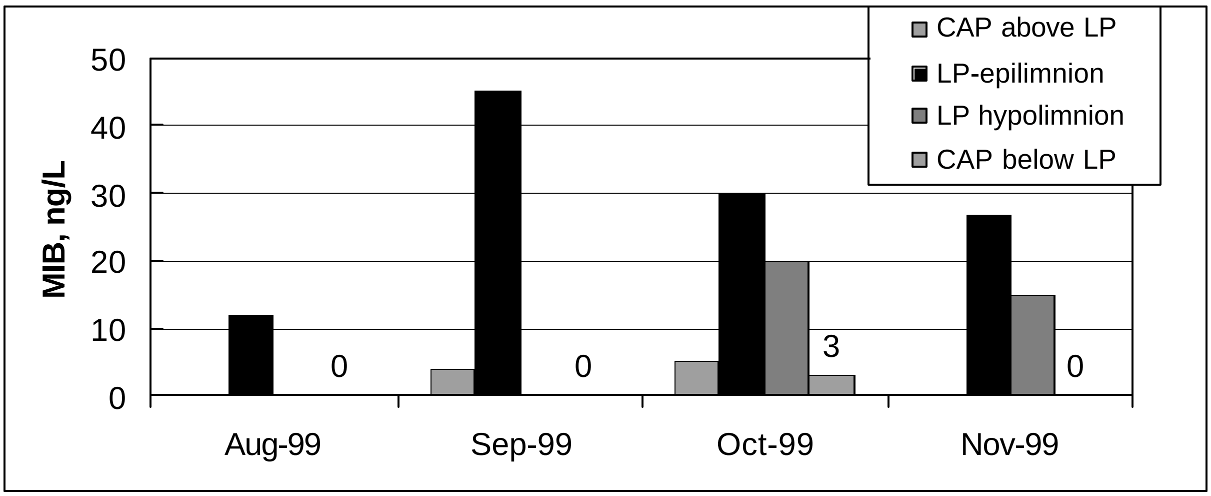


Figure 5-1. MIB in Lake Pleasant and the CAP Canal in summer-fall 1999.

From 1999 to 2001, MIB concentrations in the CAP Canal at 7th Street have consistently remained below 10 ng/L, even when MIB concentrations in the epilimnion were elevated (Figure 5-2).

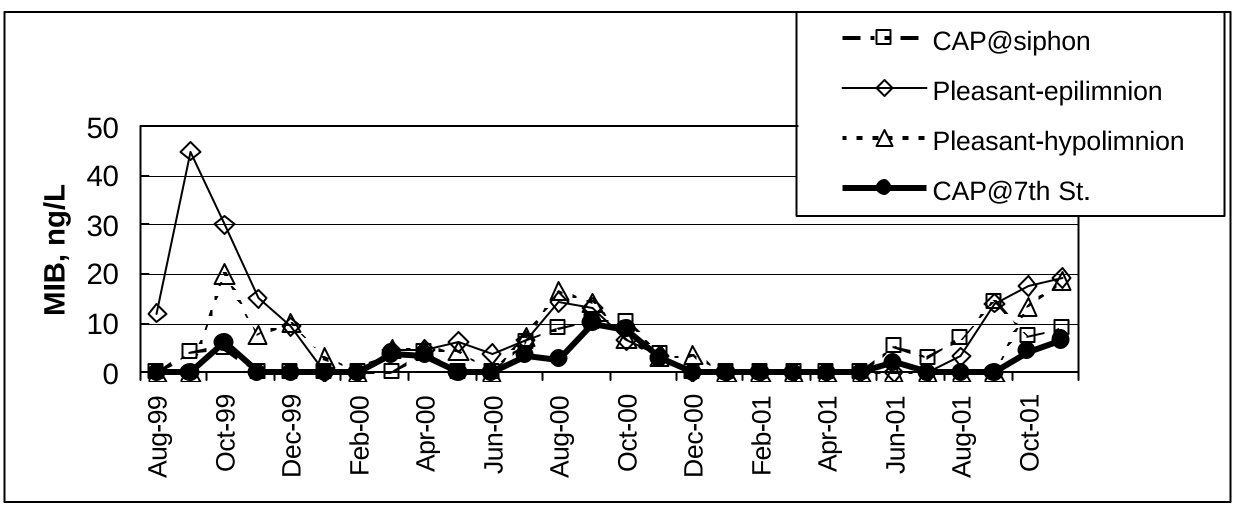


Figure 5-2. MIB in Lake Pleasant and the CAP Canal from 1999 to 2002.

The recommended weekly intensive monitoring program includes the CAP Canal at the Granite Reef Cross-Connect Facility. An observation of elevated MIB levels at this point should trigger an immediate examination of MIB in the CAP system at points R1 (Colorado River), R2A and B (Lake Pleasant), R3 (Wadell Canal), and R4 (CAP Canal at 7th Street) to determine the source of the MIB and identify an alternative source. For example, if hypolimnetic water had high MIB, releases could be stopped temporarily and deliveries could be made by routing Colorado River water past Lake Pleasant and into the Phoenix area. As a second example, if the Colorado River at R1 had elevated MIB levels during the late fall, deliveries could be halted temporarily and water could be delivered from Lake Pleasant.

In summary, modification of CAP operations has been successful in reducing MIB levels and should be continued.

5.2.3 SRP-CAP Blending

The concept of blending water sources is simple. For quantities (Q) of two water sources, A and B, the MIB concentration of the blended source (C) is:

$$[MIB]_C = \frac{\{[MIB]_A * Q_A + [MIB]_B * Q_B\}}{Q_A + Q_B} \qquad \text{Equation 5.1}$$

Blending can be used to improve water quality delivered to the Arizona and South Canals, because both canals can receive both CAP and SRP water at the Granite Reef Cross-connect Facility.

For example, if 1000 AF/day was delivered from the SRP system, with an MIB concentration of 10 ng/L and 500 AF/day was delivered from the CAP system, with an MIB concentration of 5 ng/L, the blend in the Arizona Canal would have the following MIB concentration:

$$MIB = \frac{(10)(1000) + (5)(500)}{(500 + 1000)} = 8 \text{ ng/L} \qquad \text{Equation 5.2}$$

CAP water nearly always has lower MIB levels than SRP water. This is especially true during the late summer and fall, when MIB levels in SRP water are often elevated (Figure 5-3).

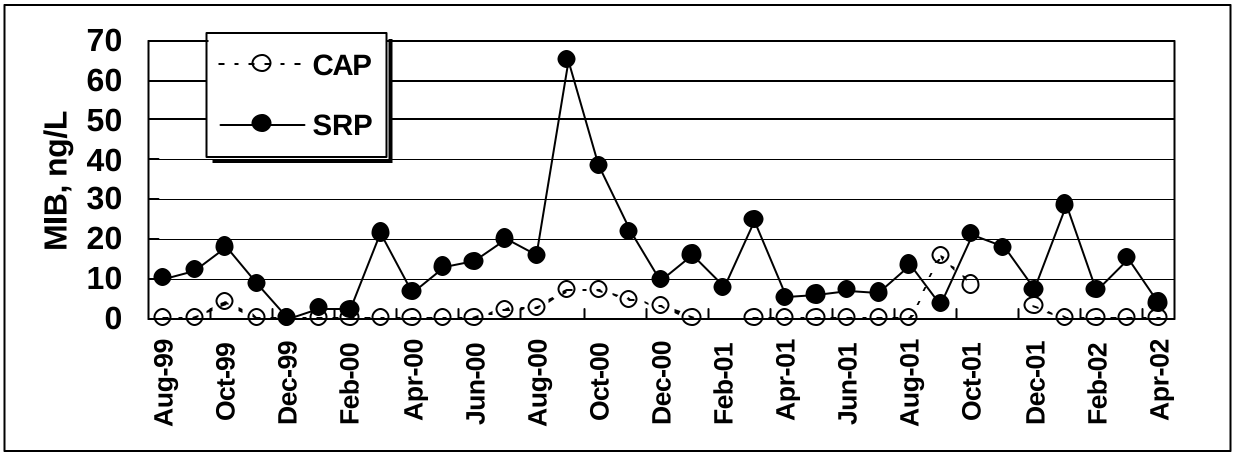


Figure 5-3. MIB in the CAP and SRP inflows to the head of the Arizona Canal.

There is always some blending of CAP and SRP water, which has reduced MIB levels in the Arizona Canal over the past few years. MIB levels at site R13 (about a mile below the CAP inlet) are well-below levels in the SRP water. By deliberately optimizing the blend, MIB levels in the Arizona Canal could be even further reduced. Note that both CAP and SRP waters have relatively low MIB during the early summer, with the exception of March, when the startup of the Salt River moves stagnant water into the Arizona Canal. Later in the summer and into the fall, MIB in CAP water remains low, while MIB in the SRP water increases.

The average monthly differences in MIB concentrations (MIB in SRP water minus MIB in CAP water) is shown in Figure 5-4.

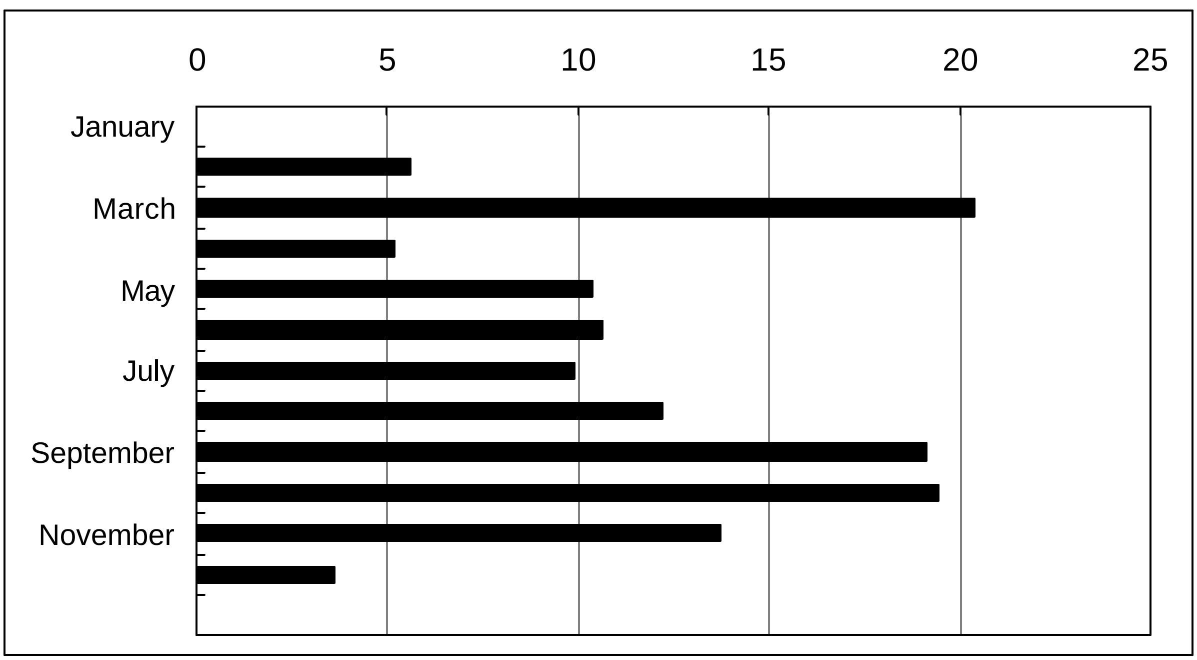


Figure 5-4. Average differences in MIB concentrations (ng/L) between SRP water and CAP water, by month, from August 1999 to April 2002.

As a general rule, blending to minimize T&O problems in the Arizona Canal would utilize a greater proportion of SRP water early in the season when MIB levels are low in both CAP and SRP waters and more CAP water later in the season, when CAP water has low MIB and SRP water typically has much higher MIB levels.

However, there are a number of institutional issues regarding blending. Some of these include:

1. Water Exchange Agreement. The Water Exchange Agreement was recently modified by the Arizona Legislature to allow water exchanges to occur over periods longer than one year. Water borrowed during one year during an exchange can now be "paid back" at some point beyond the end of that year. This increases the flexibility of SRP-CAP blending.

2. Maintenance of flood capacity. SRP must release enough water from its reservoirs during the later summer and fall to provide capacity for flood protection in the spring. This constraint applies primarily to the Verde River system, which has less storage capacity. The operating goal is to reduce the combined volume of Horseshoe and Bartlett reservoirs to 150,000 AF by the end of October. This constraint is important only in wet years.

3. M&I Agreement. The M&I Agreement between CAWCD and the cities mandates that no city can order more than 11% of its annual CAP delivery in a single month. For Phoenix, with an original allotment of 113,822 AF/yr, this translates to a maximum allotment in a given month of 135 MGD. This constraint may be circumvented during "surplus" years.

4. Capacity of the Arizona Canal. Municipalities share capacity in the "common" part of the CAP Interconnect Canal and in the Arizona and South Canals. The total capacity of the common section is 1,200 cfs. Gates to the South and Arizona Canals each have a capacity of 800 cfs. Phoenix owns 18.75% of the common canal (225 cfs), 31.25% (250 cfs) of the capacity in the turnout to the South Canal, and 60.75% (486 cfs) of the capacity in the turnout to the Arizona Canal. The limiting capacity is the leased capacity from the common portion of the CAP turnout, 225 cfs. During September-October, when T&O problems reach a peak, flows in the Arizona Canal have ranged from about 500 to 800 cfs. Phoenix's 225 cfs capacity at the CAP turnout would therefore be about one-half to one-third of the typical flow of the Arizona Canal during this period. This limits the extent of blending that can occur with Phoenix acting independently of other cities. A coordinated effort involving other cities, in which each city received CAP deliveries during the peak of the T&O season, would overcome this constraint.

5. Lost revenue. Phoenix is obligated to pay for loss of revenue incurred by SRP if it doesn't accept its water delivery. This could be a serious constraint up through the time (generally very early October) when SRP switches deliveries from the Salt River to the Verde River.

6. Apache Lake drawdown. SRP must drain 25,000 AF (833 AF/day, or 416 cfs) from Apache Lake in September to increase storage capacity. This constraint is important, because this is a considerable portion of the flow in the Arizona and South Canals during September.

7. Maintenance of minimum flow in the Verde River. SRP must maintain 100 cfs "plus orders" flow in the Verde River, per agreement with the Gila River Indian Community. This constraint has minimal effect on blending considerations.

8. Maintenance of minimum flow across the Arizona Canal fish barrier. Flow across the fish barrier at the head of the Arizona Canal must be maintained at 100 cfs. This means that at least 20% of the flow in the Arizona Canal will always be SRP water during low flow. Again, this is a minor constraint with respect to the feasibility of blending.

9. Maintenance of minimum flow from Apache Lake. Flow from Apache Lake must be maintained at 8 cfs (~ 475 AF/month) from November 1 to May 1, per agreement with U.S. Fish and Wildlife. This regulation is not important, because T&O problems generally occur in the late summer and fall.

10. Nitrate levels in the Arizona Canal. Pumping from SRP wells may be limited if it causes elevated nitrate or salt buildup. This constraint would not likely be important for the Arizona Canal, because nitrate levels never approach EPA's MCL.

The newly modified Water Exchange Agreement should give the water utilities greater flexibility with respect to blending. In general, however, other constraints probably limit the extent to which blending could be used to achieve better water quality in the Arizona Canal in normal-to-wet years. During dry years, more CAP water would be used to augment the SRP water supply. COP could take advantage of this situation in dry years to optimize the delivery of CAP and SRP waters by using a greater proportion of SRP water early in the season (April-August) and more CAP water later in the season (e.g., September-October).

5.3 MANAGEMENT OF CANALS

The canal system is a major source of MIB/geosmin production. Over a ten-fold increase in MIB/geosmin concentrations has been detected over a distance of a few miles of the canal during the summer and fall. Several species of blue-green algae, which are primarily distributed along the canal sidewalls, are confirmed producers of MIB. Two in-canal implementation strategies have been developed to prevent growth of T&O culprit organisms in the canal system. One is copper treatment and the other is canal wall brushing. The two approaches have been implemented primarily in the Arizona Canal. However, the principles and techniques involved in these treatments are applicable to other canals within the Phoenix water supply system, and may be further applicable for other regions where major open canal systems distribute water from reservoirs or other surface water supply systems.

Preventing and eliminating the growth of culprit organisms in the canal system will reduce MIB/geosmin concentrations in water entering into the WTPs. Copper treatment and canal wall brushing are effective and cost-affordable tools for reducing the T&O problem in canals. Brushing may be utilized as a more intensive localized algae control measure for known hotspots, whereas copper treatment is of greater systemic value since it affects a larger part of the canal system.

5.3.1 Copper Treatment

5.3.1.1 Selection of Desired Product

Two different types of copper-based algaecides, Cutrine-Plus and Earthtec, have been tested in the Arizona Canal. The former is a chelated elemental copper with triethanolamine, whereas the latter is a copper sulfate-based acidic solution (pH 0.5). Both are registered by the USEPA as algaecides, and the latter is certified to ANSI/NSF Standard 60, Drinking Water Treatment Chemicals.

Both algaecides reduced the production of MIB and geosmin in the canal, but Cutrine-Plus appeared to be more effective than the Earthtec copper. However, application of Cutrine-Plus in the canal resulted in a temporary increase in chlorine demand in the WTPs downstream shortly after copper application. In contrast, little chlorine demand was observed when Earthtec was introduced. The increase in chlorine demand was due to the reaction of triethanolamine residues of Cutrine-Plus with free chlorine to form organic chloramines. The Earthtec product is therefore the algaecide of choice.

5.3.1.2 Treatment Dose and Duration

The maximum recommended dosage of Earthtec solution is 0.2-0.4 mg/L Cu. Concentrations of 0.5 mg/L may result in some fish-kill. The toxicity of copper to blue-green algae and other microalgae is most pronounced under light conditions and when water temperature is at least 60° F. Therefore, it is critical to select sunny days for copper application, and to start application early in the day so that the treatment is conducted in continuous daylight. A dosing period of 6 to 8 hours achieves satisfactory results.

5.3.1.3 Treatment Site and Length

Copper addition should occur at the upper stretch of a canal section that experiences high concentrations of MIB and geosmin. Ideally, the copper solution should be added into the canal at a radial gate to facilitate even distribution and rapid mixing of copper. In case a radial gate is not available, a large dilution of concentrated Earthtec solution with water (ca. 1:10 dilution) is necessary prior to application. When Earthtec solution is added into the canal at one site, effective concentrations of copper (0.2-0.4 mg/l) may extend 5 to 6 miles downstream.

5.3.1.4 Calculation of Earthtec Dosing

Prior to treatment it is important to accurately determine water flow rates. Such data may be available from SRP headquarters. If not, it may be necessary to estimate flow in the field. To do this, estimate velocity by measuring off a short distance along the canal (e.g., 50 feet). Then drop a floating object at the upper end of the measured section and record the time it takes for the object to reach the lower end of the section in seconds. The velocity is the distance traveled divided by the travel time. The measurement should be repeated three times. Flow may be calculated as follows:

Flow, cfs = average width (feet) x average depth (feet) x velocity (feet/second) x 0.9
Equation 5.3

The amount of Earthtec needed to maintain the drip rate for a defined period of time can be calculated using the following formula:

Drip rate (L/min) = 1699 L/min/cfs x Canal flow (cfs) x Targeted concentration in canal ÷ Earthtec concentration
Equation 5.4

Where: Canal flow = CFS estimated with previous formula; Targeted concentration = 0.2-0.5 mg/l; Earthtec concentration = 60,000 mg/l.

5.3.1.5 Initial and Prolonged Treatment Effectiveness Interval

The initial copper application may be applied to the canal system in early summer (June or July) when the growth of blue-green algae mats begins to accelerate and MIB concentrations approach 10 ng/L.

Re-treatment of a canal section is necessary when significant re-growth of blue-green algae mats begins to appear on the surfaces of the submerged canal walls. A four-week interval between consecutive treatments is usually sufficient. Copper treatments appear to have an effective treatment length of about 5 to 6 miles.

5.3.1.6 Operational Issues

A 2- to 3-day advance notice is required for the SRP crew to prepare for copper application. Copper should be ordered by SRP two to four weeks prior to June to ensure its availability for application.

5.3.2 Canal Wall Brushing

5.3.2.1 Principle of Canal Wall Brushing

The biological basis of canal wall brushing rests on the fact that most, if not all, T&O culprit organisms are periphyton, growing along with other microorganisms in microbial mats attached to the canal walls. Although exact reasons are unknown, the culprit species usually exhibit slower growth rates compared to many non-producers, and thus represent minor populations within a complex microbial community. Removing microbial mats from the canal walls by physical means, such as brushing, has proved to be an effective approach to prevent culprit organisms from proliferating, and to reduce the production of MIB and geosmin. Microbial mats removed from the canal walls and floating downstream did not cause significant spikes of MIB/geosmin concentration at downstream sites.

5.3.2.2 Method of Canal Wall Brushing

Brushing can be conducted by a SRP tractor-mounted custom-designed revolving metal brush, which measures 150 cm long and 80 cm in diameter and is operated at 60 rpm. An operator can clean both sides of the canal at a rate of about 1 to 2 miles/day (Figure 5-5).

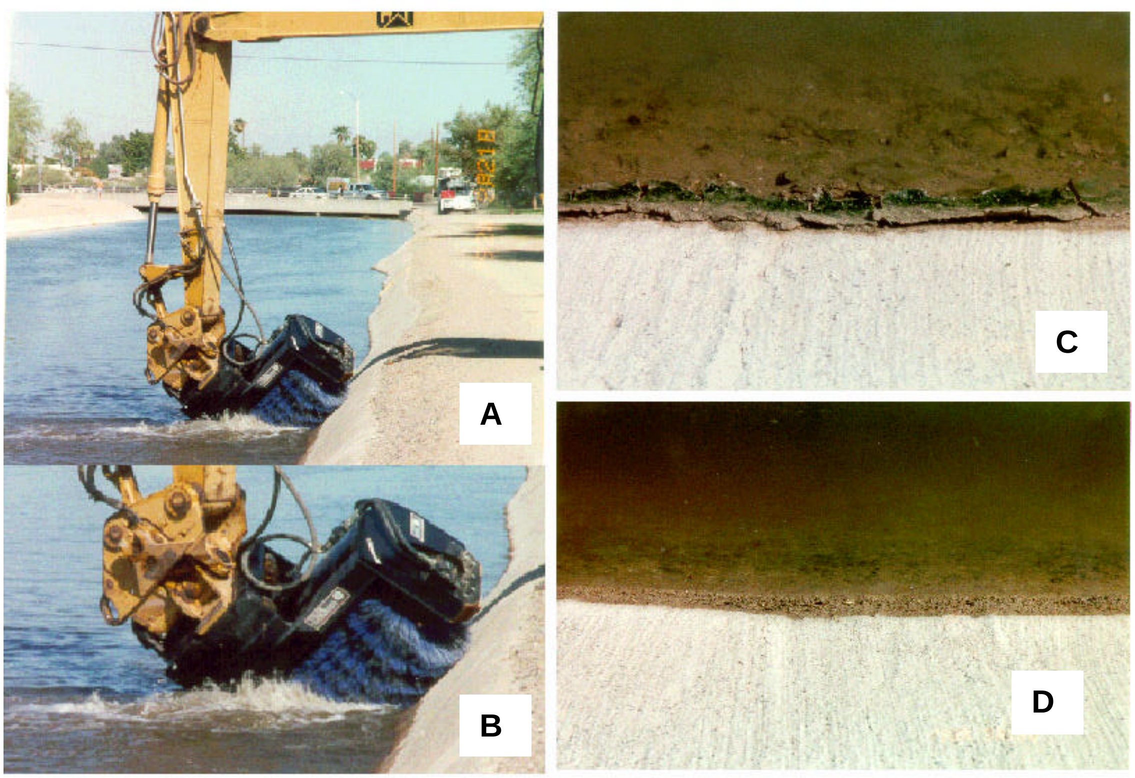


Figure 5-5. Mechanical Brushing Arizona Canal walls with custom designed device developed by SRP (A, B). Canal wall with algae mats before brushing (C) and canal wall without algae mats after brushing (D).

5.3.2.3 Initial and Prolonged Effectiveness

As with copper treatment, the initial brushing event should take place when periphyton appear as thin blue-green mats on the submerged canal walls. This usually occurs in early summer months (June to July). Brushing should be conducted on both sides of the canal, starting from the upper end of a treated section. Some 70-80% of periphyton biomass may be removed from the canal walls by brushing, resulting in reduced production of MIB and geosmin.

Periodic brushing will be needed to ensure the maximum effectiveness of the treatment. A recommended time interval between consecutive treatments is two to three weeks.

5.3.2.4 Limitations of Brushing

There are a number of physical limitations to the brushing technique. Brushing is not effective in canal sections where water depth is low (2 to 4 feet). Brushing is also difficult at the head of the canal, where water velocities are high. Water flowing at high velocity makes it difficult to maneuver the brush effectively because of the drag forces generated. Canal sections with elevated banks also make it impossible to reach the canal walls with the brushing arm. For this reason, brushing cannot be done effectively at the upper end of the Arizona Canal.

For canal brushing, two weeks advance reservation notice to SRP is required. Since a brushing unit can brush only 1 to 2 miles per day, the brushing procedure may be time-consuming if large reaches of the canal are to be treated.

5.3.3 Identification of hotspots

It is critical to identify MIB/geosmin production hotspots and, ideally, hotspots of the culprit organisms along the canal system in order to maximize the effectiveness and efficiency of copper treatment and canal wall brushing. Two reoccurring hotspots have been identified along the Arizona Canal:

- between the Beeline Highway and Mesa Drive (Figure 5-6)
- between the Squaw Peak and Deer Valley WTPs (Figure 5-7)

Hotspots can be readily identified by weekly sampling along the length of the Arizona Canal and analysis for MIB/geosmin concentrations. Rapid increases in MIB/geosmin over relatively short canal stretches represents “hotspots” of production.

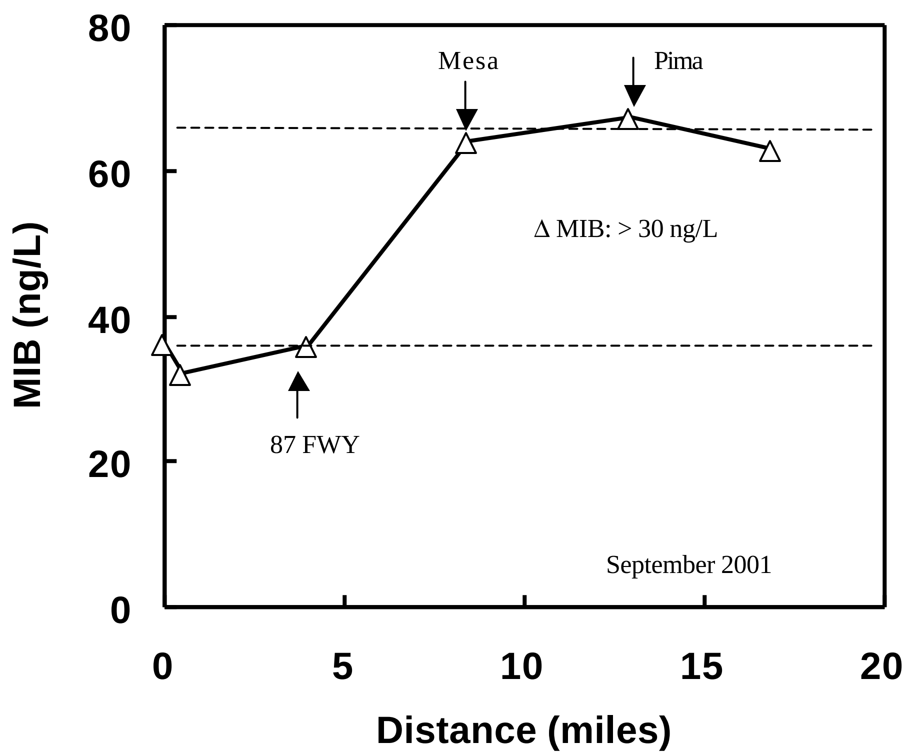


Figure 5-6. MIB concentrations along the Arizona Canal on September 20, 2001, showing a “hotspot” of MIB production between Highway 87 and Mesa Road.

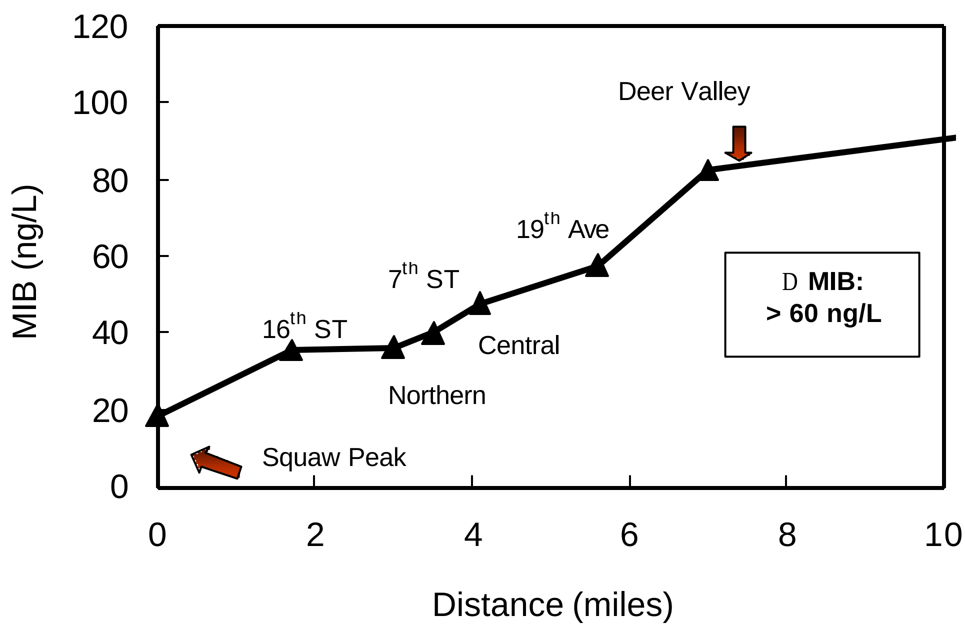


Figure 5-7. MIB Concentrations along the Arizona on during July 2000, showing “hotspot” of production between Squaw Peak and Deer Valley WTP.

Canal sampling can also confirm the effectiveness of treatment of "hotspots" (Figures 5-8 and 5-9) by demonstrating decreases in MIB/geosmin concentrations following the canal treatment.

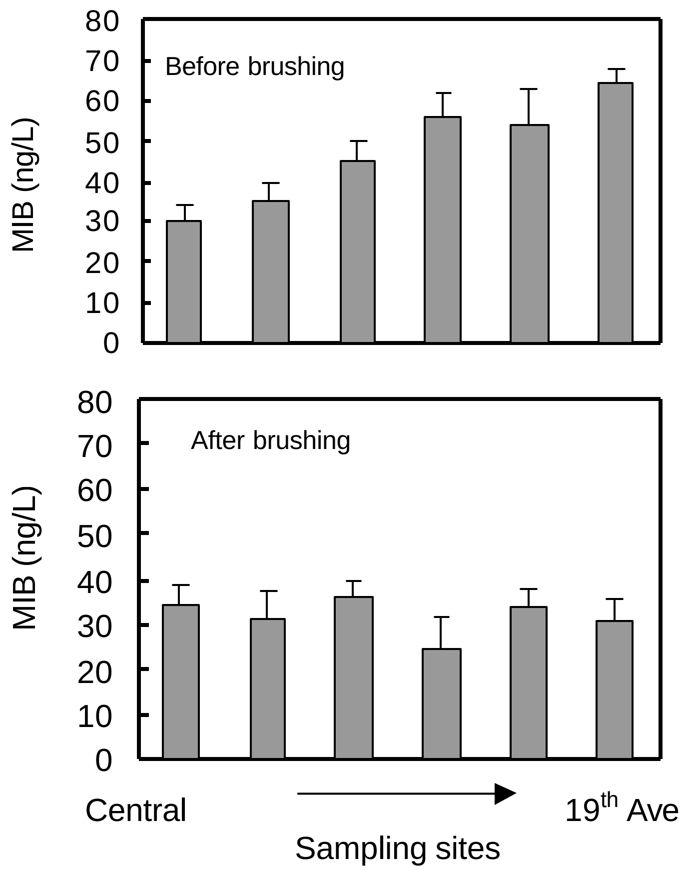


Figure 5-8. Effect of canal wall brushing on the reduction of MIB concentration. The treated Arizona Canal section was between Central and 19th Avenue (August 2000).

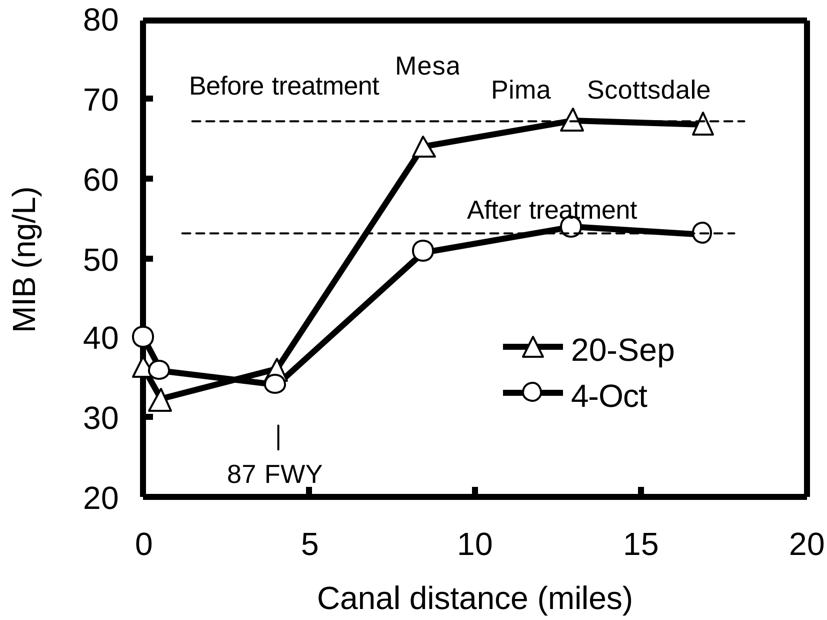


Figure 5-9. Effect of canal treatments (copper addition and canal wall brushing) on MIB production in the Arizona Canal upstream between Highway 87 and Mesa Drive.

5.3.4 Biocide Coating on Concrete Canal

Coating the concrete-lined canals could serve two benefits: (1) reduce frictional losses and increase hydraulic capacity of canals, and (2) reduce quantity of biomass attached to the surface. Two types of products were field-tested. First, a polymeric organic coating (Alphacoat 454), manufactured by Coating Systems Inc., has an active ingredient containing quaternary ammonium compounds with a trihydroxy silicone moiety. This ingredient is water-soluble and exists as a hydrated species. Thus the biocide is both water-soluble and becomes an insoluble polymer when bonded to a surface, by the process of evaporation of the water molecule. If there are hydroxy groups present in the substrate there will be better bonding as in the case of concrete and masonry. The insoluble long chain polymer ($-C_{18}H_{37}(CH_3)_2N^+CH_2CH_2CH_2Si(OH)_3Cl-$) imparts water repellency and the ammonium chloride gives the biocidal effectiveness. Second, a white-colored marine antifouling paint (EP2000) has been used on the hulls of boats to prevent algae and other marine microorganisms from attaching to the surface of the boats which reduce the efficiency of the marine vehicles. It was determined that EP2000 produces hydrogen peroxide on the surface, a mild disinfectant. Excess hydrogen peroxide can lead to chlorine consumption in water treatment applications, but was not considered significant at the low levels that may be produced in full-scale applications. Both coatings reduce surface tension, which would have the effect of decreasing surface roughness on the canal. Neither product currently has NSF approval for use in water treatment plants, but approval should be pursued. Based upon field-tests, a tentative recommendation would be to pursue the use of the antifouling paint.

The canal surfaces would need to be cleaned and then coated while the canal walls are dry. One to two coats of the product would be required. The coating should be applied from 1 foot above the high water level to a depth of 3 feet below the normal water level. It is currently unclear how frequently the coating would have to be reapplied.

5.4 WATER TREATMENT PLANT SOURCE SWITCHING

5.4.1 Rationale

Reduction of T&O problems can also be accomplished by source switching. As used here, the term source switching means switching water production from WTPs receiving poor quality water to plant(s) receiving better quality water.

Source switching can be useful to the WSD because the five main treatment plants receive water of varying quality (See Figures 2-1 and 2-2). As noted in Section 2, the order of MIB concentrations in the inflows of the treatment plants is:

(highest) Deer Valley >> Squaw Peak >> Val Vista >> Union Hills (lowest)

From a standpoint of T&O management, production should be increased at the Union Hills and Val Vista WTPs and reduced at the Deer Valley WTP, to the extent possible, during the peak of the T&O season (typically August to October).

5.4.2 Potential for Source Switching

The key factor that must be considered in using source switching is the total production capacity of the operable WTPs and the total consumer demand. Total operational production capacity can be managed, to some extent, by conducting repairs at times other than the peak of the T&O season, so that operational capacity is at a maximum when source switching is needed.

5.5 CONTROLS WITHIN WATER TREATMENT PLANTS

5.5.1 Prevent In-Plant MIB or Geosmin Production

Algae growth within WTPs pose both an operation problem and potential to form T&O compounds. Algae "mats" can clog weirs and algae cells of all types reduce filter run times. Substantial production of T&O compounds has not been observed in City of Phoenix WTPs, but MIB production within the WTP was observed by the City of Tempe and City of Chandler. Therefore, it is important to control the growth of algae within WTPs. The following techniques are recommended with certain qualifying statements:

- Prechlorination ahead of presedimentation basins is effective but increases DBP levels in finished waters by 10% to 25%.

- Liquid copper product (copper sulfate, Earthtec) ahead of presedimentation basins is effective.

- Powdered activated carbon (PAC) addition (> 3 mg/L) in presedimentation basins limits light penetration required for algae growth. PAC is removed near the head of sedimentation basins, so PAC provides limited algae control at sedimentation weirs or in filter basins.

Prechlorination treatment during periods of warm water (> 20^{o} C) could be conducted once every week for algae control. Prechlorination doses are selected to give a residual prior to additional chlorine addition near filters. Direct filtration and conventional WTPs in the metro-Phoenix region only remove 5% to 15% of the TOC. TOC can react with chlorine to form DBPs (THMs and HAAs). Therefore, delaying the point of chlorine until after TOC removal (after sedimentation basins) would be advantageous. Prechlorination for 24 hours increases DBP levels leaving the WTP for that period. Prechlorination should not take place concurrent with or prior to PAC addition because chlorine reacts with the PAC and reduces its effectiveness to adsorb MIB or geosmin. Prechlorination has not been observed to lyse algae cells resulting in release of MIB or geosmin.

Liquid copper products (e.g., copper sulfate, Earthtec) can be fed (0.3 to 0.8 mgCu/L) at the head of presedimentation basins to reduce algae growth. Copper is toxic to algae at low levels. Copper addition for 12 to 24 hours once every 9 to 14 days should control algae growth. Excessive copper addition can lead to growth of copper-resistant algae, and accumulation of copper in WTP and wastewater sludges. Recommended copper doses are below action levels for the Lead and Copper Rule. Copper addition has not been observed to lyse algae cells resulting in release of MIB or geosmin.

5.5.2 Powdered Activated Carbon (PAC) Adsorption

Geosmin is removed more efficiently by PAC than MIB. Given that MIB concentrations are usually greater than geosmin concentrations selection of PAC feed doses is usually based upon raw water MIB concentrations. The process of adsorption of MIB and geosmin by PAC takes time (> 1 hour). Therefore, maximizing the contact time between PAC and water is critical. PAC should be added and well-mixed prior to presedimentation basins. Chemical tracer tests should be conducted on presedimentation basins to assure there is no short circuiting within the basins, thus maximizing contact time between the PAC and water. Based upon suspended solids analysis, hydraulic retention time (HRT) in the presedimentation and flocculation basins only "count" towards PAC contact time. PAC is removed within the first 25% of the length of the sedimentation basins. The HRT of the presedimentation basin plus flocculation basin should exceed one hour. If HRTs are less than one hour, the PAC dose should be increased by 25%.

Not all brands of PAC remove MIB or geosmin equally. Bid selection criteria for PAC suppliers should be partially performance-based. One method for bid selection includes determination of an Index Value for each PAC brand based upon simple laboratory PAC tests. Appendix D shows a proposed test protocol developed during this study.

After selection of a PAC brand, a dose-MIB removal nomograph should be developed. A dose-MIB removal plot for Norit 20B is shown in Figure 5.10. The graphs are developed by conducting experiments similar to those used to develop the Index Values, but with a single PAC brand and two or three different initial MIB concentrations (e.g., 30, 50, 70 ng/L). In separate experiments the PAC dose is varied (e.g., 1, 3, 5, 8, 12, 16, 20, 25, 30, 40 mg/L). After the prescribed contact time the samples are syringe-filtered and analyzed for MIB. Data are plotted as C/Co versus PAC dose, where C is MIB in finished water and Co is MIB in raw water. For different initial MIB concentration the C/Co versus PAC dose should overlay, since fractional MIB removal is independent of initial concentration. All the data together should be plotted using a best-fit equation (e.g., exponential fit – Equation 5.5). The best-fit equation can be used directly to compute a PAC dose (see below) or used to generate a dose-MIB removal nomograph (e.g., Figure 5-10).

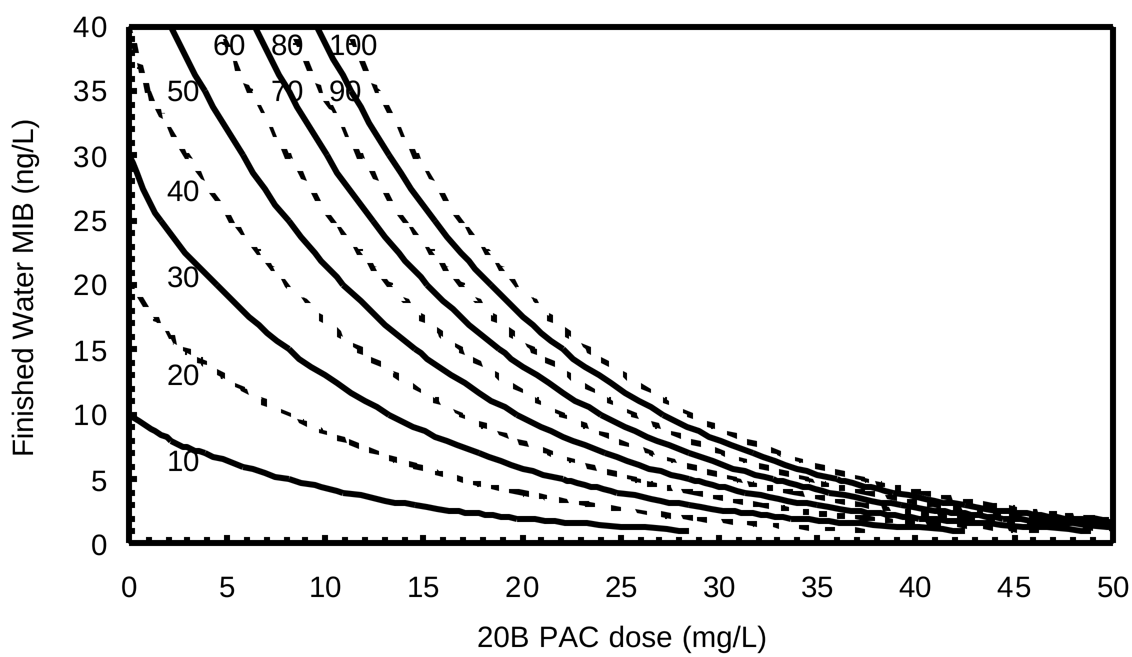


Figure 5-10. Dose response MIB removal using Norit 20B.

The following equation was developed for Norit 20B with a 4-hour contact time:

$$PACDose(mg/L) = \frac{-\ln\left[\left(\frac{MIB_{finished}}{MIB_{raw}}\right)\right]}{0.0927} \qquad \text{Equation 5.5}$$

or to achieve 10 ng/L MIB in finished water:

$$\text{PAC Dose (mg/L)} = 10.8 \times \ln(MIB_{raw}) - 24.8 \qquad \text{Equation 5.6}$$

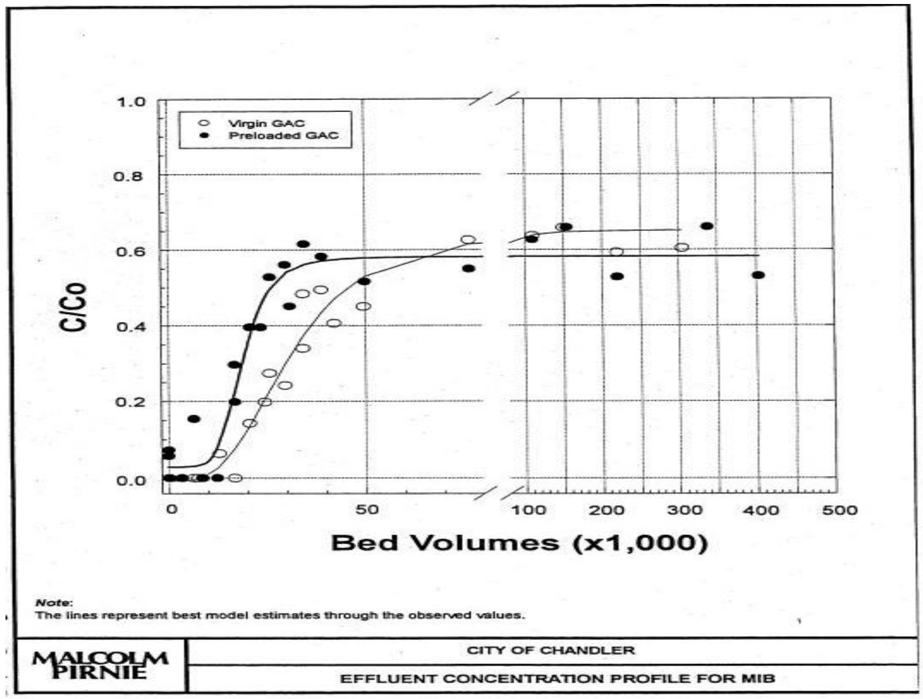
Where the raw (MIB_{raw}) and finished ($MIB_{finished}$) water MIB concentrations are in ng/L. For example, if the influent MIB concentration is 30 ng/L and the desired effluent MIB concentration is 10 ng/L, a 20B PAC dose of about 11.9 ng/L would be required using the equation and 13.5 ng/L using the nomograph. Practical operating curves were generated for future use of Norit 20B by all COP WTPs. The operating curves are easy-to-use nomographs that can be used instead of Equations 5.5 and 5.6, although the equations are more accurate than reading from the nomograph.

Slurry storage of Norit 20B PAC at a full-scale WTP for approximately six-months did not effect its removal efficiency for MIB in raw water. However, ordering and storage of PAC is critical for effective MIB removal. On-site PAC storage should be based upon maximum PAC feed rates, maximum design WTP flowrate, and deliveries every five to seven days. A schedule of PAC deliveries should be prepared and provided to PAC suppliers at least one month in advance. PAC feed facilities should be designed to handle 40 to 50 mg/L of PAC.

PAC doses should vary with flowrate and approximately weekly, based on GC/MS analysis of MIB and geosmin concentrations in raw and finished water. Alternatively FPA can be used more frequently to adjust PAC dosages. However, weekly confirmation by GC/MS should be included. Costs for PAC may exceed $25,000 per week during MIB pulses (assuming 15 mg/L, 100 MGD, $0.30/lb PAC). Therefore conducting GC/MS analysis for MIB of raw and finished water to optimize PAC dose (Equation 5.6) can be extremely cost effective. It is critical that the analytical laboratories know in advance of the MIB/geosmin sampling and the need for rapid (1 to 2 day) turnaround of the data. All WTPs within a city should be sampled and analyzed on the same day (e.g., Monday) and PAC doses adjusted accordingly within two days (e.g., Wednesday), see Figure 3-1.

5.5.3 Activated Carbon Filter Caps

GAC capped filters operated in an adsorption or biologically active mode will remove some MIB and geosmin. Existing anthracite filter caps could be replaced by GAC caps where MIB and geosmin removal is desired. The GAC caps should be 30 to 50 inches in depth. The point of chlorination should be after filtration to encourage biofiltration, which could affect CT disinfection credits. Depending upon operating conditions 20% to > 90% MIB and geosmin removal can be achieved (Figure 5-11). PAC addition may not be required when operating in adsorption modes only, while it would be required under biologically active modes (exhausted adsorption capacity). GAC caps operated under adsorption mode, and to a lesser extent under a biodegradation mode, would provide TOC removal and removal of synthetic compounds (e.g., estrogenic compounds and pharmaceuticals). WTPs with short presedimentation contact times for PAC and/or high influent T&O concentration would benefit most by GAC filter caps. GAC filter caps add another layer of treatment in a multiple-barrier approach to T&O control.



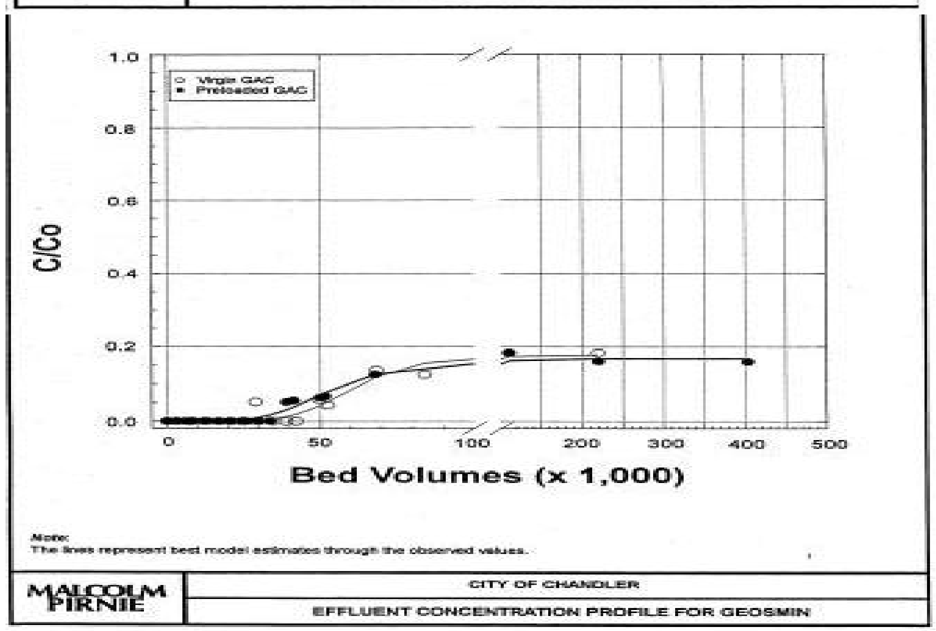


Figure 5-11. Breakthrough of MIB (upper) and geosmin (lower) in laboratory biofilters (from Malcolm Pirnie Inc. report to the City of Chandler).

5.5.4 Advanced Oxidation

Ozone and UV irradiation can be effective at removing MIB and geosmin. Ozone dosages capable of *Giardia* and *Cryptosporidium* inactivation (2 to 4 mg/L) are capable of 80% to > 95% oxidation of MIB and geosmin in CAP or SRP water. Ozone dosages of 2 to 4 mg/L will form bromate, and depending upon the initial bromide concentration in the raw water (80 to 150 μg/L), bromate concentrations approaching the MCL of 10 μg/L would be formed. Therefore, acid and/or ammonia addition prior to ozonation would be required. However, if ozone was used primarily for T&O control, lower ozone dosages (e.g., 0.75 mg/L) could achieve significant MIB removal (e.g., 60% to 80%).

UV irradiation dosages required for MIB or geosmin oxidation are approximately 100 times greater than dosages used for microbial inactivation. Therefore, UV-irradiation probably is not cost-effective.

SECTION 6

PROGRAM ASSESSMENT

6.1 CONTINUOUS EVALUATION AND COMMUNICATIONS

6.1.1 Rationale

One of the keystone concepts of the T&O management program is rapid response. It is now possible to collect and analyze water samples within 2-3 days, allowing week-by-week evaluation of the T&O situation. This makes it possible to respond quickly, implementing one or more control measures as needed.

6.1.2 Implementation

A *T&O Newsletter* was developed for this purpose. Section 3 discusses the rationale and goals of the *Newsletter*. The *T&O Newsletter* should be written and distributed weekly during the T&O season, roughly June through October. As a minimum, the *Newsletter* should contain the latest sampling data and recommendations for PAC dosing and other implementation measures. The format should be consistent from week to week, to make it easy for COP staff to find important information quickly. Electronic distribution via email attachment has worked very well. COP should encourage technical staff to utilize the *T&O Newsletter* to share observations, treatment concepts, water delivery forecasts, and other ideas with WSD staff.

6.2 ANNUAL (END OF YEAR) EVALUATION

6.2.1 Rationale

The T&O management program should continuously improve in the face of changing circumstances. Accomplishing this requires continuous evaluation of the program as it evolves. Thoughtful technical evaluation can document success, which can improve the public image of the WSD and improve staff morale, but is also needed to identify weaknesses. An annual evaluation could also be used to justify the cost of new facilities and equipment needed to improve the quality of water delivered to consumers.

6.2.2 Elements of the Annual Evaluation

The annual evaluation should include an evaluation of the quality of water delivered to customers each year, a review of operational issues, and an analysis of economic and institutional issues.

6.2.2.1 Measuring Consumer Satisfaction

A metric called "consumer days below threshold" (CDBT) has been developed to quantify the quality of water delivered to customers. The threshold is a concentration of MIB and geosmin deemed acceptable. For example, 10 ng/L is considered a reasonable taste threshold for both MIB and geosmin. Ten ng/L could therefore be considered a "primary threshold," and would be abbreviated "CDBT-10." Because consumer complaints generally do not start until MIB and geosmin levels exceed 20 ng/L (W. Alsmadi, per. comm.), 20 ng/L could be used as a "secondary" threshold for program evaluation ("CDBT-20").

For a given time period, the CDBT is calculated as:

CDBT-XX = service population x number of days with product water below threshold

Where XX is a specified numeric threshold (e.g., 10 or 20 ng/L) Equation 6.1

Consumer days below threshold can be calculated for a given treatment plant. Because water production at a given treatment plant changes over time, the service population for a given month time can be estimated from monthly water production and the average per capita water consumption rate for Phoenix (Table 6-1).

Table 6-1. Average municipal water production for Phoenix, by month, from 1996-99.

Month	Average water consumption, gallons/capita-day
January	158
February	138
March	174
April	197
May	264
June	291
July	288
August	285
September	238
October	233
November	192
December	164
Average	219

The monthly measured MIB concentration of the product water can be used to determine whether the water delivered is above or below a given threshold.

Example:

Val Vista, November 2001

MIB concentration in the source water = 17.1 ng/L (measured)

MIB concentration at the end of the sedimentation basin = 7.4 ng/L (measured)

Monthly water production = 2,526 million gallons (from production records)

Average per capita water production (from Table 6-1) = 285 gallons/day

Total consumer days = $2{,}526 \times 10^6$ gallons/(285 gallons/person/day x 31 days/month) = 8,854,678 consumer days

CDBT-10s: Since the MIB in production water was < 10, CDBT-10 = 8,854,678 days

CDBT-20s: Since MIB < 20 ng/L, CDBT-20 = 8,854,678 days

For technical evaluation of the T&O program, CDBT-10s and CDBT-20s should be computed for each plant by month, then aggregated by year and for the entire Phoenix service population. The concept is useful for system-wide program evaluation, by comparing CDBTs among years.

The reduction in CDBTs can be used as a metric of in-plant treatment. This is done by comparing the CDBTs of source water and production water. In the example of the Val Vista WTP, above:

Inlet: CDBT-10 = 0 (since MIB = 17.1 ng/L)
Outlet: MIB < 10, therefore CDBT-10 = 8,854,678 days

In-plant treatment therefore increased the CDBT-10s by 8,854,678 days.

Treatment would not always increase the number of CDBTs. For example, in May 1999, the following data apply to the Val Vista WTP:

MIB in = 9.7 ng/L
MIB out = 8.8 ng/L
Monthly water production = $3{,}055 \times 10^6$ gallons
Average per capita use in May = 264 gallons/day

Note that MIB concentrations in both the inlet and outlet of the plant were < 10 ng/L.

Inlet CDBT-10s = 3,055 x 10^6 gallons/(264 gallons/person-day x 30 days/month) = 11,568,005 days
Outlet CDBT-10s = 11,585,005 days

Increase in CDBT-10s due to treatment = 11,585,005 – 11,585,005 = 0 days

Over 11 million CDBT-10s accrued during May, but this happened because the inflow water was of high quality (MIB < 10 ng/L), not because of treatment within the plant.

For annual evaluations, both concepts, CDBTs and reduction in CDBTs due to treatment, are useful. The concept of reduction in CDBTs could also be used to evaluate cost-effectiveness of T&O mitigation efforts when the costs are clearly defined. Ultimately, most measures can be evaluated on the basis of dollars spent per CDBT ($/CDBT). The CDBT concept was used to evaluate trends in T&O reduction from 1999 to 2001 and to evaluate causes of T&O reduction in 2001 (see Final Report, July 2002).

6.2.2.2 Review of Operational Issues

A second step in program evaluation is a review of operational issues. Typical operational issues might include:

- delays in collecting or processing water samples, leaving operators without adequate information to make adjustments in treatment processes,
- unavailability of equipment needed to brush canals due to mechanical or scheduling problems,
- inadequate PAC storage and dosing facilities at the Deer Valley and Squaw Peak WTPs.
- delays in PAC deliveries, and
- poor communication among operational and administrative personnel.

These and other problems can greatly reduce the effectiveness of the T&O management program. Addressing these operational problems generally can improve implementation of the T&O management strategy for the following year.

6.2.2.3 Institutional and Economic Evaluation

Finally, institutional and economic issues should be examined during each T&O season. The total cost of the T&O program should be evaluated each year. Fairly definitive costs will include the following:

- PAC purchases,
- chemical/copper purchases,
- reimbursement to SRP/CAWCD for canal management for water quality purposes,
- water quality sampling,
- lab analysis,

- continuous communications and analysis, and
- annual evaluation.

6.2.2.4 Annual Workshops

Annual workshops among COP staff are needed to plan strategy for each T&O season. The T&O situation is different each year, so the T&O strategy must be adaptive.

Some key topics that need to be addressed in these workshops include:

1. Hydrologic forecast. The hydrologic forecast is important for planning blending and source switching options. SRP and CAWCD plan by March based on the hydrologic situation for the upcoming year.

2. Water delivery situation. This issue depends upon both the hydrologic forecast and various institutional and infrastructure issues. For example, the potential for source switching depends not only upon the hydrologic situation, but also upon the availability of excess treatment capacity. The amount of excess treatment capacity will vary from year-to-year. Legal and institutional issues also constrain the extent of blending that will be possible in a given year.

3. Other infrastructure issues. The status of PAC delivery systems, the status of plant maintenance, canal shutdowns, and other issues affect the development of the season's T&O management strategy.

4. Program evaluation. It is critical that the T&O program be evaluated at the end of each season. The program evaluation should result in a concise list of ideas to improve T&O management for the following year.

SECTION 7

CASE STUDIES

7.1 INTRODUCTION

The principles developed in this Manual are illustrated using three case studies. These are actual events that were encountered during the T&O study. They were selected to illustrate possible management practices that might be employed in response to T&O problems at the upper end of the water supply system, in the canal system, and at the water treatment plants. Specifically, the case studies are:

- high MIB in Saguaro Lake during late summer, 2001
- high MIB in a "hot spot" along Arizona Canal during July, 2001
- high MIB in the influent to the Squaw Peak WTP

7.2 CASE STUDY #1 - HIGH MIB IN SAGUARO LAKE

7.2.1 Process Control Monitoring

MIB concentrations had been higher than geosmin levels during the summer of 2001 in Saguaro Lake. By the end of August 2001 MIB concentrations in the epilimnion of Saguaro Lake had reached 47 ng/L. The following data were collected during sampling in Saguaro Lake (August 30, 2001):

Depth from surface (m)	MIB (ng/L)	Geosmin (ng/L)	Temperature (^oC)	Dissolved Oxygen (mg/L)
0	47	7	28.0	7
5	36	7	25.8	4
10	19	5	24.3	2
15	16	6	23.8	2
20	12	4	23.5	2
25	12	4	23.4	2
30	5	4	22.9	2

7.2.2 Diagnosis

Water leaving Saguaro Lake via the hypolimnion withdraw was at approximately 30 m depth. Therefore MIB concentrations were low, but significant MIB accumulated in the lake and would soon reach the withdrawal depth. The reservoir had weak thermal stratification ($\Delta Temp_{max}$ = 28.0 – 22.9 = 5.1 ^oC) but still exhibited a strong dissolved oxygen stratification. Water above 5 m had oxygen concentrations > 4 mg/L and water at and below 10 m had oxygen concentrations of ~ 2 mg/L. It was concluded that the reservoir would probably destratify within 30-45 days, resulting in higher MIB concentrations throughout the water column as the water became completely mixed. The result would be a significant increase in MIB concentration in the water leaving the reservoir from approximately 5 ng/L to > 15 ng/L.

7.2.3 Treatment Selection

Logistical, economic and political considerations prevented chemical or biological treatment for MIB in Saguaro Lake. Therefore, it was decided that three implementation strategies should be undertaken to minimize MIB concentrations at downstream locations.

First, SRP was contacted to determine the feasibility of switching from the Salt River to the Verde River as the dominant water source earlier than usual. This switch in water supplies generally occurs in mid-October to mid-November. Bartlett lake on the Verde River had much lower MIB concentrations (< 15 ng/L in the epilimnion and < 5 ng/L in the hypolimnion). SRP determined that the Verde River did not have sufficient water volume to make the switch in water supplies earlier than scheduled. This option was therefore not implemented.

Second, CAP and SRP were contacted to determine if more CAP water could be delivered into the Arizona Canal and less SRP water (i.e., Salt River water). The CAP canal had low MIB levels (< 5 ng/L) as did Lake Pleasant (< 15 ng/L). It was determined that for approximately two weeks in late September or early October a larger delivery of low-MIB CAP water could be delivered into the Arizona Canal. This would dilute MIB concentrations originating from Saguaro Lake via the Salt River. This option was implemented.

Third, City of Phoenix water production staff were contacted to evaluate the potential to increase finished water production at the Union Hills WTP rather than WTPs on the Arizona Canal. MIB levels in the CAP canal would be significantly lower than MIB levels in the Salt River that supplies the major flow in the Arizona Canal. It was decided to keep Deer Valley WTP off-line, minimize production at Squaw Peak WTP and increase production at Union Hills WTP. This option was implemented.

7.2.4 Treatment Application

Increased CAP flows into the head of the Arizona Canal were implemented and production shifted from WTPs on the Arizona Canal to the CAP canal.

7.2.5 Follow-up Monitoring

Continued monitoring of Saguaro Lake proved that the MIB concentrations in the epilimnion continued to increase after August 30, 2001 as “predicted” (see Figure 7-1). MIB concentrations leaving Bartlett Lake on the Verde River never exceeded 10 ng/L that fall. MIB concentrations were somewhat higher in the CAP canal between September and November of 2001 due to MIB coming from the Colorado River (15 ng/L), but not from Lake Pleasant. MIB concentrations in the Arizona canal were maintained at < 30 ng/L at Squaw Peak WTP. Switching production from Deer Valley WTP to Union Hills WTP prevented any necessity to treat high MIB concentrations in water that would have otherwise reached Deer Valley WTP (Figure 7-2).

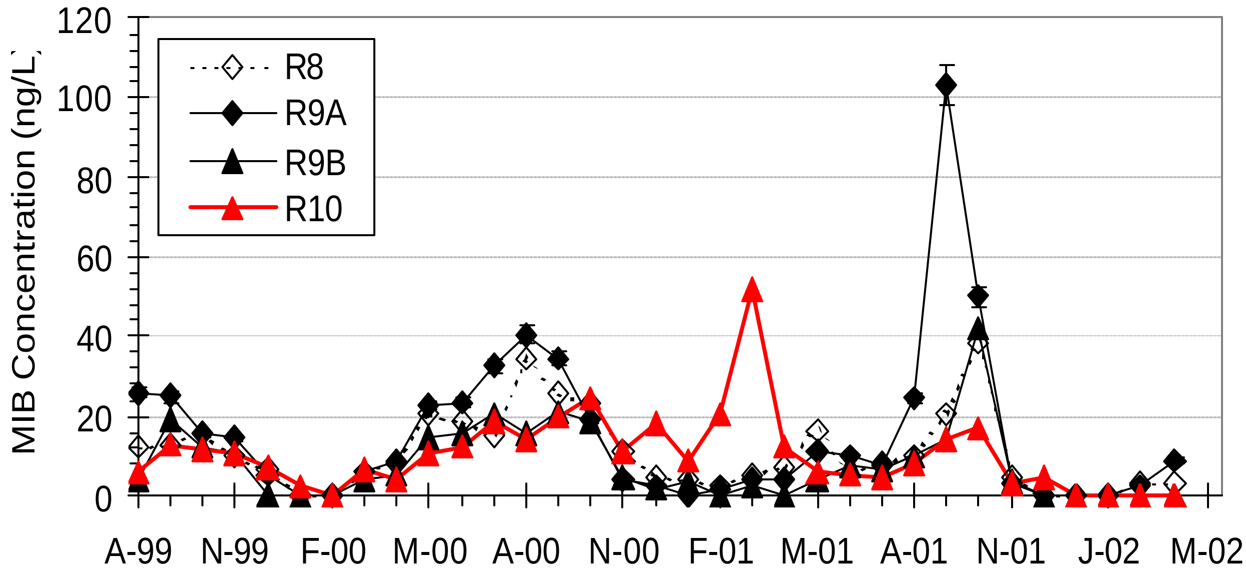


Figure 7-1. MIB in Salt River cluster (Saguaro Lake) from August 1999 through March 2002.

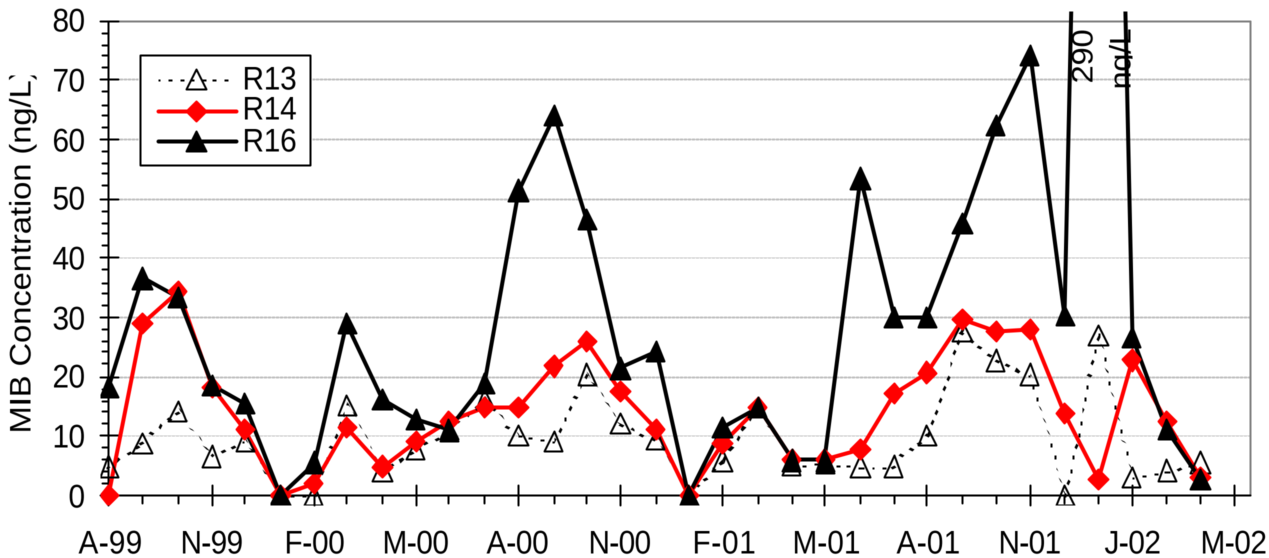


Figure 7-2. MIB in Arizona canal (SRP cluster) from August 1999 through March 2002. MIB in January 2002 (R16) was 290 ng/L.

7.3 CASE STUDY #2 - HIGH MIB "HOT SPOT" ALONG ARIZONA CANAL

7.3.1 Process Control Monitoring

Throughout June and early July of 2001 significant production of MIB was observed in the Arizona Canal between Squaw Peak WTP and Deer Valley WTP, a distance of roughly 10 miles along the canal (Figure 7-3).

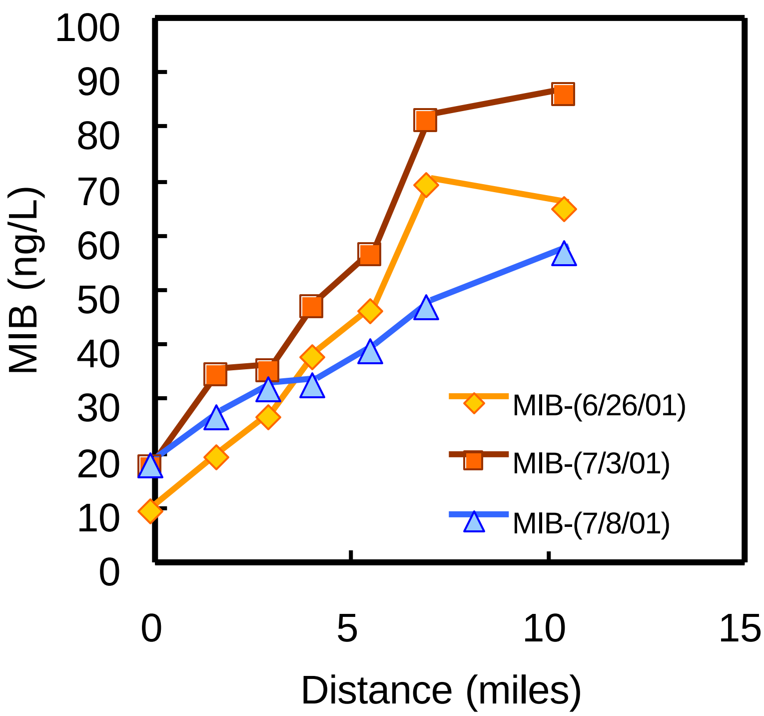
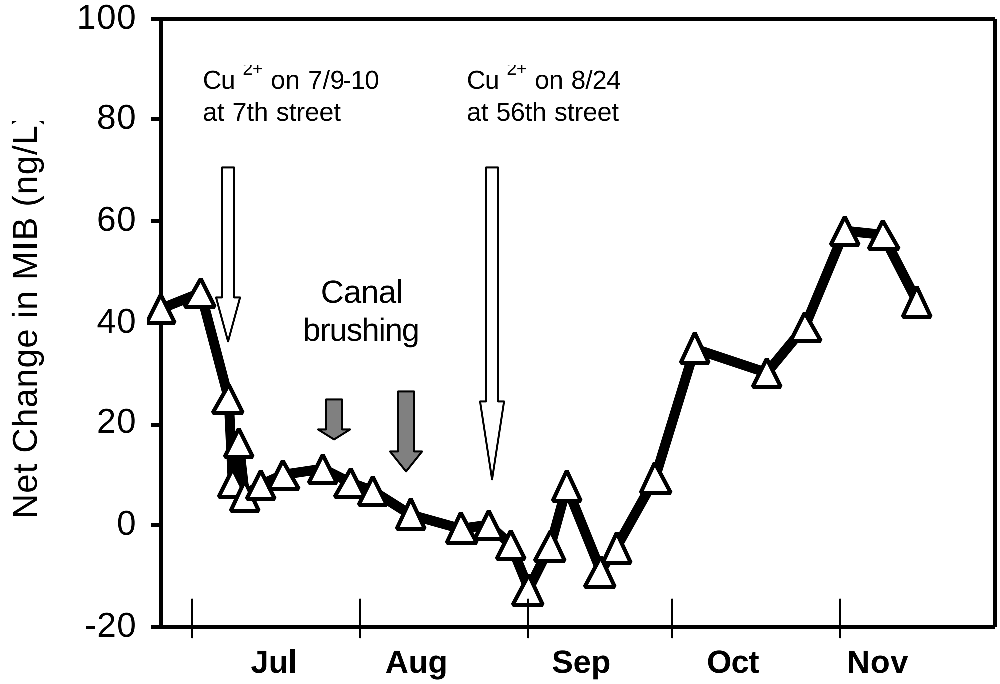


Figure 7-3. Increasing MIB along the Arizona Canal between Squaw Peak and Deer Valley WTPs

To determine the exact amount of MIB produced in the canal over time, Figure 7-4 was developed. It shows the MIB production between these two WTPs. Net MIB production was calculated as MIB concentration of raw water at Deer Valley WTP minus MIB concentration of raw water at Squaw Peak WTP.



Canal brushing: 8/1-2/01 (24th St - Central); 8/14-17/01 (24th St - 29th Ave)

(Net change in MIB = MIB at 29th Ave - MIB at 24th St.)

Figure 7-4. Calculated net production of MIB in Arizona Canal between Squaw Peak and Deer Valley WTPs, by month, before, during and after canal brushing and copper application.

7.3.2 Diagnosis

Based upon Figures 7-3 and 7-4 it was obvious that MIB was being produced in this section of the canal. SRP was contacted as to the pumping status of groundwater wells located around Central Avenue. We were informed that the wells which contained nitrate were in fact being operated (Well #12.5E13.1N has 12.6 mg NO_3-N/L; Well #12E13.3N had 7.0 mg NO_3-N/L). However the wells could not be turned off due to downstream water demands and lack of hydraulic capacity in the upper Arizona Canal to convey more surface water.

7.3.3 Treatment Selection

The canal management "toolbox" included several options, each of which are described for the above scenario:

1. Reduce nitrate input into canal from groundwater pumping. Based upon discussions with SRP this was not deemed feasible due to lack of surface water supplies (drought period) in conjunction with limited hydraulic capacity at the head of the Arizona canal for increased flow of surface waters. Nitrate-rich groundwater could not be diverted, and was probably a factor for the MIB production in this section of canal.

2. Mechanically remove periphytic (attached) algae from canal walls. Mechanical brushing of canal walls was deemed feasible. Visual observations of the canal indicated a 3 to 6 cm thick mat of attached (periphytic) algae on the sides of the canal. SRP was contacted to schedule mechanical brushing. An approximately 2-week lead time was required.

3. Apply liquid biocides to canal water. Liquid copper addition was considered feasible for control of attached algae. It would be preferable to add copper after mechanical brushing removed dense algae from the canal walls. Copper would treat the walls and bottom of the canal.

4. Apply fixed biocides to canal walls during canal dry-up. This option was only deemed feasible during canal dry-up (December to January), so this option was not implemented.

5. Shift finished water production to WTP with lower T&O levels. Deer Valley WTP was scheduled for a construction plant shut-down in September 2001, and had to be on-line during part of July 2001 for quarterly regulatory monitoring. After discussions with City of Phoenix water production staff it was decided that Union Hills WTP on the CAP Canal could increase production earlier and allow Deer Valley WTP to go off-line sooner. This would decrease the number of days Deer Valley WTP had to operate, and treat water with potentially high MIB levels. This option was implemented.

7.3.4 Treatment Application

Several treatment options were implemented. Mechanical brushing was conducted on July 19-21, August 1-2 and again on August 14-17. Copper addition was applied between Squaw Peak and Deer Valley WTPs on July 10, 2000, at 7th Street for 6 to 8 hours. Copper was also applied above Squaw Peak WTP throughout August and October (56th Street and Beeline Highway) to address MIB "hot spots" further upstream. Copper residuals of 0.3 to 0.7 ppm were monitored for 5 to 7 miles downstream of the copper application point. Reductions in attached (periphytic) algae biomass indicated that both copper and brushing were effective for the duration of the application (2 to 3 weeks). Switching of water production to Union Hills WTP also proved very effective.

7.3.5 Follow-up Monitoring

Figure 7-4 shows that after implementation of in-canal treatments the MIB production in the Arizona Canal between Squaw Peak and Deer Valley WTPs was maintained at < 5 ng/L. Later in the summer, as Deer Valley WTP production was shifted to other City of Phoenix WTPs, no further canal treatments along that section were implemented. MIB production in the canal increased again, but had no impact on the City of Phoenix's water treatment plants. A combination of in-canal treatments and shifting production was effective at minimizing MIB levels entering the WTPs.

7.4 CASE STUDY #3 – TREATING MIB IN SQUAW PEAK WTP INFLUENT WATER

7.4.1 Process Control Monitoring

By late July 2001 MIB concentrations entering Squaw Peak WTP were approaching 30 ng/L (Figure 7-5). During July 2001 no PAC was added.

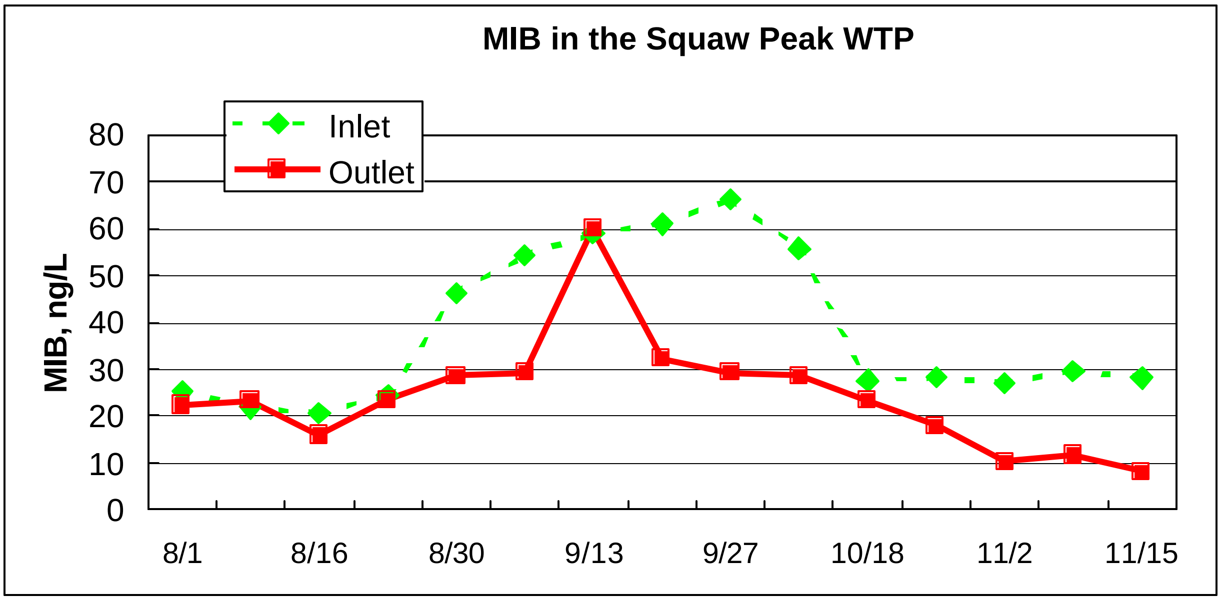


Figure 7-5. MIB in raw (SP-IN) and finished (SP-OUT) water at the Squaw Peak WTP

7.4.2 Diagnosis

Options to minimize MIB production in the upstream canal were being implemented. However, elevated MIB levels (> 30 ng/L) still entered the WTP. It was determined that in-plant MIB control was required.

7.4.3 Treatment Selection

Squaw Peak WTP had no documented in-plant production of MIB, therefore chlorine or copper addition in the WTP would not be effective at reducing MIB levels. Squaw Peak WTP does not have ozone or chlorine dioxide feed capabilities. Since the WTP feeds chlorine prior to filtration, biological filtration was not an option. This left powdered activated carbon (PAC) addition as the only means of MIB treatment.

7.4.4 Treatment Application

Squaw Peak WTP had residual Norit HDB PAC in slurry storage tanks and used that supply up by the end of July. Norit 20B was ordered; this PAC was deemed more effective at removing MIB from the local water source based upon laboratory performance comparisons. However, Norit HDB was delivered and had to be used during early September. PAC ran out around September 20, 2001, and no MIB removal was achieved. It is important to monitor PAC supplies and coordinate new deliveries accordingly. Once Norit 20B was delivered the PAC dose was calculated based upon laboratory dose-removal nomographs (Figure 5-10) verified the prior year at Val Vista WTP in full-scale tests. The following equation can be used for PAC dose calculation:

$$C/C_0 = 0.95 \times EXP(-0.18 \times PAC\_Dose) \qquad \text{Equation 7.1}$$

OR

$$PAC\_Dose = -\left\{ \frac{\ln\left(0.95 * \frac{C}{C_0}\right)}{0.079} \right\}$$

Equation 7.2

An example Norit B PAC dose calculation for September 12, 2001, to achieve 10 ng/L of MIB in finished water (C) when a MIB concentration of 55 ng/L was present in the raw water (C_0) follows:

C = 10 ng/L
C_0 = 55 ng/L

PAC Dose (mg/L) = - [ln(0.95 *10/55)] / 0.079 = 22 mg/L

The WTP was operating near capacity (120 MGD) and detention time in the presedimentation basins where the PAC was added was only one hour. However, the nomographs were developed based upon a three-hour contact time. Revised nomographs for shorter contact times were required to determine PAC doses.

7.4.5 Follow-up Monitoring

PAC (8 to 16 mg/L doses) removed MIB, but not to below 10 ng/L (Figure 7-5). PAC doses of greater than 16 mg/L were necessary to achieve 10 ng/L MIB in the finished water, but the PAC feed facilities were not rated for a feed rate this high. Recommendation: improve and increase capacity of PAC feed system.

Once, after November 2001, Norit 20B was used and detention times in the presedimentation basins were above 1.25 hours the observed and predicted MIB removal was adequate and the target of 10 ng/L of MIB in finished water was achieved. The experience suggested that slight refinements in PAC dose-removal nomographs may be necessary to account for varying hydraulic retention times, and that scheduling delivery of PAC was critical.

REFERENCES

American Public Health Association, American Water Works Association and Water Environment Federation. (1999) Standard Methods for the Examination of Water and Wastewater. 20th Edition.

Baker, L., Westerhoff, P., Sommerfeld, M., Bruce, D., Dempster, T., Qiang, H. and Lowry, D. (2000) Multiple barrier approach for controlling taste and odor in Phoenix's water supply system, Water Quality Technology Conference, Salt Lake City, Utah, November, 2000.

Baker, L A., Westerhoff, P. and Sommerfeld, M. (1999) Multibarrier concept for taste and odor control, North American Lake Management Society Conference, Reno, Nevada, Dec. 1-4, 1999.

Bruce, D., Westerhoff, P., Sommerfeld, M., Baker, L., Nguyen, M. L., Lowry, D., Dempster, T. and Hu, Q. (2000) Occurrence of MIB and geosmin in Arizona drinking waters, Arizona Water Pollution Control Association Conference, May 4-5, 2000.

Lloyd, S. W., Lea, J. M., Zimba, P. V., and Grimm, C. C. (1998) Rapid analysis of geosmin and 2-methylisoborneol in water using solid phase micro extraction procedures. Wat. Res. 37(7):2140-2146.

Means, E. G. and McGuire, M. J. (1986) An early warning system for taste and odor control. *Journal AWWA*: March, 1986, 77-83.

Nguyen, M. L. (2002) *Sources and characteristics of dissolved organic carbon in arid region water supplies*, Ph.D. Dissertation, Civil and Environmental Engineering, Tempe, Arizona State University, .

Nguyen, M. L., Baker, L. A. and Westerhoff, P. (2002) Sources of DOC and DBP precursors in western U.S. watersheds and reservoirs. *J. Am. Water Works Assoc.* 94(5):98-112.

Suffet, I. H., Khiari, D. and Bruchet, A. (1999) The drinking water taste and odor wheel for the millenium: beyond geosmin and 2-methylisoborneol. Wat. Sci. Tech. 40(6):1-13.

Taylor, W. D., Losee, R. F., Isaguirre, G., Crocker, D. J., Otsuka, D. J., Whitney, R. D., Kemp, J. and Faulconer, G. (1994) Application of limnological principles for management of taste and odor in drinking water reservoirs: a case study, Water Quality Technology Conference, San Francisco, CA, Nov. 6-10, 1994.

Watson, S. B., Brownlee, B., Satchwill, T., and Hargesheimer, E. E. (2000) Quantitative Analysis of trace levels of geosmin and MIB in source and drinking water using headspace SPME. Wat. Res. 34(10): 2818-2828.

APPENDIX A
SAMPLE DATA SHEETS FOR LAKE, CANAL AND WTP SAMPLES

Taste and Odor Project – Lake Sampling

Site #: ______________ Location:____________Date: ___________Time: _________

Personnel: ___________Weather: _______________________________ Elevation: ___

Description of water:

Description: ____ *Water Depth* _____________ *m*
(circle): Turbid clear green blue-green brown yellow-brown white floc white foam

Secchi Disk Reading 1 __ m Secchi Disk Reading 2 __m Average Reading ___m

Field measurements:

Depth (m)	T (°C - D.O.)	D.O. (mg/L)	pH	sample (yes/no)	comments
0					
5					
10					
15					
20					
25					
30					
35					
40					
45					

Description of phytoplankton (free-floating):

____

Color (circle): Green Brown yellow-brown Blue-green Pink Other: ____________________

Visible clumps: yes no

Comments: ________________________________

Water Odor Characteristics:

Odor in epilimnion composite water sample:
Odor strength (circle one): Strong Medium Weak Absent
Odor (circle): musty earthy moldy fishy sulfidic grassy chlorine Other
Comments: ____

Odor in hypolimnion composite water sample:
Odor strength (circle one): Strong Medium Weak Absent
Odor (circle): musty earthy moldy fishy sulfidic grassy chlorine Other
Comments: ____

Samples collected:

Comments:
____
____
____
____
____
____

Taste and Odor Project – Canal Sampling

Site #: Specify Site ID   Location: Specify location   Date: ____________Time: ________

Personnel: ____________Weather: ___________________________   Elevation: _____

Description of water:

Description:

____

(circle): Turbid   clear   green   blue-green   brown   yellow-brown   white   floc
white foam

Description of phytoplankton (free-floating):

Description: ____

Color (circle): Green   Brown/yellow-brown   Blue-green   Pink   Other:
Visible clumps: yes no Comments: ________________________________

Description of periphyton (attached to canal walls):
Description:
____

Depth less than 15 cm:
Approximate thickness of mat: _____ cm Comments: ________________________
Color of mat (circle): Green   Blue-green   Brown or goldish-brown   Black   Other:
____

Depth 15 – 30 cm:
Approximate thickness of mat: __________ cm Comments: __________________
Color of mat (circle): Green   Blue-green   Brown or goldish-brown   Black   Other:
____

Depth greater than 30 cm:
Approximate thickness of mat: ______ cm Comments: ______________________
Color of mat (circle): Green   Blue-green   Brown or goldish-brown   Black   Other:
____

Field measurements:
Temp (^{o}C - DO): ______ D.O. (mg/L): ______ Temp (^{o}C - pH meter): ________ pH: ______

Odor in water sample:

Odor strength (circle one):   Strong   Medium   Weak   Absent
Odor (circle):   musty   earthy   moldy   fishy   sulfidic   grassy   chlorine   Other

Samples collected:

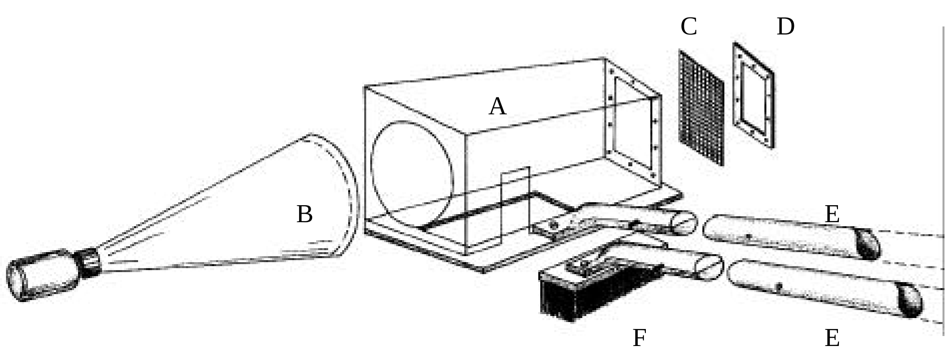
Used scraping device? (yes or no) __________ # of scrapes (2 if possible) ______________

Comments:

APPENDIX B
DESIGN AND OPERATION OF PERIPHYTON SAMPLER

A periphyton sampler was designed for this project. The periphyton sampler is a rectangular chamber, measuring 25 cm long, 18 cm wide and 18 cm high. The upper part of the chamber is made of a clear PVC plate, whereas the bottom is a metal plate with a 10 x 15 cm open area (0.015 m^2). The side of the chamber facing the canal bank is a small slot through which a wire pool brush inside the chamber is attached to a telescoping pole. The upstream side of the chamber has a large opening that is covered by a fine plastic screen that allows water to flow through the chamber. The downstream side of the chamber is a large circular opening with an attached plankton net (80 um mesh). Two people are required to collect samples. The sampler is placed on the canal wall and held into position with the telescoping pole by one person. A second individual brushes the wall a predetermined number of times. As periphyton mats are removed from the canal wall, they are carried by water flow into the plankton net. Because vertical zonation of periphyton is evident on canal walls, sampling is done at three depths (just below the surface and at 30 cm intervals. The three samples are composited and stored in a sterile whirl-pak bag at 4^0 C until laboratory analysis.

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



APPENDIX C
SPME METHOD FOR MEASURING MIB AND GEOSMIN

Twelve (12) ml of sample is added to a 25 ml septum capped vial that contains 4 g desiccated sodium chloride. An internal standard (10 ng/L IPMP, Sulpelco #47527 U) is added through the septum and the vial is placed in a heat block 50 ± 1.5 ^{0} C. A SPME fiber (Supelco # 57348 U) is introduced into the head space through the septum and the sample is shaken for 30 minutes. The fiber is removed from the vial and inserted into the gas chromatograph injector at 250 ^{0} C for 5 minutes. The fiber is then retracted into the holder, removed from the GC inlet and reused for the next sample. Compounds from the fiber are desorbed in the column gas chromatograph (MDN-5 capillary column; Supelco, Pennsylvania) and eluted into a mass spectrometer set for selective ion monitoring (selective *m/z* values: MIB = 95, geosmin = 112 and IPMP = 124, 136). Calibration curves are generated using MIB and geosmin standards (mixture standard: Supelco # 47525 U). Analysis of MIB and geosmin was performed on a Varian Star 3400 CX gas chromatograph and mass spectrometer (GC/MS). (QA/QC analysis of MIB measurements by the City of Phoenix and ASU labs has shown a nearly 1:1 correlation (actual slope was 0.95), and a statistical R^2 value of 0.72 for approximately 150 samples since inception of the project.) The method detection limit (MDL) for MIB and geosmin is ca. 1ng/L ng/L.

APPENDIX D
TEST PROTOCOL FOR EVALUATING PAC MIB ADSORPTION CAPACITY

A PAC slurry should be prepared by adding 1000 mg of PAC to 1 liter of 0.45 μm filtered water and allowed to hydrate overnight while being mixed with a magnetic stir. Filter approximately 2 liters of raw water and spike with MIB and geosmin to give a representative concentration (e.g., 30 ng/L). Fill amber glass bottles (no headspace; 250 mL) with this water sample. The hydrated PAC slurry will have a PAC concentration of 1 mg/ml. Select representative PAC doses for the performance-based experiments (e.g., 15 mg/L). Calculate the volume of PAC slurry (V_{PAC}) required for addition to the 250mL sample (e.g., a PAC dose of 15 mg/L would equate to 3.75 mL of PAC slurry); remove and add V_{PAC} of the PAC slurry to the 250 mL amber bottle. Using a magnetic stir or wrist-shaker, rapidly agitate the bottle containing the water sample and PAC for a desired period representative of average HRT of the presedimentation basins (e.g., 1 to 4 hours). Immediately after the prescribed agitation period use a syringe-filter (0.2 μm) and filter the water sample/PAC mixture. Collect the filtrate in a 100 mL amber vial (no headspace). Conduct MIB and geosmin analysis on the filtrate. Repeat for each PAC brand, and repeat for a blank (no PAC added). Calculate the fraction of MIB remaining: C/C_o where C_o is the MIB or geosmin concentration in the blank and C is the concentration after contact with the PAC. Compute the Index Value based upon the fraction of MIB remaining (C/C_o) and the unit cost of the PAC (e.g., $/lb):

$$\text{Index Value} = [C/C_o] \times [\text{PAC unit Cost}] \qquad \text{Equation D.1}$$

The PAC brand with the lowest Index Value is the most cost-effective. This assumes that there are no limitations to PAC feed rates. For example, to achieve a desired MIB removal, one PAC brand may require 40 mg/L of PAC while a more expensive PAC brand may only require 30 mg/L of PAC feed. Therefore, the actual fraction removed (C/C_o) should be examined. High PAC feed rates can increase the frequency of PAC shipments, sludge production, handling costs and maintenance on equipment, etc.