ELSEVIER

Water Research 39 (2005) 4899–4912

WATER RESEARCH

www.elsevier.com/locate/watres

Seasonal occurrence and degradation of 2-methylisoborneol in water supply reservoirs

Paul Westerhoff[a,*], M. Rodriguez-Hernandez[a],
Larry Baker[b], Milton Sommerfeld[c]

[a]Department of Civil and Environmental Engineering, Arizona State University, Box 5306, Tempe, AZ 85287-5306, USA
[b]Minnesota Water Resources Center, 173 McNeal Hall, 1985 Buford Avenue, St. Paul, MN 55108, USA
[c]Plant Biology, School of Life Sciences, Arizona State University, Box 1701, Tempe, AZ 85287-1701, USA

Received 25 August 2004; received in revised form 28 June 2005; accepted 29 June 2005

Abstract

Methylisoborneol (MIB) and geosmin are cyanobacterial metabolites that occur at nanograms per liter levels in surface water supplies and are responsible for many taste and odor complaints about the aesthetics of drinking water. This study evaluated three water supply reservoirs with bottom-release (hypolimnion) outlet structures in Arizona. MIB concentrations were always higher than geosmin concentrations, but both followed similar seasonal trends. MIB concentrations increased from spring to late summer, and stratified vertically with depth in the water column; the highest concentrations were always in the upper 10 m of the water column. Thermal destratification in the autumn increased MIB concentrations released from the outlet of reservoirs and impacted downstream utilities for several months. By winter of each year MIB concentrations were non-detectable. Mass balance analyses on MIB indicated that in-reservoir reactions were more important in changing MIB concentrations than conservative hydraulic "flushing" of the reservoir. Maximum net loss rates for MIB in the field ($R_{F,max}$) were on the order of 0.23–1.7 ng/L-day, and biodegradation appeared more important than volatilization, photolysis or adsorption. Using lake water in laboratory experiments, bacterial biodegradation rates (R_L) ranged from 0.5–1 ng/L-day and were comparable to $R_{F,max}$ values. Based upon these rates, MIB concentrations in a reservoir would decrease by approximately 30 ng/L over a period of 1 month. This was the magnitude change in MIB concentrations commonly observed after autumn thermal destratification of the reservoirs.

Keywords: Cyanobacteria; Biodegradation; Reservoir; Taste and odor; MIB; Drinking water

1. Introduction

Many cyanobacteria (blue-green algae) produce intracellular and extracellular metabolites, such as biotoxins and/or taste and odor (T&O) compounds, impact water supplies (e.g., 2-methylisoborneol (MIB), trans-1,10-dimethyl-trans-9-decalol (geosmin)) (Carmichael, 1997; Gerber, 1979; Juttner, 1995; Kaas and Henriksen, 2000; Suffet et al., 1999). Planktonic and periphytic cyanobacteria, as well as some actinomycetes, produce MIB and geosmin in reservoirs, rivers, canals, and within water treatment plants (WTPs) (Gerber, 1965; Izaguirre and Taylor, 1995; Suffet et al., 1995). The

---

*Corresponding author. Fax: +1 602 965 0557.
E-mail addresses: p.westerhoff@asu.edu (P. Westerhoff), baker127@umn.edu (L. Baker), milton.sommerfeld@asu.edu (M. Sommerfeld).

0043-1354/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.watres.2005.06.038

biological function of these algal metabolites is unknown, although they may be intermediates or by-products of pigment production (Bafford et al., 1993; Zimba et al., 1999). MIB and geosmin are of particular interest because they are unpalatable, imparting earthy/musty/moldy tastes and odors to drinking water. MIB and geosmin odors in drinking water are noticeable at concentrations of 2–10 ng/L (Wnorowski, 1992). A quarter to half of US all WTPs using surface water report problems with T&O compounds related to algae metabolites (Suffet et al., 1996). In a US nationwide survey of drinking water consumers, 52% of respondents expressed concern about "smell or taste" of water (WQA, 2001). In a similar survey of five southwestern cities, 60% of respondents were "somewhat concerned" or "very concerned" about the taste and smell of public water supplies (Baker and Wolf, 2003).

Treatment plants generally accomplish T&O compound removal by carbon adsorption or ozonation (Bruce et al., 2002; Lawton et al., 1998). These treatment processes greatly increase the costs of water treatment. Consequently, it is desirable to mitigate the occurrence of MIB and geosmin at their sources (Izaguirre and Taylor, 1995; Means and McGuire, 1986). MIB and geosmin often accumulate in surface water reservoirs, so knowledge regarding production and degradation of these compounds is valuable for developing management strategies to reduce their concentrations in upstream reservoirs before water arrives at treatment plants.

Some soil and aquatic bacteria are capable of biodegrading MIB and geosmin. The Cam Operon includes the primary genes responsible for biodegradation of these alcohols (Hoehn, 1965; Izaguirre and Taylor, 1998; Izaguirre et al., 1999; Oikawa et al., 1995; Trudgill, 1990). Although the kinetics of algal metabolite biodegradation in biological treatment systems have been evaluated and modeled (Nerenberg et al., 2000; Rittmann, 1995), very little is known about MIB or geosmin degradation in water supply reservoirs.

The goal of this paper is to better understand the significance of mechanisms responsible for affecting MIB and geosmin concentrations in water supply reservoirs. Seasonal T&O concentrations plus hydrological, chemical, and biological data were collected over a 3-year period for three water supply reservoirs near Phoenix, AZ. Mass balance analyses of T&O compounds in the reservoirs were used to calculate in situ field rates of net MIB production and loss. Laboratory experiments confirmed MIB and geosmin biodegradation using native lake organisms, and data were used to estimate biodegradation rates. The significance in changing MIB or geosmin concentrations within the reservoirs was addressed by comparing conservative mixing mechanisms (destratification, flushing water through the reservoir) and reaction mechanisms (production, biodegradation, volatilization, photolysis, sorption).

2. Methods and analyses

2.1. Site descriptions

The three reservoirs studied are major components of the water supply system for nearly 3 million inhabitants of the Phoenix, AZ, metropolitan area. The reservoirs are located in the semi-arid Sonoran desert within 50 km of the metropolitan area. The reservoirs range from oligotrophic to mesotrophic (Table 1). During thermal stratification the epilimnion is usually 5–15 m deep and accounts for 30–60% of the total reservoir volume. Important differences in reservoir operation may affect both the production and degradation of MIB and geosmin and the release of these compounds to downstream WTPs. The reservoirs supply water to approximately 15 WTPs, several major industries, and many agricultural users; water travels to these users via open, concrete-lined canals. A site location map for the reservoirs and other water supply infrastructure information is available elsewhere (Bruce et al., 2002).

Bartlett Lake is an on-stream reservoir on the Verde River located 3 km downstream of Horseshoe Lake. Horseshoe Lake was at less than 20% capacity during the study period. Most water enters the reservoir following snowmelt at higher elevations between February and May. Water is stored throughout the summer and released from October to April. Bartlett Lake as a single outlet near the bottom (hypolimnetic withdrawal) located at the downstream (i.e., outlet) end of the lake. Interactions between hydrology and dissolved organic carbon (DOC) in Bartlett Lake have been studied previously (Nguyen et al., 2002; Parks and Baker, 1997).

Saguaro Lake is the lowest of five reservoirs on the Salt River. Three of the upstream Salt River reservoirs have hydropower generation facilities, and pump-back piping from Saguaro to upstream reservoirs occurs during summer months to increase hydropower revenue: water released from upstream reservoirs during peak demand periods (daytime) is pumped back to the upstream reservoirs upstream during off-peak periods (nighttime). This operational mode results in a very short reservoir hydraulic residence time (HRT = outflow/volume = ~0.25 years). Saguaro Lake typically remains near capacity; very little (2–4 m) variation in surface elevation occurs throughout the year. Saguaro Lake also has one outlet near the bottom of the reservoir at the downstream end of the lake. Most releases occur in the summer ($>8.5\,\mathrm{m^3/s}$) and cease around early October, with minimal flow ($\sim 0.1\,\mathrm{m^3/s}$) between October and April.

Lake Pleasant is an off-stream water supply reservoir located on the Agua Fria river near the Central Arizona Project (CAP) canal in the Phoenix metropolitan area. Water pumped from Lake Havasu on the Colorado River travels to Lake Pleasant through an open, concrete-lined CAP canal approximately 200 km in