Tastes and odours in the aquatic environment : A review

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Abstract

This review deals with substances which impart tastes and odours to water and aquatic life. Most of these substances are of microbial origin. They are metabolites of certain cyanobacteria, algae and actinomycetes. Some of them, like geosmin and 2- methylisoborneol, can taint water and fish with an earthy/musty flavour even if present in concentrations of a few nanograms per liter. The methods of detection and identification of tastes and odours include sensory analysis and instrumental analysis by means of gas chromatography/mass spectrometry. The water industry faces difficult problems with the removal of off-flavours from potable water. Conventional treatment fails to destroy many of the odorous compounds. Treatment methods most often used in taste and odour control include activated carbon adsorption, ozone, chlorine dioxide and peroxone. Efficiencies, advantages and disadvantages of these as well as alternative methods, are discussed.

Introduction

Tastes and odours (T and O) appearing in surface waters have received increasing scientific attention over the last 30 years. Public opinion, demanding odourless water supplies and aesthetic recreational waters, has put constant pressure on the relevant authorities to prevent or remove off-flavours. On the other hand, progressive eutrophication and pollution of surface waters aggravates the problem, causing a steady increase in the number of taste and odour incidents.

In spite of the extensive literature on the subject, taste and odour problems continually recur, resulting in considerable costs. Interest shown by government and local authorities is essential regarding legislation on discharge limits and appropriate action towards watershed protection. Expertise, requiring interdisciplinary co-operation between biologists, chemists and engineers, is not always readily available.

A useful practical handbook on the investigation and treatment of various tastes and odours for the water purification industry was compiled by Lyonnaise des Eaux and the American Water Works Association (AWWA) Research Foundation (Mallevialle and Suffet, 1987). This book deals with a variety of odours encountered in water sources, methods of identification and the treatment options. There are also several valuable review articles on the subject. Sources of tastes and odours in water were discussed by Lin (1976a, 1976b) and Hoehn (1988). The chemistry of aquatic off-flavours was summarised by Skulberg (1988) and Juttner (1988). Treatment measures were described by Hrubec and De Kruijf (1983) and by Montiel (1983). A comprehensive study of tastes and odours was carried out by Le Roux (1988a). State-of-the-art overviews on aquatic odours were produced by Persson (1983, 1988).

Taste and odour surveys

World-wide research on T and O problems is evidence of its importance in many countries (Persson, 1983). A survey by Sigworth (1957), conducted among water works officials revealed that 82% of a total of 241 respondents had T and O problems originating from algae and 67% from decaying vegetation, which makes biological factors the prime causative agent of T and O problems. In treatment, only activated carbon was applied successfully (82 to 85% of the plants), in contrast to other methods such as free residual chlorination, superchlorination, chlorine dioxide and aeration, for which success never exceeded 10%. Another survey of this kind, by Mackenthun and Keup (1970) revealed that biological problems in waterworks were reported by about 25% of the 800 respondents, with algal causes of T and O problems still ranked first. This study reported that chlorine and copper sulphate treatment were employed most often, with activated carbon in the third place (25% of the positive respondents). High costs of T and O treatment were also reported. Generally, the results of this survey are comparable with those obtained from the water-related industries in South Africa (Wnorowski et al., 1989).

Consumer-orientated surveys (Gallup Poll, 1973; Manwaring et al., 1986) indicated that organoleptic quality of drinking water became the main concern of consumers, after concern for safety had been eliminated. Although in both surveys only about 10% of the respondents rated their tap water "poor", as much as 30% complained of bad taste, odour, after-taste or colour. Twenty per cent of the respondents indicated that they used alternative sources of water (e.g. bottled water) or tap filtering devices. A recent investigation by the Water Quality Association in the USA (Anonymous, 1989c) indicated, that consumers' awareness and expectations of drinking-water quality is rising. Although 79% of the respondents considered their tap water to be "acceptable", only 70% regarded it as free from harmful contaminants and about 63% had a positive opinion about its quality.

In South Africa public opinion was also gauged regarding expectations about recreational water quality (Thornton and McMillian, 1989). Aesthetic values, mainly the lack of algal blooms and scums, and the lack of tastes and odours, were rated as the most important by respondents to the questionnaire.

Chemistry of off-flavours

Sources of tastes and odours in water

Water acquires its taste and odour from a variety of sources. Only a few are of truly natural origin, for example, mineral salts which may be leached from the substrate and which may impart a taste to the water. Most tastes and odours are the result of human influence: indirectly by rapid enhancement of the growth of aquatic organisms under eutrophication or directly by waste-water dumping or accidental spillage as well as by agricultural runoff. The most problematic condition at present appears to be

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TABLE 1
MOLECULAR CHARACTERISTICS OF ORGANIC COMPOUNDS CAUSING EARTHY ODOURS (LALEZARY ET AL., 1986A). REPRINTED FROM *AWWA JOURNAL*, VOL. 78, NO. 3 (MARCH 1986), BY PERMISSION. COPYRIGHT 1986, AMERICAN WATER WORKS ASSOCIATION

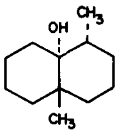
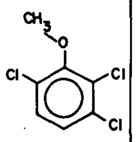
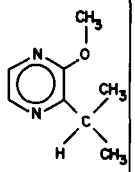
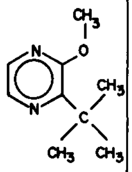
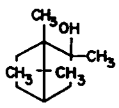
Name	*trans*-1,10-Dimethyl-*trans*-9-decalol (geosmin)	2,3,6-Trichloroanisole (TCA)	2-Isopropyl-3-methoxy pyrazine (IPMP)	2-Isobutyl-3-methoxy pyrazine (IBMP)	2-Methylisoborneol (MIB)
Molecular structure					
Molecular weight	182	212	152	166	168
Molecular formula	$C_{12}H_{22}O$	$C_7H_5OCl_3$	$C_8H_{12}ON_2$	$C_9H_{14}ON_2$	$C_{11}H_{20}O$

TABLE 2
CHARACTERISTICS OF EARTHY ODORANTS (KRASNER et al., 1983) (Reprinted from *Water Sci. Technol.* (1983) 15 127-138, with permission from the publishers, Pergamon Press, and the copyright holders, IAWPRC)

Compound	Chemical name	Threshold odour concentration (ng/ℓ)	Odour description
Geosmin	Trans-1, 10-dimethyl-trans-9-decalol	10	earthy/musty
MIB	2-methylisoborneol	29	earthy/musty/camphorous
IPMP	2-isopropyl-methoxy pyrazine	2	earthy/musty/potato-bin
IBMP	2-isobutyl-methoxy pyrazine	2	earthy/musty/bell pepper
TCA	2,3,6-trichloroanisole	7	musty

algal production of earthy/muddy odours in eutrophied sources.

Earthy odours

A range of volatile and semi-volatile organic compounds may cause odours in water and render it unpalatable. From a practical point of view the most important substances are those with a low threshold odour concentration. Some are offensive to the human senses even if present only in trace amounts of a few ng/ℓ. Some microbial metabolites, like geosmin and 2-methylisoborneol, (MIB) belong to this category. Geosmin was identified, first in actinomycetes and later in cyanobacteria and algae, as the main component imparting an "earthy" odour to soil and water (Gerber and Lechevalier, 1965). MIB, another earthy-smelling microbial by-product, is also periodically reported in taste and odour incidents (Izaguirre et al., 1983; Berglind et al., 1983b). Both geosmin and methylisoborneol are tertiary alcohols whose structure makes them resistant to oxidation, a process routinely applied in water purification. This, together with their extremely low odour threshold values makes them the foremost nuisance-substances in taste and odour incidents.

Other earthy/musty-smelling microbial metabolites can periodically be found to be present in water. These are 2,3,6-trichloroanisole, 2-isopropyl-3-methoxypyrazine and 2-isobutyl-3-methoxypyrazine (Gerber, 1979, 1983; Krasner et al., 1983; Mallevialle and Suffet, 1987). The chemical structure of all five odorants is given in Table 1 and their threshold odour concentrations in Table 2.

Biochemical investigation of MIB and geosmin production by actinomycetes has led to the conclusion that these substances are synthesised by methylation of L-methionine and folic acid (Aoyama, 1990). The biosynthesis paths for geosmin in *Oscillatoria brevis* were studied by Naes and Post (1988) and by Naes et al. (1989). The environmental conditions influencing geosmin production by actinomycetes in water were analysed by Wood et al. (1983). Conditions found to be relevant to the production of earthy taints by actinomycetes in water were: high nutrient level, presence of plant debris, structure of the reservoir banks, allowing sediment accumulation, and the aerobic conditions in the sediments. Nitrogen was confirmed as an environmental factor influencing geosmin production by actinomycetes by Lind and Katzif (1988). The conditions influencing geosmin production by the cyanobacterium *Fischerella muscicola* were studied by Wu and Juttner (1988). Maximum geosmin production was obtained during the lag-phase and decreased with age. Geosmin was produced under both aerobic and anaerobic conditions and its concentration was the highest at the minimum and maximum temperature ranges of the species studied. At optimum growth temperature for the strain, geosmin production was at its minimum. Similarly, Miwa and Morizane (1988) found that the deterioration of physiological conditions of *Anabaena macrospora* in the absence of chelating agents such as EDTA and humic acid resulted in increased geosmin production. Wu and Hsu (1988) established that 98% of geosmin produced by *Anabaena* was retained within the cells rather than being released to the medium and air. This finding was confirmed for *Anabaena macrospora* Klebahn, *Phormidium tenue* Meneghini and *Oscillatoria tenuis* Agardh from Lake Biwa in Japan (Negoro et al., 1988). The influence of light, nitrogen and phosphorus on geosmin production by *Oscillatoria* was investigated by Naes et al. (1988). It was concluded that these three factors do not have a direct effect on the geosmin biosynthesis rate. The increase in geosmin concentration in eutrophied waters is the result of increased algal biomass rather than enhanced geosmin production. A laboratory method for high-yield production of geosmin in fermenters followed by extraction and purification was given by Gerber and Lechevalier (1977).

Other microbial odours

Microbial odorous substances of some importance, other than those described above, are chiefly organic sulphur compounds and hydrogen sulphide. The production of hydrogen sulphide, dimethyl sulphide and methylmercaptan was reported for a range of bacterial and fungal strains by Kadota and Ishida (1972). The role played by bacterial enzymes in the production of volatile sulphur compounds from methionine and cyst(e)ine was studied by Herbert and Shewan (1976). High concentrations of dimethylsulphide (up to 2 500 ng/ℓ) and dimethyldisulphide (up to 1 600 ng/ℓ) were found in algal cultures. The dimethylsulphide concentration in pond water also reached 70 ng/ℓ in summer, especially in *Nostoc* and decaying *Spirogyra* and *Oedogonium* communities (Bechard and Rayburn, 1979).

There are several papers dealing with the identification of volatile organic compounds produced by algal cultures. Most of these substances are odorous, giving taints to water and may be potential causes of taste and odour incidents. Juttner et al. (1986) identified over 60 volatile compounds in lake waters containing phytoplankton populations dominated by *Dinobryon, Microcystis* and *Aphanizomenon*. Apart from the substances described above, ß-cyclocitral (a tobacco-smelling substance of the nor-carotenoid group) was found to be the dominant volatile product of *Microcystis* cultures. ß-cyclocitral was also found in *Microcystis* by Hayes and Burch (1989). They also identified a cucumber-smelling odorant, frequently reported from *Synura* blooms, as trans-2,cis-6-non-adienal. A study on the odorous compounds produced by *Anabaena* and *Nostoc* was done by Mohren and Juttner (1983). *Synechococcus* products were investigated by Henatsch and Juttner (1983). A useful summary of volatile cyanobacterial metabolites was compiled by Slater and Blok (1983a) and, for algae, by Juttner (1983).

Chlorination by-products

Chlorination is one of the most important stages in conventional water purification schemes. It disinfects the finished water, delivers a residual concentration for the distribution system and destroys many of the harmful substances by oxidation. It is also relatively cheap and easy to apply. Apart from the advantages, chlorine application may bring about some undesirable effects. Over-chlorination causes consumer complaints because of the "chlorine" smell in the water. In fact, according to a South African survey (Wnorowski et al., 1989), 13% of reported taste and odour problems are caused solely by excessive chlorination. Further, not all organics present in the raw water will be easily oxidised. For example, geosmin and MIB, which are major odorants in surface water, are resistant to chlorine even at high dosages (Lalezary et al., 1986a) and require other methods for their removal. A matter of concern, however, is the creation of additional taste, odour and health problems by the very chlorination procedure. This is true especially when applied in the early phase of a treatment process, as a pre-chlorination of raw water prior to the removal of intact algal cells and other organic matter by sedimentation or flotation. Chlorination of algae causes their lysis and release of taste and odour producing substances and other organic compounds contained mainly within the cells (Wu and Juttner, 1988). Their release into the water may drastically increase the concentration of odorous substances, making their removal even more difficult. In addition, chlorine derivatives may also present a health hazard by the production of trihalomethanes (Pieterse, 1988), as well as creating an odour nuisance like medicinal-smelling chlorophenols, especially 2-chlorophenol, 2,4-dichlorophenol and 2,6-dichlorophenol (Burttschell et al., 1959). Oxidation products may also be odorous; for example, low molecular weight aldehydes such as methylpropanal, methylbutanal and phenylacetaldehyde (Hrudey et al., 1988). Organohalogens may find their way into surface waters through industrial pollution, e.g. during the process of chlorobleaching of pulp (Paasivirta et al., 1983).

Taste and odour in water with reference to fisheries and aquaculture

Fish tissue readily absorbs off-flavours from water which can render the fish unpalatable and therefore unmarketable. Serious commercial losses may result from taste and odour in water both in fish husbandry and marine and freshwater fisheries. Aquaculture encounters similar problems to the water treatment industry with fish being tainted mainly by geosmin but also by other natural algal by-products accumulating in fish ponds (Lovell, 1983; Martin et al., 1988; Wu and Hsu, 1988).

Algal growth in commercial ponds is inadvertently enhanced by over-fertilisation with fish feed and faeces. Fish in intensive cage-culture systems (trout and catfish) are particularly susceptible to off-flavours produced by algae, as the fish are unable to move away from the algal blooms. Their removal to clean, odourless water to purge geosmin and MIB is a means of off-flavour abatement (Wu and Hsu, 1988) but this decreases profitability as it leads to a three- to ten-day delay in the processing of market sized fish until the flavour subsides.

On the other hand, fish occurring in natural waters are often tainted by industrial effluents, apart from acquiring the muddy-musty odours produced by algae. Fresh- and brackish-water fish in Finland were found to be spoiled mainly by oil and kraft pulp mill odours (Kuusi and Suihko, 1983). Terpenes from paper mill effluents were identified as a source of off-flavours in fish in polluted rivers in Norway (Berg, 1983), while chlorophenols and anisoles from pulp and paper industries were found to give odours to fish in Finland (Paasivirta et al., 1983). Industrial pollution was also the suspected cause of an iodine-like taste in the Baltic Sea herring. The odorous substance was identified as o-bromophenol (Bemelmans and Den Braber, 1983).

The petrochemical industry also contributes to taste spoilage of aquatic fauna. Oily, petroleum-like off-flavours were investigated by Jardine and Hrudey (1988). Threshold odour concentrations for several hydrocarbons from oil sands waste waters were established for fish flesh. Effluents from marine petrochemical installations in Japan were found to contaminate fish with mainly toluene and benzene (Ogata, 1988). Fish tainted with petroleum chemicals was the subject of a review by Motohiro (1983). Off-flavours in other seafood were discussed by Whitfield and Freeman (1983) and Whitfield (1988).

Methods in taste and odour research

The analytical methods available for the determination of odorous compounds in water include sensory evaluation by the human senses and gas chromatographic techniques.

Sensory analysis

Human senses are the most sensitive tools for taste and odour detection and quantification. Their practical utilisation, however, encounters several drawbacks. Sensory evaluation is subjective and difficult to standardise. It is unable to discriminate specific odours in the presence of stronger ones and it rapidly suffers from fatigue. Because of differences in olfactory sensitivities (Amoore, 1986), a panel consisting of several individuals is usually employed. Sensory analysis has been used for years especially in drinking-water assessment. The traditional method used is the threshold odour number (TON). At present the flavour profile analysis (FPA) has been developed for water analysis. Both methods are recommended by *Standard Methods* (1989). The TON is a value reflecting the highest dilution of the odorous sample at which odour is still perceptible. Threshold concentrations are very difficult to assess; they are subjective and vary between individuals. Nevertheless, it is still used in many routine waterworks laboratories, producing comparable results among panels (Bousquet et al., 1983), as well as some research laboratories (Popovska, 1983; Tomita et al., 1988).

The FPA method, using the undiluted sample, has been introduced to overcome drawbacks in TON assessment. It was first designed for food and beverages flavour analysis and then adapted to drinking water (Krasner et al., 1985; Krasner, 1988). It was rapidly developed into a standard method for sensory analysis of water (Suffet et al., 1988). It is based on the rating of odour intensity in the undiluted sample, together with odour description, given by a group of trained panelists. A library of reference substances and odour descriptors has been established (Bailey et al., 1988). The method proved to be precise, reproducible and accurate, provided the panelists have been properly trained (Brady et al., 1988). The training methods for FPA have been established (Bartels et al., 1987; Mallevialle and Suffet, 1987).

Instead of a trained panel, a large, untrained consumer panel is sometimes used primarily for assessment of consumer satisfaction with water produced by a given utility (De Greef et al., 1983). The trained panel's sensitivity is usually more acute than the consumer's (Sano, 1988), but the latter represents more closely the receivers opinion on drinking-water quality.

Instrumental analysis

Because of the extremely low threshold odour concentration of many of the odorous organic compounds (lying within the range of a few ng/ℓ), chemical analysis was inadequate for many years. Development by Grob (1973) of the closed-loop stripping analysis (CLSA) made it possible to concentrate trace organic compounds in water to fall within the necessary detection limits for instrumental methods. Concentrated compounds are then detected by capillary gas chromatography and identified by mass spectrometry (Krasner et al., 1983). Some modifications to Grob's method (Savenhed et al., 1983) and alternative extraction and concentration techniques (Brownlee et al., 1988; Lundgren et al., 1988a) have been proposed.

An interesting modification of the gas chromatographic technique has been developed (Veijanen et al., 1983, 1988). This combines instrumental and sensory analysis and is called chromatographic sniffing. The capillary column is equipped with an outlet leading to an odour observer. The system is both highly sensitive and accurate for the determination of retention times (Savenhed et al., 1985).

Case studies

Actinomycetes

Proven cases of taste and odour in water attributable to actinomycetes are scarce. Silvey and Roach (1953) demonstrated a persistent earthy odour in Lake Hefner and Lake Overholser near Oklahoma City to be caused by actinomycetes. Bacteria were growing inside the cells of attached green alga *Cladophora* which was forming mats along the concrete or stone banks of both reservoirs. The odour was most pronounced in winter, when disintegrating algae released actinomycete by-products into the water. Eradication of algae with copper citrate completely contained the problem. The authors also expressed their conviction that taste and odour incidents involving cyanobacteria are in fact induced by actinomycetes inhabiting algal cells. This opinion proved errant when more evidence on the subject was collected.

Suspected actinomycete involvement can be attached to a geosmin incident in the Vaal Dam in South Africa, early in 1988 (Bailey, 1988). The dam, filled to only a quarter of its capacity for several years due to severe drought, rapidly filled at the end of 1987 due to extensive rains in the catchment area. Some 32 ha of previously exposed dam sediment was flooded and shortly afterwards a taste and odour incident occurred. Algae or cyanobacteria could not account for the incident (Scott, 1988). One can presume that actinomycetes developed profusely in the dried-out fertile sediment and their odorous metabolites gave rise to taste and odour in the water when they were rapidly leached out by the rising water level. Additionally, decaying vegetation which colonised exposed sediments during drought provided a rich nutrient source for odorous actinomycetes.

In spite of the firm views of Silvey (1954) and Roach and Silvey (1958) on taste and odour formation by water actinomycetes, most of the publications monitoring actinomycetes during taste and odour incidents could not find any positive correlation between their numbers and the presence of the odour in water (e.g. Leventer and Eren, 1969; Berglind et al., 1983b; Yagi et al., 1983; Raman and Arbuckle, 1989). Finding a relationship is complicated by the fact that most of the actinomycetes may survive in water in the form of spores (Boon, 1989) while only active and metabolising cells are responsible for the synthesis of odorous by-products (Cross, 1981). Indeed, even the mere existence of truly aquatic actinomycetes was questioned (Cross, 1981) and any odour production in water disavowed.

On the other hand, actinomycetes are known producers of earthy odours and, even if not directly involved with taste and odour formation in surface waters, they may still contribute to taste and odour incidents, provided the specific conditions occur. The wash-out of odorous by-products from soil may take place, as soil is the natural habitat for actinomycetes, where they proliferate profusely (Romano and Safferman, 1963; Cross,1981; Persson, 1988). This hypothesis seems logical and feasible but has not been confirmed by reliable scientific evidence. Plant-populated water margins may provide a nutrient-rich environment for the growth of actinomycetes (Cross, 1981; Wood et al., 1983). Enrichment of a water body is also a potential factor, as actinomycetes show a positive correlation between nitrogen concentration and odour production (Lind and Katzif, 1988).

Cyanobacteria and algae

There is abundant documentation on taste and odours in surface waters caused by algae and cyanobacteria. Studies have been done world-wide with most originating in North America and Japan.

The Metropolitan Water District of Southern California supplies potable water to approximately 13 m people (Means and McGuire, 1986). Water sources of Metropolitan have, since 1967, had numerous taste and odour incidents. From Lake Mathews a littoral attached cyanobacterium, *Oscillatoria curviceps*, and from Phoenix Reservoir a benthic strain of *Oscillatoria tenuis* var. *levis* Gardner, were isolated as the main odour producers. Planktonic bloom of *Anabaena scheremetievi* Elenkin was responsible for odours in the Tinemaha Reservoir (Izaguirre et al., 1982). *O. curviceps* and *O. tenuis* produced 2-methylisoborneol, while *A. scheremetievi* produced geosmin (Izaguirre et al., 1982, 1983). The proficient preventive and treatment measures applied in this case will be discussed under **Treatment**.

Geosmin, produced by a non-identified attached cyanobacterium was also responsible for two taste and odour incidents in the Schuylkill River in Philadelphia (Burlingame et al., 1986). Effective eradication of odour in both cases was a result of an existing taste and odour control programme. From Saskatchewan, Canada, Buffalo Pound Lake was reported to have experienced taste and odour incidents (Slater and Blok, 1983b). Blooms involving *Anabaena, Oscillatoria* and *Aphanizomenon* are often present there. Chemical analysis of the lake water revealed the presence of geosmin and tobacco-smelling ß-cyclocitral.

Japan, an overpopulated and highly industrialised country, has experienced severe taste and odour problems in its drinking water during the last 20 years. The Yodo River basin, which includes Lake Biwa (the largest lake in Japan), serves a population of some 13 m people, including the inhabitants of Kyoto and Osaka. Taste and odours of biological origin, first noted in 1969, became recurrent and created considerable social problems (Toui, 1989). Initially these incidents were caused by the MIB-producing strain of *Phormidium tenue* Meneghim, but in 1981 the geosmin-producing strain of *Anabaena macrospora* Klebahn was also isolated (Yagi et al., 1983). Later, a strain of *Oscillatoria tenuis* Agardh, with significant MIB production was identified (Negoro et al., 1988). The highest values for MIB and geosmin were recorded in Lake Biwa water in the autumn of 1985 giving readings of 1 050 and 860 ng/*ℓ* respectively (Yagi, 1988).

The Yodo River originates from Lake Biwa and therefore also experiences musty odour problems. Geosmin and MIB are monitored along the river. Geosmin concentration was found to decrease along the river course while the MIB level was not affected, probably due to its resistance to biodegradation (Hishida et al., 1988).

The Nunobiki Reservoir near Kobe has experienced several blooms of the alga *Uroglena americana* from the family Chrysophyceae. Blooms were accompanied by a strong fishy odour. Two isomers of 2,4-heptadienal were detected and associated with these episodes (Yano et al., 1988).

Five water sources in Tokyo were studied by Matsumoto and Tsuchiya (1988). Two MIB-producing cyanobacteria (*Oscillatoria geminata* and *Oscillatoria limnetica*) and 3 geosmin-producing cyanobacteria (*O. amoena, O. splendida* and *Aphanizomenon flos-aquae*) were identified as sources of taste and odour in these impoundments.

Taste and odour problems involving cyanobacteria have been reported from Norway. Berglind et al. (1983a) investigated south-eastern Norwegian water bodies and were able to associate *Oscillatoria bornetti* f. *tenuis* Skuja with geosmin incidents in Lake Mjosa and River Glama, *Oscillatoria agardhii* Gom. with geosmin in Lake Arungen and *Oscillatoria agardhii* var. *isothrix* with muddy odours in Lake Vansjo. Benthic mats of *Oscillatoria brevis* (Kütz). Gom. are abundant in Norwegian inland eutrophic rivers and lakes. A strain of *O. brevis* collected from the River Nitelva was found to produce both MIB and geosmin in culture (Berglind et al., 1983b).

Benthic *Oscillatoria chalybea* was found to induce earthy smells in the Tsalmon reservoir in Israel (Leventer and Eren, 1969).

A *Synura* bloom was associated with the cucumber-smelling taste and odour incident in Hubenov Reservoir in Czechoslovakia (Popowska, 1983).

Odorous algae have also been reported in the Southern Hemisphere. In Australia (Hayes and Burch, 1989) *Oscillatoria, Anabaena* and *Microcystis* were found to produce several odorous metabolites, among them geosmin, MIB and ß-cyclocitral. The cucumber odour produced by *Synura* was found to be due to 2,6-nonadienal. In South Africa Joubert et al. (1989) reported on severe earthy odours which appeared in February 1988 in Nagle Dam, the main water source for Durban. The cause was identified as a geosmin-producing *Anabaena* strain. The problem recurred in subsequent years, always associated with a bloom of *Anabaena solitaria* (Wnorowski and Scott, 1990). Geosmin-involving incidents were also noted in Vaal Dam, Klipvoor Dam, Bospoort Dam and Wentzel Dam in the northern part of the Republic of South Africa. In all of them *Microcystis aeruginosa* was found to be the most prominent micro-organism present at the time of taste and odour formation (Wnorowski and Scott, 1990).

Treatment

Conventional water treatment, with the routine sequence of coagulation- sedimentation-filtration-chlorination, does not efficiently remove taste and odour, especially the earthy type, from water (Montiel, 1983). Known techniques deal with tastes and odours either by decomposition of the chemical structure or actual removal of the odorous compounds from the water. A schematic representation of treatment methods for taste and odour removal is presented in Table 3. Some of them will be discussed in more detail below.

Physical-chemical treatment

Oxidation is the major chemical treatment process for taste and odour removal. Oxidising agents utilised in the water industry include chlorine, chloramines, ozone, chlorine dioxide and potassium permanganate, with chlorine gas (Cl_2) being the most popular oxidant/disinfectant used. It is cheap, easy to apply, provides a long-lasting residual concentration in the distribution system and is efficient in destroying certain tastes and odours found in raw water, for example, organic sulphides (Krasner et al., 1989). On the other hand, it has several serious disadvantages:

- Firstly it produces chlorinated by-products with many trace organic compounds present in the water. These organohalogens may be odorous (for example, medicinal-smelling chlorophenols) or present a potential health risk (for example, trihalomethanes).
- Secondly, chlorine itself, if improperly dosed, gives an unpleasant chlorinous odour to the water.
- Thirdly, there are a number of odours, particularly geosmin and MIB, which do not yield to oxidation by chlorination. For these substances chlorine treatment is totally inappropriate (Lalezary et al., 1986a).

Replacement of chlorine with chloramines was reported to improve disinfection of drinking water (Cuncliffe et al., 1990) but failed to remove the fishy/swampy odours imparted by methylpolysulphides (Krasner et al., 1989). Oxidation of five earthy/musty odorants was studied by Lalezary et al. (1986a). For all of these chlorine dioxide proved to be the most efficient with potassium permanganate displaying the least efficiency. Ozone was rated second for recalcitrant MIB and geosmin compounds. A successful chlorine dioxide application for taste and odour removal, disinfection and prevention of trihalomethane formation was reported from Brussels (Masschelein, 1985). Chlorine dioxide was also reported useful for the removal of chlorophenols but not hydrocarbons (Walker et al., 1986). Permanganate may be used for the oxidation of odorous substances, but it should be accompanied by activated carbon addition (McTighe, 1971). Ozone has been studied extensively for taste and odour removal. It was found to be effective for the removal of earthy and fishy odours but not astringent and plastic-like odours, and in addition it generated an intense fruity odour of its own (Anselme et al., 1988). Ozone, if applied in low concentrations, improves flocculation, but in concentrations over 1 mg/ℓ may cause degradation of algogenic organic matter leading to formation of carboxilic acids which have the ability to stabilise colloids and impair flocculation efficiency (Hoyer et al., 1987). In comparison with other oxidants the greatest disadvantage of ozone is that it cannot supply an active residue for the reticulation system and so must be supplemented with an additional disinfecting agent. Ozone is, however, recommended for the treatment of earthy/musty odours, as well as for the oxidation of manganese (Barker and Palmer, 1977; Gammie et al., 1988). Most recently (Glaze et al., 1990), advanced oxidation processes have been introduced. They involve combination of an oxidant with an agent (ozone, UV), facilitating oxidation by forming free hydroxyl radicals from hydrogen peroxide or humic substances. The hydroxyl radical is a much more powerful oxidant than chlorine or ozone alone, especially towards aliphatic molecules such as geosmin and MIB. The systems employing O_3 - H_2O_2 (peroxone), O_3-UV and H_2O_2-UV have been tested (Glaze et al., 1990). The optimisation of peroxone treatment on a pilot-plant scale was studied by Ferguson et al. (1990).

Physical taste and odour treatment involves many diverse technologies. Simple measures comprise the blending of the odorous water with an odour-free counterpart to dilute the odour concentration below its threshold value, or manipulation of the draw-off point to a water level less affected by an odour problem. Air-stripping is satisfactory only for very volatile odorous substances such as hydrogen sulphide (McGuire and Gaston, 1988a, 1988b). Radiation technologies (ultra-violet, gamma rays) are efficient but, at present, cost-prohibitive, and have only sporadically found full-scale application (Anonymous, 1989b;

TABLE 3
TREATMENT METHODS FOR TASTE AND ODOUR ABATEMENT

Treatment options			
Decomposition			Removal
Oxidation	Radiation	Biodegradation	
Chlorine Chloramines Chlorine dioxide Ozone Permanganate Peroxone	Gamma rays UV light High energy electrons	Bacteria Yeasts Protozoa	Aeration Powdered activation carbon (PAC) Granular activated carbon (GAC) Powdered activated carbon/dissolved air flotation (PAC/DAF)

Comar, 1989).

Activated carbon, with its enormous sorption capacity for organic and inorganic molecules, is decidedly the best solution for the removal of odorous substances. Concomitantly, it removes other contaminants from the treated water, some of which being a potential health hazard. The only serious disadvantages of this material are its high prices and non-selectiveness. Both powdered activated carbon (PAC) and granular activated carbon (GAC) have been successfully applied in practice. Le Roux (1988b) listed PAC characteristics making this carbon superior to the granular form, especially for small treatment facilities:

- more rapid adsorption equilibrium;
- no major capital costs involved;
- intermittent application possible; and
- low cost per unit mass.

On the other hand GAC, although involving high installation costs, may be used for prolonged periods of time before reaching saturation point and may also be regenerated. Performance and optimisation of conditions for the different types of carbons were evaluated by Lalezary et al. (1986b) and Lalezary-Craig et al. (1988). MIB proved to be the substance less adsorbed than geosmin. Presence of chlorine, chloramines and humic acid exerted an adverse effect on geosmin and MIB adsorption on to carbon. Examples of successful application of GAC filters in pilot and full-scale plants have been extensively published (for example Flentje and Hager,1964; Hansen, 1972; Gammie et al., 1988; Hattori, 1988; Terashima, 1988; Vik et al., 1988). The PAC is generally used in conjunction with sedimentation/filtration procedures (Joubert et al., 1989). An interesting alternative seems to be the combination of PAC with the dissolved air flotation technique, namely the PAC/DAF process (Le Roux, 1988b). Cyanobacteria, like *Microcystis* spp., possess a system of gas vacuoles, allowing them to maintain the necessary buoyancy in water (Reynolds and Walsby, 1975). This phenomenon makes them difficult to sediment. The DAF method concentrates the biomass on the top of the reservoir rather than at the bottom. PAC floats together with algal cells and both materials can then be removed simultaneously. The sludge obtained is dense and easy to handle and does not present odour problems on disposal due to the residual capacity of the PAC which adsorbs any odours arising from decay of the biomass.

An interesting development in water purification seems to be point-of-use treatment. This is an option which is gaining acceptance and popularity in the USA and Europe. In particular, the use of compact units employing activated carbon, ion exchange resin and even reverse osmosis are involved, such units are typically connected to a tap in the home (EPA Proceedings, 1988). Use of these devices indicates the urgency with which consumers view the problem of water quality, to the extent that they treat the water themselves. One must not, however, forget that these filters may eventually become overloaded, allowing contaminants to pass through, and that they provide support for bacteria which may contribute new tastes and odours and other by-products to the "filtered" water (Hadeed, 1989).

Biological treatment

Biological degradation of odorous organic compounds is an attractive alternative to chemical/physical treatment. Narayan and Nunez (1974) found that *Bacillus cereus* and *Bacillus subtilis* were able to degrade geosmin. The efforts of Danglot et al. (1983) to isolate the enzyme, responsible for geosmin decomposition and disappearance of the earthy odour, were unsuccessful. A yeast *Candida* sp., isolated from a slow sand filter, showed a marked ability to degrade MIB, both in a cell-form and as a crude enzyme preparation (Sumitomo, 1988; Sumitomo et al., 1988). Gel-immobilised biomass or enzyme removed MIB efficiently, but required prolonged (20 to 40 h) contact times. Biodegradation of MIB was also reported by Izaquirre et al. (1988a, 1988b) who found that mixed bacterial populations, consisting mainly of *Pseudomonas* spp., slowly decreased (in 7 to 17 d) the MIB content of water samples. *Thiobacillus thioparus*, immobilised on porous propylene pellets, was employed for the removal of sulphur-containing odorants from air and gases (Tanji et al., 1989) and biologically active sand filters were employed for the efficient odour removal from drinking water by Lundgren et al. (1988b). Biological processes also have the potential for the removal of total organic carbon, ammonia and nitrate from drinking water (Bouwer and Crowe, 1988).

The large number of odorous compounds and their many causal factors indicate the importance of the identification of off-flavours before deciding upon one or more of a variety of treatment methods. Correct and cost-efficient treatment needs to be determined for each case individually. A summary of the available water treatment processes to control some of the off-flavours is given in Table 4.

Reservoir management

Lake and river management, orientated on the improvement of water quality, requires complex activities. It relates to nutrient level, toxic chemicals, microbial life, aquatic macrophytes, zooplankton, macroinvertebrates and fish (McDonnel and Crocker, 1989). Preventative treatment by management of the water source is a long-term strategy and, if successful, may resolve the taste and odour problem completely. The elements of source management are given in Table 5.

Undoubtedly, the most holistic approach is proper watershed protection. The efficiency of such a strategy would depend on the co-operation of all those who influence discharge into the water, including industries, municipalities, residents and farmers in the catchment area. A single body carrying sole responsibility for management of a watershed could handle all water matters more easily than a divided authority (Anonymous, 1989a). There are voices that water from properly protected areas may attain such a high quality that filtration of potable supplies could be discontinued (Kirner and Merry, 1988). A restoration policy, applied to a dangerously eutrophied Swedish lake, brought about reversal to its original oligotrophic status (Persson et al., 1989).

An early warning system has been proposed by McGuire et al. (1983) and Means and McGuire (1986). It consists of regular monitoring of nutrient levels in the lake, as well as thorough monitoring of troublesome algae, including benthic inhabitants, when necessary. The odour intensity in the water is also periodically checked. At the early sign of odour development measures are applied, for example adequate dosage with copper sulphate, to prevent the odorous algae from forming a bloom. Aeration of shallow aquifers as well as destratification and hypolimnetic aeration in deep lakes without destratification, may reverse the undesirable effects of oxygen depletion. Maintenance of adequate oxygen levels prevents the formation of an anaerobic zone. Anaerobic odorous products will not be formed and odour- forming cyanobacteria are usually replaced by other algal populations. Aeration also helps to mineralise iron and manganese salts and oxidises the top sediment layer, thus reducing its demand for oxygen (Geney and Randolph, 1988). Long-term destrafication of Illinois Lake allowed for return of this reservoir to service as a potable water source (Bartels et al., 1987).

The simpler measures of source treatment are manipulation of the reservoir's level to expose and dehydrate benthic cyanobacteria (McGuire and Gaston, 1988a, 1988b), application of algicides, especially for blue-green algae (Barnhard, 1980; Scott et al., 1989) and prevention of light (Montiel, 1983). Montiel (1983) mentions popular algicides in use: amongst the mineral algicides are copper sulphate, potassium permanganate, chlorine, chlorine dioxide and silver preparations, while the organic algicides include aramzide, 2,3-dichloronaphtoquinone and polymyxime. It must be remembered, however, that algicide treatment of the algal bloom may bring about the disastrous effect of a sudden kill, with the release of odorous and toxic metabolites and the subsequent deterioration of the water.

Prevention of light in the aquifer can be attained by maintaining water turbidity, e.g. with silt or activated carbon or by covering the reservoir (Montiel, 1983). Cutting off the light prevents photosynthesis and reduces production of odorous metabolites. Krasner and Means (1986)achieved a marked improvement in microbial quality when the finished water reservoir was covered with floating covers.

Biomanipulation techniques are only in the early stages of development. Some biomanipulation successes were unplanned, such as the reduction of turbidity by cyanobacteriovorous *Daphnia* population which suddenly increased in number in Lake Washington (Edmonson and Abella, 1988). Biomanipulation involves introducing useful species, from a lake management point of view, or promoting the success of indigenous desirable organisms. This leads to reduction in the rate of reproduction and survival of undesirable organisms. Natural competition and antagonism are employed, predation or parasitism commonly being the most practical (Sudo et al., 1989). Control of nutrient input and removal of excess nutrients may also aid in biomanipulation procedures.

Biodegradation of odorous organic compounds, mentioned earlier with biological water purification (**Biological treatment**), is the naturally occurring phenomenon. The concentration of odorous compounds in water is a function of the speed at which the bacterial population degrade it (Means and McGuire, 1986). Some microbial populations, able to degrade MIB, were found by Izaguirre et al. (1988a; b).

Lake management strategies aimed at maintaining the overall balance of the water body bring advantages to nature conservation, wildlife, tourism, health and water purification industries. The analysis of costs, brought about by the adverse effects of algal growth on drinking-water supplies, was performed by Magara and Kunikane (1986). The cost of conventional treatment increases five times and, together with the additional costs of taste and odour and organohalide removal, results in a twentyfold increase when algae are present. Intensive lake management activities result in improved water quality and that brings both aesthetic and economic advantages for the whole community.

References

AMOORE, JE (1986) The chemistry and physiology of odour sensitivity. *J. AWWA* **78**(3) 70-76.

ANONYMOUS (1989a) Umgeni Water calls for river basin management. *Water, Sewage* and *Effluent* **9**(3) 31.

ANONYMOUS (1989b) UV water treatment. *Water* and *Waste Treatment* **32**(6) 18.

ANONYMOUS (1989c) *Water Newsl.* **31**(10) 4.

ANSELME, CA, SUFFET, IH, and MALLEVIALLE, J (1988) Effect of ozonation on tastes and odors. *J. AWWA* **80**(10) 45-51.

AOYAMA, K (1990) Studies on the earthy-musty odours in natural water (IV). Mechanism of earthy-musty odour production of actinomycetes. *J. Appl. Bacteriol.* **68** 405-410.

BAILEY, AJ (1988) Odours in drinking water: A case study. *Water, Sewage* and *Effluent* **8**(4) 13-16.

BAILEY, AJ, VILJOEN, FC, and VAN ZYL, G (1988) A preliminary evaluation of descriptors and odor reference standards recommended by the IAWPRC Specialist Group on Tastes and Odors. *Water Qual. Bull.* **13**(2/3) 84-89 and 101.

BARKER, MR and PALMER, DJ (1977) Persistent odour-taste removal: The use of ozone and microcoagulation or carbon. *Water SA* **3**(2) 53-65.

BARNHARD, DR (1980) Finding the right therapy for tastes and odours. *Public Works* June, 95-96 and 130.

BARTELS, JHM, BRADY, BM and SUFFET, IH (1987) Training panelists for the Flavour Profile Analysis method. *J. AWWA* **79**(1) 26-32.

BECHARD, MJ and RAYBURN, WR (1979) Volatile organic sulfides

TABLE 4
SUMMARY OF WATER TREATMENT PROCESSES TO CONTROL OFF-FLAVOURS (McGUIRE AND GASTON, 1988b)
(Reprinted from *Water Sci. Technol.* (1988) 20 215-228, with permission from the publishers, Pergamon Press, and the copyright holders, IAWPRC)

Off-flavour characteristic	Compound*	Treatment processes Effective	 Ineffective
Earthy/musty	MIB, geosmin	O_3, O_3/H_2O, PAC, GAC, biological	Aeration, Cl_2, ClO_2 $KMnO_4$, NH_2Cl
	IPMP, IBMP	Cl_2, ClO_2, PAC, GAC	Aeration, $KMnO_4$
	TCA	ClO_2, O_3, PAC, GAC, biological	Aeration, Cl_2, $KMnO_4$
Fishy/swampy	DMTS, DMDS, and other compounds	Most oxidants, PAC, GAC, biological	Chloramines
Grassy	Unknown	Most oxidants (?), PAC, GAC	Chloramines
Chlorinous	$HOCl/OCl^-$, $NHCl_2$, NCl_3, chlorinated organics	PAC, GAC	Biological
Petroleum	Low-molecular-weight aliphatics and aromatics	Aeration, PAC, GAC, biological	Oxidants
Medicinal	Phenol, chlorophenols	ClO_2, O_3, PAC, GAC, biological	Cl_2, NH_2Cl, $KMnO_4$
Rotten egg	H_2S	Aeration, oxidants	--

***Abbreviations:**

MIB = 2-methylisoborneol
IPMP = 2-isopropyl-3-methoxy pyrazine
IBMP = 2-isobutyl-3-methoxy pyrazine
TCA = 2,3,6-trichloroanisole
DMTS = dimethyl trisulphide
DMDS = dimethyl disulphide
PAC = powdered activated carbon
GAC = granular activated carbon

TABLE 5
SOURCE MANAGEMENT TOOLS

Watershed protection
Early warning system
Aeration, destratification and hypolimnetic aeration
Manipulation of reservoir level
Application of algicides
Prevention of light
Biological control
- biodegradation
- removal of nutrients
- biomanipulation

from freshwater algae. *J. Phycol.* **15** 379-383.

BEMELMANS, JMH and DEN BRABER, HJA (1983) Investigation of an iodine-like taste in herring from the Baltic Sea. *Water Sci. Technol.* **15**(6/7) 105-113.

BERG, N (1983) Chemical and sensory analysis of off-flavours in fish from polluted rivers in Norway. *Water Sci. Technol.* **15**(6/7) 59-65.

BERGLIND, L, HOLTAN, H and SKULBERG, OM (1983a) Case studies on off-flavours in some Norwegian lakes. *Water Sci. Technol.* **15** 199-209.

BERGLIND, L, JOHNSEN, IJ, ORMEROD, K, and SKULBERG, OM (1983b) *Oscillatoria brevis* (Kutz.) Gom. and some other especially odouriferous benthic cyanyophytes in Norwegian inland waters. *Water Sci. Technol.* **15**(6/7) 241-246.

BOON, PI (1989) Relationship between actinomycete populations and organic matter degradation in Lake Mulwala, Southeastern Australia. *Regul. Rivers: Research* and *Manage.* **4** 409-418.

BOUSQUET, G, OUVRARD, J, RIGAL, S and VILAGINES, R (1983) Statistical evaluation of the blind test method for water quality control. *Water Sci. Technol.* **15**(6/7) 35-46.

BOUWER, EJ and CROWE, PB (1988) Biological processes in drinking water treatment. *J. AWWA* **80**(9) 82-93.

BRADY, BM, BARTELS, JHM and SUFFET, IH (1988) Sensory analysis of drinking water. *Water Qual. Bull.* **13**(2/3) 61-68 and 99.

BROWNLEE, BG, GAMMIE, L, GUMMER, WM D and MacINNIS, GA (1988) A simple extraction procedure for moderately volatile taste and odour compounds such as geosmin and 2-methylisoborneol - Method and application. *Water Sci. Technol.* **20**(8/9) 91-97.

BURLINGAME, GA, DANN, RM and BROCK, GL (1986) A case study of geosmin in Philadelphia's water. *J. AWWA* **78**(3) 56-61.

BURTTSCHELL, RH, ROSEN, AA, MIDDLETON, FM and ETTINGER, MB (1959) Chlorine derivatives of phenol causing taste and odour. *J. AWWA* **51**(2) 205-214.

COMAR, D (1989) New developments in water disinfection by ultraviolet light. *Water* **16**(1) 46-48.

CROSS, T (1981) Aquatic actinomycetes: A critical survey of the occurrence, growth and role of actinomycetes in aquatic habitats. *J. Appl. Bacteriol.* **50**(3) 397-423.

CUNCLIFFE, DA, CHRISTY, PE, ROBINSON, B and WALTERS, RP (1990) Effect of changing from chlorination to chloramination on microbiological quality. *Water* **17**(1) 28-30.

DANGLOT, C, AMAR, G AND VILAGINES, R (1983) Ability of bacillus to degrade geosmin. *Water Sci. Technol.* **15**(6/7) 291-299.

DE GREEF, E, ZOETEMAN, BCJ, VAN OERS, HJ, KOSTER, EP and ROOK, JJ (1983) Drinking water contamination and taste assessment by large consumer panels. *Water Sci. Technol.* **15**(6/7) 13-24.

EDMONSON, WT and ABELLA, SEB (1988) Unplanned biomanipulation in Lake Washington. *Limnologica* **19**(1) 73-79.

EPA PROCEEDINGS (1988) *Proceedings of the Conference on Point-of-Use Treatment of Drinking Water*, Cincinatti, Ohio, 6-8 October, 1987.

FERGUSON, DW, McGUIRE, MJ, KOCH, B, WOLFE, RL and AIETA, EM (1990) Comparing peroxone and ozone for controlling taste and odor compounds, disinfection by-products, and microorganisms. *J. AWWA* **32**(4) 181-191.

FLENTJE, E and HAGER, G (1964) Advances in taste and odour removal with granular carbon filters. *Water and Sewage Works* **111**(2) 76-79.

GALLUP POLL. (1973) Water quality and public opinion. *J. AWWA* **65**(8) 513-519.

GAMMIE, L, BROWNLEE and GUMMER, WMD (1988) Taste and odor control by granulated activated carbon filtration in a western Canadian water treatment plant. *Water Qual. Bull.* **13**(2/3) 69-71 and 99.

GENEY, RS and RANDOLPH, NJ (1988) Improving water quality by reservoir management. *Waterworld News* **4**(6) 10-13.

GERBER, NN (1979) Volatile substances from actinomycetes: Their role in the odor pollution of water. *CRC Crit. Rev. Microbiol.* **7** 191-214.

GERBER, NN (1983) Volatile substances from actinomycetes: Their role in the odor pollution of water. *Water Sci. Technol.* 15(6/7) 115-125.

GERBER, NN and LECHEVALIER, HA (1965) Geosmin, an earthy-smelling substance isolated from actinomycetes. *Appl. Microbiol.* **13**(6) 935-938.

GERBER, NN and LECHEVALIER, HA (1977) Production of geosmin in fermentors and extraction with an ion-exchange resin. *Appl. Environ. Microbiol.* **34**(6) 857-858.

GLAZE, WH, SCHEP, R, CHAUNCEY, W, RUTH, EC, ZARNOCH, JJ, AIETA, EM, TATE, CH and McGUIRE, MJ (1990) Evaluating oxidants for the removal of model taste and odor compounds from a municipal water supply. *J. AWWA* **82**(5) 79-84.

GROB, K (1973) Organic substances in potable water and in its precursor. Part I - Methods for their determination by gas-liquid chromatography. *J. Chromatogr.* **84** 255-273.

HADEED, SJ (1989) Home water purification systems : Liquid vodoo? *WPCF Federation Highlights* **26**(7) 5.

HANSEN, E (1972) Granular carbon filters for taste and odour removal. *J. AWWA* **64**(3) 176-181.

HATTORI, K (1988) Water treatment systems and technology for the removal of odour compounds. *Water Sci. Technol.* **20**(8/9) 237-244.

HAYES, KP and BURCH, MD (1989) Odorous compounds associated with algal blooms in South Australian waters. *Water Res.* **23**(1) 115-121.

HENATSCH, JJ and JUTTNER, F (1983) Volatile odorous excretion products of different strains of *Synechococcus* (Cyanobacteria). *Water Sci. Technol.* **15**(6/7) 259-266.

HERBERT, RA and SHEWAN, JM (1976) Roles played by bacterial and autolytic enzymes in the production of volatile sulphides in spoiling North Sea cod (*Gadus morhua*). *J. Sci. Fed. Agric.* **27** 89-94.

HISHIDA, Y, ASHITANI, K and FUJIWARA, K (1988) Occurrence of musty odour in the Yodo River. *Water Sci. Technol.* **20**(8/9) 193-196.

HOEHN, RC (1988) Biological causes of tastes and odors in drinking water supplies. *Water Qual. Bull.* **13**(2) 46-51.

HOYER, O, BERNHARD, H and LUSSE, B (1987) The effect of ozonation on the impairment of flocculation by algogenic organic matter. *Z. Wasser-Abwasser-Forsch.* **20** 123-131.

HRUBEC, J and DE KRUIJF, HAM (1983) Treatment methods for the removal of off-flavours from heavily polluted river water in the Netherlands - A review. *Water Sci. Technol.* **15**(6/7) 301-310.

HRUDEY, SE, GAC, A and DAIGNAULT, SA (1988) Potent odour-causing chemicals arising from drinking water disinfection. *Water Sci. Technol.* **20**(8/9) 55-61.

IZAGUIRRE, G, HWANG, CJ, KRASNER, SW and McGUIRE, MJ (1982) Geosmin and 2-methylisoborneol from cyanobacteria in three water supply systems. *Appl. Environ. Microbiol.* **43**(3) 708-714.

IZAGUIRRE, G, HWANG, CJ, KRASNER, SW and McGUIRE, MJ (1983) Production of 2-methylisoborneol by two benthic cyanophyta. *Water Sci. Technol.* **15**(6/7) 211-220.

IZAGUIRRE, G, WOLFE, RL and MEANS, EG (1988a) Degradation of 2-methylisoborneol by aquatic bacteria. *Appl. Environ. Microbiol.* **54**(10) 2424-2431.

IZAGUIRRE, G, WOLFE, RL and MEANS, EG (1988b) Bacterial degradation of 2-methylisoborneol. *Water Sci. Technol.* **20**(8/9) 205-210.

JARDINE, CG and HRUDEY, E (1988) Threshold detection values of potential fish taining substances from oil sands wastewaters. *Water Sci. Technol.* **20**(8/9) 19-25.

JOUBERT, P, KERDACHI, DA, KHAN, A and SMITH, B (1989) Problems caused by *Anabaena* in the water supply to Durban. Paper presented at WISA 1st Bienn. Conf. and Exhib., Cape Town, 28-31 March 1989.

JUTTNER, F (1983) Volatile odorous excretion products of algae and their occurrence in the natural aquatic environment. *Water Sci. Technol.* **15**(6/7) 247-257.

JUTTNER, F (1988) Biochemistry of biogenic off-flavour compounds in surface waters. *Water Sci. Technol.* 20(8/9) 107-116.

JUTTNER, F, HOFLACHER, B and WURSTER, K (1986) Seasonal analysis of volatile organic biogenic substances (VOBS) in freshwater phytoplankton populations dominated by *Dinobryon, Microcystis* and *Aphanizomenon*. *J. Phycol.* **22** 169-175.

KADOTA, H and ISHIDA, Y (1972) Production of volatile sulfur compounds by microorganisms. *Ann. Rev. Microbiol.* **26** 127-139.

KIRNER, JC and MERRY, KJ (1988) Watershed control: A substitute for filtration? *Waterworld News* **4**(6) 14-15.

KRASNER, SW (1988) Flavour-profile analysis: An objective sensory technique for the identification and treatment of off-flavours in drinking water. *Water Sci. Technol.* **20**(8/9) 31-36.

KRASNER, SW, BARRET, SE, DALE, ME and HWANG, CJ (1989) Free chlorine versus monochloramine in controlling off-tastes and off-odours. *J. AWWA* **81**(2) 86-93.

KRASNER, SW, HWANG, CJ and McGUIRE, MJ (1983) The standard method for the quantification of earthy-musty odorants in water, sediments, and algal cultures. *Water Sci. Technol.* **15**(6/7) 127-138.

KRASNER, SW, McGUIRE, MJ and FERGUSON, VB (1985) Tastes and odors: the Flavour Profile Method. *J. AWWA* **77** 34-39.

KRASNER, SW and MEANS, EG (1986) Returning recently covered reservoirs to service: Health and aesthetic considerations. *J. AWWA* **78**(3) 94-100.

KUUSI, T and SUIHKO, M (1983) Occurrence of various off-flavours in fish in Finland from 1969 to 1981. *Water Sci. Technol.* **15**(6/7) 47-58.

LALEZARY, S, PIRBAZARI, M and McGUIRE, MJ (1986a) Oxidation of five earthy-musty taste and odour compounds. *J. AWWA* **78**(3) 62-69.

LALEZARY, S, PIRBAZARI, M and McGUIRE, MJ (1986b) Evaluating activated carbons for removing low concentrations of taste- and odour-producing organics. *J. AWWA* **78**(11) 76-82.

LALEZARY-CRAIG, S, PIRBAZARI, M, DALE, MS, TANAKA, TS and McGUIRE, MJ (1988) Optimizing the removal of geosmin and 2-methylisoborneol by powdered activated carbon. *J. AWWA* **80**(3) 73-80.

LE ROUX, JD (1988a) Tastes and odours in drinking water. *Munic. Eng.* **19**(7) 19-26.

LE ROUX, JD (1988b) The treatment of odorous algae-laden water by dissolved air flotation and powdered activated carbon. *Water Qual. Bull.* **13**(2/3) 72-77.

LEVENTER, H and EREN, J (1969) Taste and odor in the reservoirs of the Israel National Water System. *Developments in Water Qual. Res. Proc. of the Jerusalem Int. Conf. on Water Qual. and Pollut. Res., June 1969,* 19-37.

LIN, SD (1976a) Sources of tastes and odors in water. Part 1. *Water and Sewage Works* **123**(6) 101-104.

LIN, SD (1976b) Sources of tastes and odors in water. Part 2. *Water and Sewage Works* **123**(7) 64-67.

LIND, OT and KATZIF, D (1988) Nitrogen and the Threshold Odour Number produced by an actinomycete isolated from lake sediments. *Water Sci. Technol.* **20**(8/9) 185-191.

LOVELL, RT (1983) Off-flavors in pond-cultured channel catfish. *Water Sci. Technol.* **15**(6/7) 67-73.

LUNDGREN, BV, BOREN, H, GRIMVALL, A, SAVENHED, R and WIGILIUS, B (1988a) The efficiency and relevance of different concentration methods for the analysis of off-flavours in water. *Water Sci. Technol.* **20**(8/9) 81-89.

LUNDGREN, BV, GRIMVALL, A and SAVENHED, R (1988b) Formation and removal of off-flavour compounds during ozonation and filtration through biologically active sand filters. *Water Sci. Technol.* **20**(8/9) 245-253.

MIWA, M and MORIZANE, K (1988) Effects of chelating agents on the growth of blue-green algae and the release of geosmin. *Water Sci. Technol.* **20**(8/9) 197-203.

MOHREN, S and JUTTNER, F (1983) Odorous compounds of different strains of *Anabaena* and *Nostoc* (Cyanobacteria). *Water Sci. Technol.* **15**(6/7) 221-228.

MONTIEL, AJ (1983) Municipal drinking water procedures for taste and odour abatement - A review. *Water Sci. Technol.* **15**(6/7) 279-289.

MOTOHIRO, T (1983) Tainted fish caused by petroleum compounds. A review. *Water Sci. Technol.* **15**(6/7) 75-83.

NAES, H and POST, AF (1988) Transient states of geosmin, pigments, carbohydrates and proteins in continuous cultures of *Oscillatoria brevis* induced by changes in nitrogen supply. *Arch. Microbiol.* **150** 333-337.

NAES, H, UTKILEN, HC and POST, AF (1988) Factors influencing geosmin production by the cyanobacterium *Oscillatoria brevis. Water Sci. Technol.* **20**(8/9) 125-131.

NAES, H, UTKILEN, HC and POST, AF (1989) Geosmin production in the cyanobacterium *Oscillatoria brevis. Arch. Microbiol.* **151** 407-410.

NARAYAN, LV and NUNEZ, WJ (1974) Biological control: Isolation and bacterial oxidation of the taste-and-odor compound geosmin. *J. AWWA* **66** 532-536.

NEGORO, T, ANDO, M and ICHIKAWA, N (1988) Blue-green algae in Lake Biwa which produce earthy-musty odours. *Water Sci. Technol.* **20**(8/9) 117-123.

OGATA, M (1988) Oil-tainted water and fish. *Water Qual. Bull.* **13**(2/3) 56-60.

PAASIVIRTA, J, KNUUTNEN, J, TARHANEN, J, KUOKKANEN, T, SURMA-AHO, K, PAUKKU, R, KAARIAINEN, H, LAHTIPERA, M and VEIJANEN, A (1983) Potential off-flavour compounds from chlorobleaching of pulp and chlorodisinfection of water. *Water Sci. Technol.* **15**(6/7) 97-104.

PERSSON, P-E (1983) Off-flavours in aquatic ecosystems - An introduction. *Water Sci. Technol.* **15**(6/7) 1-11.

PERSSON, P-E (1988) Aquatic off-flavours - Past, present and future. *Water Sci. Technol.* **20**(8/9) 283-288.

PERSSON, G, OLSSON, H, WIEDERHOLM, T and WILLEN, E (1989) Lake Vattern, Sweden: A 20-year perspective. *AMBIO* **18**(4) 208-215.

PIETERSE, MJ (1988) The potential health risk of trihalomethanes in drinking water: A perspective. *SA J. of Sci.* **84** 166-170.

POPOVSKA, P (1983) Odour problems in two reservoirs. *Water Sci. Technol.* **15**(6/7) 25-33.

RAMAN, RK and ARBUCKLE, BR (1989) Long-term destratification in an Illinois Lake. *J. AWWA* **81**(6) 66-71.

REYNOLDS, CS and WALSBY, AE (1975) Water blooms. *Biol. Rev.* **50** 437-481.

ROACH, AW and SILVEY, JKG (1958) The morphology and life cycle of freshwater actinomycetes. *Trans. Amer. Microscopical Soc.* **77** 36-47.

ROMANO, AM and SAFFERMAN, RS (1963) Studies on actinomycetes and their odors. *J. AWWA* **55**(2) 169-176.

SANO, H (1988) The detection of taste and odor in Osaka's drinking water. *Water Sci. Technol.* **20**(8/9) 37-42.

SAVENHED, R, BOREN, H and GRIMVALL, A (1985) Stripping analysis and chromatographic sniffing for the source identification of odorous compounds in drinking water. *J. Chromatogr.* **328** 219-231.

SCOTT, WE (1988) Personal communication. CSIR, Pretoria, RSA.

SAVENHED, R, BOREN, H, GRIMVALL, A and TJEDER, A (1983) Stripping techniques for the analysis of odorous compounds in drinking water. *Water Sci. Technol.* **15**(6/7) 139-148.

SCOTT, JH, BAYNE, DR and BOYD, CE (1989) Effects of potassium ricinoleate on water quality, phytoplankton and off-flavour in channel catfish ponds. *J. Aquat. Plant Manage.* **27** 26-31.

SIGWORTH, EA (1957) Control of odor and taste in water supplies. *J. AWWA* **49** 1507-1520.

SILVEY, JKG (1954) Newer concepts of tastes and odors in surface water supplies. *Water and Sewage Works* **101** 208-211.

SILVEY, JKG and ROACH, AW (1953) Actinomycetes in the Oklahoma City water supply. *J. AWWA* **45**(5) 409-416.

SKULBERG, OM (1988) Chemical ecology and off-flavour substances. *Water Sci. Technol.* **20**(8/9) 167-178.

SLATER, GP and BLOK, VC (1983a) Volatile compounds of the cyanophyceae - A review. *Water Sci. Technol.* **15**(6/7) 181-190.

SLATER, GP and BLOK, VC (1983b) Isolation and identification of odorous compounds from a lake subject to cyanobacterial blooms. *Water Sci. Technol.* **15**(6/7) 229-240.

STANDARD METHODS (1989) *Standard Methods for the Examination of Water and Wastewater* (17th edn.). American Public Health Association. Port City Press, Baltimore.

SUDO, R, INAMORI, Y, KUNIYASU, Y and OUCHIAMA, T (1989) Predation and deodorization of musty odor-producing filamentous algae by the protozoa *Trithigmostoma cucullulus. Water Sci. Technol.* **21** 1743-1746.

SUFFET, IH, BRADY, BM, BARTELS, JHM, BURLINGAME, G, MALLEVIALLE, J and YOHE, T (1988) Development of the Flavour Profile Analysis method into a standard method for sensory analysis of water. *Water Sci. Technol.* **20**(8/9) 1-9.

SUMITOMO, H (1988) Odour decomposition by the yeast *Candida. Water Sci. Technol.* **20**(8/9) 157-162.

SUMITOMO, H, OHMURA, Y, ITO, S and TAKAYA, R (1988) Odour decomposition by an immobilized crude enzyme. *Water Sci. Technol.* **20**(8/9) 163-166.

TANJI, Y, KANAGAWA, T and MIKAMI, E (1989) Removal of dimethyl sulfide, methyl mercaptan and hydrogen sulfide by immobilized *Thiobacillus thioparus* Tk-m. *J. Ferment. Bioeng.* **67**(4) 280-285.

TERASHIMA, K (1988) Reduction of musty odor substances in drinking water - A pilot plant study. *Water Sci. Technol.* **20**(8/9) 275-281.

THORNTON, JA and McMILLIAN, PH (1989) Reconciling public opinion and water quality criteria in South Africa. *Water SA* **15**(4) 221-226.

TOMITA, M, ICHIKAWA, N and GODA, T (1988) Correlation between Threshold Odour Numbers and the concentration of odorous substances in water. *Water Sci. Technol.* **20**(8/9) 27-30.

TOUI, S (1989) The oxidation of manganese and the disinfection by ozonation in water purification process. *Proc. of 9th Ozone World Cong. 1989, New York. Vol. 1. Ozone in water treatment.* 243-255.

VEIJANEN, A, LAHTIPERA, M, PAUKKU, R, KAARIAINEN, H and PAASIVIRTA, J (1983) Recent development in analytical methods for identification of off-flavour compounds. *Water Sci. Technol.* **15**(6/7) 161-168.

VEIJANEN, A, PAASIVIRTA, J and LAHTIPERA, M (1988) Structure and sensory analysis of tainting substances in Finnish freshwater environments. *Water Sci. Technol.* **20**(8/9) 43-48.

VIK, EA, STORHAUG, R, NAES, H and UTKILEN, HC (1988) Pilot scale studies of geosmin and 2-methylisoborneol removal. *Water Sci. Technol.* **20**(8/9) 229-236.

WALKER, GS, LEE, FP and AIETA, EM (1986) Chlorine dioxide for taste and odor control. *J. AWWA* **78**(3) 84-93.

WHITFIELD, FB (1988) Chemistry of off-flavours in marine organisms. *Water Sci. Technol.* **20**(8/9) 63-74.

WHITFIELD, FB and FREEMAN, DJ (1983) Off-flavours in Crustaceans caught in Australian coastal waters. *Water Sci. Technol.* **15**(6/7) 85-95.

WNOROWSKI, AU and SCOTT, WE (1990) Case histories of algal caused taste and odour problems in South African impoundments. *Proc. of the Symp. of S. Afr. Soc. for Aquat. Sci., Bloemfontein.* 2-4 July.

WNOROWSKI, AU, SCOTT, WE and LE ROUX, JD (1989) Taste and odour occurrence in South African waters. *Proc. of the Symp. of S. Afr. Ind. Water Ass., Johannesburg.* 11-12 September.

WOOD, S, WILLIAMS, ST, WHITE, WR and JONES, F (1983) Factors influencing geosmin production by a streptomycete and their relevance to the occurrence of earthy taints in reservoirs. *Water Sci. Technol.* **15**(6/7) 191-198.

WU, J-T and HSU, Y-M (1988) Relation of algae to earthy odors of fish in Taiwan. *Bot. Bull. Acad. Sin.* **29** 183-188.

WU, J-T and JUTTNER, F (1988) Effect of environmental factors on geosmin production by *Fischerella muscicola*. *Water Sci. Technol.* **20**(8/9) 143-148.

YAGI, M (1988) Musty odour problems in Lake Biwa 1982-1987. *Water Sci. Technol.* **20**(8/9) 133-142.

YAGI, M, KAJINO, M, MATSUO, U, ASHITANI, K, KITA, T and NAKAMURA, T (1983) Odor problems in Lake Biwa. *Water Sci. Technol.* **15**(6/7) 311-321.

YANO, H, NAKAHARA, M and ITO, H (1988) Water blooms of *Uroglena americana* and the identification of odourous compounds. *Water Sci. Technol.* **20**(8/9) 75-80.