Efficient taste and odour removal by water treatment plants around the Han River water supply system

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Abstract Seven major water treatment plants in Seoul Metropolitan Area, which are under Korea Water Resources Corporation (KOWACO)’s management, take water from the Paldang Reservoir in the Han River System for drinking water supply. There are taste and odour (T&O) problems in the finished water because the conventional treatment processes do not efficiently remove the T&O compounds. This study evaluated T&O removal by ozonation, granular activated carbon (GAC) treatment, powder activated carbon (PAC) and an advanced oxidation process in a pilot-scale treatment plant and bench-scale laboratory experiments. During T&O episodes, PAC alone was not adequate, but as a pretreatment together with GAC it could be a useful option. The optimal range of ozone dose was 1 to 2 mg/L at a contact time of 10 min. However, with ozone alone it was difficult to meet the T&O target of 3 TON and 15 ng/L of MIB or geosmin. The GAC adsorption capacity for DOC in the three GAC systems (F/A, GAC and O₃ + GAC) at an EBCT of 14 min is mostly exhausted after 9 months. However, substantial TON removal continued for more than 2 years (> 90,000 bed volumes). GAC was found to be effective for T&O control and the main removal mechanisms were adsorption capacity and biodegradation.

Keywords Biotreatment; GAC; geosmin; methylisoborneol; ozone; taste and odour

Introduction

Taste and odour (T&O) occurrence in drinking water is not a health issue, but an aesthetic matter. However, consumer perception regarding the safety of drinking water is often based on the aesthetic properties, thus T&O issues are regarded as one of the largest dilemmas that most water utilities throughout the world face (Graham et al., 1995). Seven major water treatment plants in Seoul Metropolitan Area, which are under Korea Water Resources Corporation (KOWACO)’s management, take water from the Paldang Reservoir in the Han River System for drinking water supply. The conventional treatment processes effectively control some of the T&O problem, but they do not efficiently remove the T&O compounds that originate from algae or other microorganisms. Therefore, efforts are being made to control the T&O problem at these plants. As part of that, KOWACO is planning to introduce advanced treatment processes in the near future. Practical information is needed for process selection and for the efficient process operation. This study evaluated T&O removal by powder activated carbon (PAC) addition, ozonation, granular activated carbon (GAC) treatment and an advanced oxidation process (AOP) in a pilot-scale treatment plant and bench-scale laboratory experiments. Treatment targets of 3 TON (Threshold Odour Number) and 15 ng/L of geosmin and MIB were used.
**Material and methods**

**Source water**

The water treatment plants around the Han River Water Supply System in Korea draw their source water from the Paldang Lake. The quality of the raw water from November 2000 through August 2004 is summarised in Table 1. The water is of varying quality, with seasonal turbidity and temperature swings. The maximum concentration of total algae cell number and chlorophyll-a concentration in water from the Paldang Lake were 10,857 cells/mL and 76.7 mg/m³, respectively, in the spring.

**Pilot- and bench-scale set-up**

The pilot plant had a capacity of 150 m³/day and was designed to simultaneously evaluate GAC filter adsorbers (F/A), GAC post-filter adsorbers (GAC) and ozone/GAC post-filter adsorbers (O₃ + GAC) after conventional water treatment with alum coagulation, sedimentation and filtration (anthracite/sand). The pilot plant also had pre-ozonation and PAC feed systems. The operation duration of the pilot system was approximately two and half years; March 2003–August 2005. The ozone/air mixture from the ozone generator in the main plant was applied to the pilot plant through a nozzle into the ozone treatment column at an ozone dosage (1–3 mg/L) set to yield a residual ozone concentration of 0.2 mg/L. The transfer efficiency of pre-ozone and post-ozone were 98 ± 1% and 90 ± 1%, respectively. The study evaluated empty bed contact times (EBCT) of 7, 14 and 20 min. The F/A contained 8 × 20 mesh GAC (Calgon Carbon F820) and the GAC post-filter adsorbers contained 12 × 40 mesh GAC (Calgon Carbon F400). The PAC employed in this study was WPH (Calgon Carbon Corp.). During certain times of the pilot plant operation, aqueous MIB and gesomin (WACO Chemical, water based) solutions were spiked into the raw water or into the water after sedimentation with a target concentration of 100 ng/L. Preliminary studies of PAC, ozone and AOP effectiveness were conducted at the bench scale.

**Methods**

Two analytical schemes, including sensory and instrumental methods were employed. In this study, the analytical method for geosmin and MIB used a headspace microextraction gas chromatography-mass (GC-MS) protocol, with routine replicability of ±10–12% and a detection limit of 2 ng/L. The samples were sealed with a septum-lined screw cap, stirred rapidly and extracted for 30 min using a polydimethylsiloxane/divinylbenzene (65 μm fibre coating) solid-phase microextraction fibre that passed through the septum and extended into the headspace. Samples (200 mL) for threshold odor number (TON) measurement were presented in flasks (wide neck 500 mL conical flasks with ground glass stoppers) to trained operators. A detailed procedure can be found in the *Standard Methods* (APHA et al., 1992).

The dissolved organic carbon (DOC) samples were prefiltered with a 0.45 μm-pore membrane filter. DOC analyses were performed using Dohrmann TOC analyzer

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### Table 1 Water quality characters of source water

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>pH</th>
<th>Turbidity (NTU)</th>
<th>Alkalinity (mg/L as CaCO₃)</th>
<th>Total algae cell number* (cells/mL)</th>
<th>Chlorophyll-a* (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max.</td>
<td>24.2</td>
<td>9.3</td>
<td>600</td>
<td>65</td>
<td>10,857</td>
</tr>
<tr>
<td>Min.</td>
<td>1.4</td>
<td>6.5</td>
<td>2</td>
<td>1</td>
<td>1,281</td>
</tr>
<tr>
<td>Mean</td>
<td>13.8</td>
<td>7.8</td>
<td>12</td>
<td>32.5</td>
<td>4,973</td>
</tr>
<tr>
<td>95% value</td>
<td>24</td>
<td>8.8</td>
<td>50</td>
<td>47</td>
<td>8,704</td>
</tr>
</tbody>
</table>

*January 2002 – November 2004
Dohrmann, Phoenix 8000). The methodology followed was in accordance with the manufacturer’s instructions and with Standard Methods 5310C, “Persulfate-Ultraviolet Oxidation Method” (APHA et al., 1992).

Results and discussion
The occurrence and removal of T&O compounds varied during the study. Initially, April 2003 to May 2004, the TON (mainly fishy odour) values in the raw water were in the range of 5 to 13, however, starting in June 2004 the values exceeded 30 with maximums above 50 (mainly earth and musty odours). In the winter and spring of 2004 and spring of 2005, elevated levels of MIB were found with maximums of 26 and 33 ng/L in February 2004 and April 2005, respectively. Geosmin levels remained below 6 ng/L. This constant low level of T&O and occasional peak concentrations indicated that a treatment approach which utilises constant low levels of T&O removal coupled with seasonal peak control will likely be needed. Conventional treatment was successful in reducing the TON values to below 5 for most of the year. However, TON levels in filtered water were above the target value of 3 for 60% of operation period. Finished TON values exceed the target of 3 many times during the year and were above 5 in the spring and fall of 2003 and for nearly all of the 2004 and 2005 seasons. This level of T&O removal by conventional treatment was higher than expected.

Bench-scale PAC results, Figure 1a, shows that meeting the TON target of 3 when the influent geosmin and/or MIB concentrations are at 100 ng/L required extremely high PAC doses (>35 mg/L). While this is not economical, PAC dosed at 20 to 25 mg/L did yield substantial removal; 50 to 80%. Figure 1b shows that increasing the contact time beyond 20 min at a PAC dose of 20 mg/L did not substantially increase the removal beyond the 50–70% range. At these MIB and geosmin influent levels, 100 ng/L, T&O control to the treatment target of 3 TON and 15 ng/L of geosmin and MIB, will not be achieved by PAC alone, which has been shown by other researchers (Herzing et al., 1977; Graham et al., 2000).

Figure 2 shows removal efficiency of ozonation in bench-scale experiments with raw water (pH 7.5 ± 0.3) (2a) and settled water (pH 7.1 ± 0.3) (2b). Ozone at a dose of 1 mg/L oxidized geosmin and MIB (100 ng/L) by 20 to 50% and by increasing the dose to 2 mg/L, an additional removal of up to 15% was seen at the bench scale. At the pilot scale, ozone in the dose range of 1 to 2 mg/L, was a little more effective with geosmin removals in the range of 50 to 75%. However, these removals are not enough for ozone alone to be an effective treatment process during high T&O periods. In this economical dose range, ozone will only remove approximately half of the T&O, thus its effective use will be
limited to geosmin and MIB influent concentrations below 30 ng/L and an influent TON of 6. The optimal ozone dose range was 1–2 mg/L and optimal contact time was 10 min.

The removal efficiency by AOP for geosmin (100 ng/L) was evaluated at the bench scale (pH 7.5 ± 0.3, alkalinity 40 ± 3 mg/L as CaCO₃) at different H₂O₂ to ozone dose ratios (0, 0.1, 0.3, 0.5 wt:wt) at an ozone dose of 1 and 2 mg/L. At an ozone dose of 1 mg/L, H₂O₂ addition was able to increase the removal by 25%, (from 27% with ozone alone to 52%), but at an ozone dose of 2 mg/L, H₂O₂ addition had no impact as the removal remained in the range of 65–71%.

Figure 3 shows the average TON profile through the pilot plant over the period March 2003 to August 2005. Removal by conventional treatment and conventional treatment with ozone was unable to reach the target TON of 3. The three GAC systems at an EBCT of 14 min were able to achieve the target, with few exceptions. Since GAC has a finite adsorption capacity, the performance with time will decrease. Figure 4 shows the DOC and TON values for the three GAC systems at an EBCT 14 min. DOC breakthrough to 0.75 mg/L occurred at approximately 3 months for an EBCT of 7 min (not shown) and 5 months for an EBCT of 14 min. The GAC adsorption capacity for DOC in all three processes was mostly exhausted after 9 months. However, substantial TON removal continued for more than 2 years (>90,000 bed volumes). The raw water TON values increased from approximately 15 to 30 in the spring of 2004. At this time, the F/A yielded a few values above the TON target of 3, after a few months the effluent TON from the F/A returned to 3 or below. The GAC and O₃ + GAC systems all performed very well during this time.

The DOC removal by all three GAC systems was 20–30% over the last year of operation. This long-term removal is likely biological removal, since the chlorine

Figure 2 Removal efficiency of geosmin and MIB for ozone processes; (a) with raw water, (b) with settled water

Figure 3 The average TON profile though the pilot plant over the operation period March 2003 to August 2005, EBCT = 14 min for all GAC systems
residual has been removed by GAC in the upper part of the column. Other researchers have shown that a long acclimation time is needed for biological removal to occur (Huck et al., 1995; Liu et al., 2001; Namkung and Rittman, 1987; Swertfeger et al., 1993; Meyer et al., 2005). While the data are not shown, the effluent TON from the GAC columns at an EBCT of 7 min was nearly the same as it was from the columns at an EBCT of 14 min, even though one has twice as much GAC as the other. This response indicates that the main TON removal mechanism is biodegradation. The F/A and the GAC column at 20 min EBCT were also effective in controlling the TON, with all values below 3 for the duration of the study. After 12 months of operation, the relatively small difference between the TON values in the effluent of the columns at EBCT 20 min (23,000 bed volumes) and EBCT 14 min (36,000 bed volumes) is another indication that adsorption is no longer the main removal mechanism, and that biodegradation likely dominates.

The first 3-day geosmin spike with a target concentration of 100 ng/L was added after approximately 7 months of operation. The effluent geosmin and TON targets were quickly (1–3 days) exceeded at both the 7 and 14 min EBCTs in all three columns. Overall, the 14 min EBCT columns in all three systems produced only a slightly lower effluent, indicating that adsorption was nearing exhaustion. All three systems yielded similar control for geosmin, but the O₃ + GAC system yielded higher TON values compared to the effluent of the other two systems at both EBCTs. This behaviour may indicate that ozone reacted with natural organic matter to form other odorous compounds.

Figure 5 shows the geosmin and TON profiles (averaged two or three samples after 3 days) during the second and third 3-day geosmin spikes (target 100 ng/L) at 12 and 19 months of operation, respectively. The effluent geosmin and TON targets were quickly exceeded with the 14 min EBCT GAC column (<3 days), but not exceeded with 20 min EBCT in either the F/A or GAC column. Intermediate sampling of the 20 min EBCT GAC column at 5, 10 and 15 min EBCTs showed that most of the TON was removed, even after just 5 min EBCT. At the spiking of less than 26 to 61 ng/L in the influent of GAC systems, GAC adsorber and O₃ + GAC processes could meet the treatment target. The better spike control after 12 and 19 months of operation compared to that after 7 months of operation is a strong indication of biological control. In other research, it has been shown that it takes several months for the microbial community to acclimate to MIB and geosmin (Meyer et al., 2005). For this system, the biodegradation seems to be the dominant removal mechanism after 12 months of operation.
A PAC dose of 20 mg/L in the raw water before the GAC pilot plant was found to be effective in one of the two trials. A 45–60% reduction in TON and geosmin by PAC with conventional water treatment was found in the first trial, and only 15% in the second trial. Used only during the high peak T&O episodes, PAC could be used to “shave” the peaks, thus reducing the load on the downstream processes such as GAC.

**Conclusions**

At the influent level (maximum 32 TON, MIB 33 ng/L) the design and operation of the pilot plant GAC and O₃ + GAC processes were very efficient at meeting the treatment target of 3 TON and 15 ng/L of geosmin and MIB. During the high T&O episodes, PAC as a pretreatment together with GAC could be a useful option for T&O control. The optimal dose range of ozone was 1–2 mg/L at a contact time of 10 min. However, with ozone alone it was difficult to meet the T&O target. In this study, the GAC adsorption capacity for DOC in the three GAC systems (F/A, GAC and O₃ + GAC) at an EBCT of 14 min was mostly exhausted after 9 months of operation. However, substantial TON removal continued for more than 2 years (>90,000 bed volumes). During the 3-day geosmin spikes, the GAC system could not control a spike after 7 months of operation, but could control one after 12 and 19 months of operation. It is likely that between the spikes, the biomass on the GAC was able to acclimatise to the T&O causing compounds, and then able to control the second spike, as well as provide long-term control as a biological activated carbon (BAC) system. The results presented in this study have shown that GAC was found to be effective for T&O control and the main removal mechanisms were adsorption capacity and biodegradation. Additional work is necessary to determine the acclimation time for the biofilter.
The frequency and concentration of the influent T&O compounds required to keep the biofilter acclimatised needs to be established. Also, the impact of background natural organic matter on the GAC adsorption capacity for T&O compound needs to be established to optimise the EBCT and GAC replacement frequency.

References


